Evaluating Alternative Operations Strategies to Improve Travel Time Reliability

DETAILS

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The Second

STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-L11-RR-1

Evaluating Alternative Operations Strategies to Improve Travel Time Reliability

KITTELSON & ASSOCIATES, INC.

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The Second Strategic Highway Research Program

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FOREWORD

William Hyman, *SHRP 2 Senior Program Officer, Reliability*

This research report should be of interest and practical value to transportation planners and analysts, including systems engineers. This research resulted in information useful for strategic and performance-based planning, as well as project- and program-level decision making. State departments of transportation and metropolitan planning organizations may be interested in this research as they take steps to comply with the Moving Ahead for Progress in the 21st Century Act (MAP-21) with respect to performance reporting of travel time reliability.

This report sets out requirements for travel time reliability within a performance-based planning process. The authors present two succinct tables that describe requirements for person and freight trips for reliable transport. A discussion of goals, performance measures, and performance targets follows. Performance measures are presented that pertain to roadway users and agencies. The report examines the cost-effectiveness of different ways to improve travel time reliability. The analysis draws from a wide range of literature, but because few data on outcomes of different strategies to improve travel time reliability are available, assessment of cost-effectiveness is qualitative. Nonetheless, in perusing the tables of information, one can form reasonable conclusions about what large, medium, and small expenditures for different types of operations and capacity improvement projects can produce in terms of a small, modest, or large effect on travel time reliability.

The research included an effort to determine the economic value of improvements in travel time reliability by applying options theory from the financial sector. This method is predicated on determining the certainty equivalent of the variability of speed. This innovative approach, briefly summarized in the body of the report and described in an appendix, deserves further exploration despite the lack of consensus from experts about its validity.

A prominent part of the report presents a forecast of the year 2030 under alternative assumptions that may influence travel time reliability. The researchers set out three alternative outcomes—optimistic, mediocre, and pessimistic—regarding climate change, economics, and demographics. In addition, they examined a range of technological developments that might affect reliability. To paint a picture of the future, they prepared a concept of operations for the year 2030. Among the various ways to improve travel time reliability, pricing is strongly emphasized by the researchers.

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Executive Summary

The objective of this project is to identify and evaluate strategies and tactics intended to satisfy the travel time reliability requirements of users of the roadway network—those engaged in freight and person transportation in urban and rural areas. This report presents a set of options related to technological changes, operational solutions, and organizational actions that have the potential to improve travel time reliability both now and in the future (by the year 2030).

An Introduction to Travel Time Reliability

Travel time reliability is defined as the variation in travel time for the same trip from day to day (“same trip” implies a trip made with the same purpose, from the same origin, to the same destination, at the same time of the day, using the same mode, and by the same route). If variability is large, the travel time is considered to be unreliable, because it is difficult to generate consistent and accurate estimates for it. If there is little or no variation in the travel time for the same trip, the travel time is considered to be reliable.

Travel time reliability is important. Variable or unpredictable travel times make it more difficult for travelers and shippers to plan their travel, often forcing them to add extra time to protect themselves against the uncertainty of arrival times. This uncertainty may lead to ineffective or even counterproductive travel decisions that waste time and money.

The basic causes of unreliable travel times are an imbalance between demand and capacity and the congestion that can result. Once congestion occurs, travel times become more variable (less reliable and thus less predictable). Moreover, congested facilities lack the resilience to accommodate unexpected travel interruptions, which leads to flow breakdowns and serious degradation of reliability. Travel times vary from one day to the next because conditions influencing traffic differ each day. The seven sources of congestion that influence travel time reliability are fluctuations in normal travel, physical bottlenecks, special events, traffic incidents, weather, traffic-control devices, and work zones.

These sources of congestion can be aggregated into (*a*) factors that affect the demand for roadway capacity (including normal traffic demand levels, routine fluctuations in that demand, and special events that cause abnormal levels of demand) and (*b*) factors that affect the functional capacity of any roadway or set of roadways (bottlenecks, incidents, weather conditions, work zones, and traffic controls).

Two categories of actions can be used to respond to these factors. The first category, addressing the demand for travel, includes the use of travel information to influence when, where, how, and how much travel (both personal travel and freight movement) occurs. Included in this category is the application of pricing mechanisms to influence travel behavior as well as to generate funds needed for operating, maintaining, and improving the transportation system.

The second category includes actions to increase roadway capacity, such as the following:

- Expansions of or additions to highway facilities;
- Application of better operational and technical systems to maximize the performance of existing infrastructure;
- Advances in technology and procedures that more quickly restore capacity that has been lost as a result of disruptions (incidents, weather conditions, work zones); and
- Optimal use of existing transportation system capacity controlled by other transportation agencies, firms, or individuals. (This can be accomplished by providing incentives for mode shifts from single-occupant vehicles to multi-occupant vehicles and more effective use of alternative rights-of-way.)

The types of solutions that can address demand and capacity imbalances depend on whether congestion can be anticipated or whether it results from unexpected events. When volume routinely approaches or exceeds capacity (recurring congestion), demand management and capacity increases are likely to be effective in improving reliability. In cases in which unexpected disruptions cause the bulk of congestion, techniques that detect disruptions and facilitate rapid recovery from those events are more likely to be effective. Even for situations in which unexpected disruptions cause the majority of congestion, however, strategies for demand management and capacity increase will also warrant consideration. These strategies create a capacity margin that helps to ensure the system's resilience in effectively responding to unexpected events.

Improved Travel Time Reliability: What Is Needed?

The most-significant benefits in improving travel time reliability will be attained when technological changes, operational solutions, and organizational actions are used in an integrated fashion to improve the balance between travel demand and capacity.

A variety of technological changes, operational solutions, and organizational actions currently exist or will become available in the next 20 years. Among the possibilities, with different emphases on economic efficiency and equity, are the following:

- Through better-informed travelers, allocate limited highway capacity to road users that is based on their expected travel time and unreliability (e.g., likelihood of being late). Historically, travel time has been regarded as the primary price road users pay on free roads; this has been the basis for allocating insufficient roadway capacity.
- Charge each road user the full costs for using the roadway network.
- Establish reservation systems and allow people to reserve space in the traffic stream at a specific point in time.

These types of changes, solutions, and actions will allow more effective management of transportation demand, increases in person and freight moving capacity, and faster recovery of the capacity lost to various types of disruptions. A wide range of activities will be employed by groups ranging from individual travelers, carriers, and shippers, to highway agencies, local governments, and private companies that supply services that support roadway operations.

To do this would require decision makers to consider major institutional and functional changes in how our roadways (and the transportation system as a whole) are currently funded and operated. That is, technical improvements, while highly beneficial in specific instances, would provide only a modest benefit to travel time reliability. An important option is to balance travel demand and transportation supply (capacity).

Balancing travel demand and transportation supply would require changes in the following areas:

- Cooperation among all agencies that provide transportation supply to integrate the multimodal transportation services they support to maximize available (useful) capacity.
- Ready accessibility to accurate information describing available travel options, the expected travel times for those options, and the prices to be paid for each option, so that travelers and shippers can make informed choices when planning a trip, just before beginning a trip, and during the trip.
- If pricing is used, charging travelers more directly for the transportation services they receive. Volumes of cars and trucks that use a particular roadway influence prices to reflect both the cost of providing transportation services—to providers as well as to other users—and the value received by the traveler.
- Accountability of agencies for the quality of services they deliver.
- Return of funds generated from user fees to the agencies that supply the multimodal, integrated transportation services to provide a significant incentive to identify, select, and deploy effective services and technologies.

Operating a more reliable transportation system would require a more holistic view of funding, managing, and operating that system than now occurs in the United States. Consumers (individual travelers, shippers, and carriers) would be given travel options, as well as information about those travel options, and would be charged separately and explicitly for each option; the cost associated with each option would reflect the costs of providing those transportation services. Consumers would then be able to select intelligently among different transportation options, by weighing cost against level of service, including reliability. By examining consumer decisions, transportation agencies would learn which travel options are valued and could gain the funds required to supply those travel options through effective pricing.

In this system, some consumers would choose high-cost, faster, more-reliable travel options (e.g., overnight air express shipping, single-occupancy-vehicle commuting on high-occupancy toll [HOT] lanes) for some trips. Other consumers would choose slower options with less-reliable travel times but that would cost them considerably less (e.g., conventional ground shipping, local bus service operating in mixed traffic). The expected results would be as follows:

- Travel consumers have choices and know what those choices are.
- Monetary incentives can be applied in selecting among travel options on the basis of the agency and social costs to provide the services.
- The revenue generated goes toward providing and improving that combination of selected transportation services.

Improved transportation system reliability does not mean that all travel would take place at the available speed limit. It means that consumers will be able to obtain estimates of how long a trip will take, will know that the estimate is reasonably accurate, and can make travel decisions accordingly.

Next Steps for Migrating Toward More Reliability

The most-important changes necessary to produce significant improvements in travel reliability are to (*a*) bring market forces to bear on travel decisions, which results from better and more-ubiquitous information available to all travelers, and (*b*) provide additional supply in a way that is adjusted to demand. As noted at the beginning of this summary, a more reliable roadway system will occur on a sustainable long-term basis only when travel demand and roadway capacity are in balance. Achieving that balance requires a combination of technical improvements. But those technical improvements themselves depend on institutional and attitudinal changes that drive both how our transportation system is operated and how customers (travelers, shippers, carriers) make their travel decisions.

Travel is an economic good. It behaves like all economic goods: when price is low, demand is high; when price is higher, demand is lower. Because price is not an integral part of most current roadway travel decisions, the following results: (*a*) roadway agencies are constantly faced with situations in which demand exceeds capacity, (*b*) the resources to remedy that situation are not being generated and deployed to meet those demands, and (*c*) travelers have insufficient information and incentive to change their behavior so as to travel at less-congested times or by way of alternative modes.

There is a strong argument for market forces to apply to both demand and supply. Economic efficiency increases when the full social costs of travel become part of the travel decision. In addition, there is better resource allocation when the funding generated by travel is spent in those corridors where it is generated to support needed increases in supply (travel capacity). These ideas constitute a major philosophical shift from how our roadway system is currently operated.

As a practical matter, there will continue to be reliance on free roads, a growing emphasis on toll roads and pricing, and the emergence of innovative or relatively untried approaches for addressing imbalances between supply and demand. However, once the shift to a more information-driven approach to travel has occurred, there will be increased demand for expenditure accountability. This would create the incentive systems that are needed to encourage the technical and institutional changes that would result in the appropriate level of travel time reliability (as valued by travelers). These technical and institutional changes include the following:

- An increase in the quality and completeness of traveler information systems, as consumers of travel services demand better information about their choices, the price for their choices, and the performance of those choices;
- A continued rise in the importance of improvements to the real-time control and operational performance of transportation systems;
- The capability to fully integrate highway operations with arterial and transit system operations;
- Better, faster, and more-capable systems for responding to capacity disruptions (e.g., incidents, bad weather) and for restoring capacity lost to those disruptions;
- More engagement of the private sector, especially for the collection and dissemination of information about travel options and the performance of the transportation network; and
- An increase in revenue targeted at capacity enhancements for which demand is high.

To implement these improvements, the following steps have been identified:

- Steps toward balancing demand and capacity;
- Steps to strengthen interagency and intermodal relationships; and
- Technical and technological steps to improve reliability.

Steps Toward Balancing Demand and Capacity

To achieve more-effective market-based strategies for both funding transportation and guiding the expenditure of those funds will require considerable effort. A number of actions can be taken now to facilitate this shift. These include the following:

- Educate the public and decision makers to generate the support necessary for the economic management of roadway capacity. The case is often most easily made if there is a strong connection between where revenue is generated and where improvements are made, although expenditures could be targeted in other ways in the face of market inefficiencies or for equity reasons.

- Select performance measures and the ways that those performance measures are applied to ensure that agencies and jurisdictions are accountable for their actions.
- Participate in more-comprehensive demand management programs (see interagency cooperation below).

Of particular significance is determining the base price–performance level that is acceptable. A congestion-free HOT-lane price is acceptable because low-cost and no-cost general-purpose lanes also exist. However, pricing all roads to the point at which congestion does not exist and roads are perfectly reliable in a currently congested urban area would require setting the price higher than is tolerable for a large segment of the population.

As long as congestion exists, some nontrivial level of travel time unreliability will remain. A part of gaining buy-in to the shift to a more market-based system involves finding the base price point at which a satisfactory balance between price and congestion occurs. That is, how much congestion (and, consequently, how much variability in travel times) will people endure in comparison to how much money are they willing to pay to help manage a limited roadway capacity?

The answers to these basic questions in congested urban areas will undoubtedly differ from those in uncongested rural areas. Answers will also be different in areas with many travel options, as opposed to areas with no acceptable travel options. Of significant interest is the response to pricing on roads in rural areas subject to seasonal (e.g., recreational) traffic congestion. For areas where only limited pricing is possible, use of at least some of the funds to improve traveler information dramatically (so that travelers know the nature of probable delays before they make travel decisions) and improve operations (to minimize delays and maximize reliability) may be the best mechanism for reducing travel time uncertainty and improving travel time reliability. Better information will tell consumers when travel times are not reliable.

Another important step is to reach agreement that funds generated by pricing would be made available to improve all forms of capacity within the corridor in which they are collected. That includes, in some cases, expansion of roadways. This step also includes funding for operations and for alternative sources of capacity, which includes improvements to transit service and parallel arterials. Gaining the buy-in for these types of improvements and balancing these improvements with expenditures will require time and effort.

Equity concerns will likely be among the major obstacles to road pricing, particularly income equity—the impacts of networkwide pricing on low-income travelers. Once the public and its leaders begin to understand the merits of road pricing, equity will become addressable through various paths, which include providing better information on travel and location options, offering alternative services, enhancing transit services, and providing discounts and subsidies.

Steps to Strengthen Interagency and Intermodal Relationships

A more reliable roadway network requires the integration of arterial network operations with adjoining freeway operations. This integration includes adjusting arterial traffic controls to correlate to freeway performance. (This does not mean that arterials must sacrifice local performance in favor of regional travel time reliability; it does mean that local arterials need to operate differently during times when adjacent freeways are unreliable.) Similarly, transit system operations need to be an integral part of corridor demand and capacity management actions. The fact is that a roadway network operates as a system that is independent of jurisdictional boundaries. Network operators need to consider this to foster interagency cooperation.

An important step that the public sector could take now is to work more closely with the private sector. The private sector is making significant technological breakthroughs in both performance monitoring and traveler information. Working with private companies to make use of their expertise has great potential to improve travel time reliability, increase traveler satisfaction, and reduce the public-sector cost of communicating effectively with travelers.

Public agencies could consider the following five actions in the near term to foster interagency and intermodal relationships:

- Change the agency "culture" so that agencies work together (and perhaps even coalesce) to achieve better system performance, rather than working toward only agency-specific goals.
- Strengthen relationships with neighboring jurisdictions, especially when improved integration of facilities benefits the involved agencies (e.g., shared traffic operations centers, multiagency incident-response teams, and corridor management teams).
- Create easily accessed, standardized transportation system performance data and provide them to those who need the data.
- Work with the private sector to support community goals. (For example, encourage the private sector to limit the amount of "cut through" traffic on residential streets by avoiding the use of portable navigation devices to reroute traffic through local streets.)
- Work with private-sector trip generators and private-sector information providers to obtain and disseminate better information on travel demand fluctuations; provide better coordination of demand management activities.

A key element that could help to strengthen interagency and intermodal relationships is the consideration of corridor-based revenue sharing associated with use-based and value-based revenue generation structures.

Technical and Technological Steps to Improve Reliability

Identifying which technical improvements will likely have the greatest impact on travel time reliability by 2030 is a challenge. It is difficult to forecast technical improvements 20 years into the future, especially those that will result in quantum improvements in traffic operations. As noted in the U.S. Department of Transportation's (DOT's) congestion management process, technical improvements will occur in four basic areas:

- Improved capacity from both targeted infrastructure improvements and better operational controls (see, for example, the new operational strategies evaluation tools developed under the SHRP 2 Capacity Project C05, Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs);
- Reduced occurrence of incidents through improved vehicle technology, supported by targeted infrastructure improvements;
- Improvements in the speed of roadway recovery from incident-induced capacity losses; and
- More balance between travel demand and available capacity through better demand management.

The U.S. DOT Vehicle Infrastructure Integration (VII) program (now called the Connected Vehicle Research program) has considerable potential to contribute to many of these areas. But, the simplest technical aspects of the VII program highlight the major technical improvements that are likely to contribute in all of these areas: improved sensors, better communications and sharing of data collected from those sensors, and advanced control and response systems that take advantage of those shared data.

Consequently, the following six technological steps could be taken now to enhance travel time reliability:

- Make previously collected data widely available to partners (see the previous section on strengthening interagency and intermodal relationships).

- Ensure that data collected from new systems can be and are widely shared by establishing common architectures and open data-sharing agreements.
- Actively look for partners, particularly in the private sector, who can provide data that are already collected, which can be useful for improving the demand–capacity balance.
- Actively seek partners, particularly in the public sector, that can leverage data already being collected to improve the demand–capacity balance.
- Establish and use performance measures computed from those data to identify (*a*) the actual causes of unreliable travel time in the areas specific to the agency and its partners and (*b*) the effectiveness of technologies, responses, and actions that are implemented to improve travel time reliability. That is, use the transportation network strategically as a laboratory to continue to learn what works and what does not work in a particular setting.
- Develop and apply more-robust traffic management and traffic-control strategies to improve facility operations, better coordinate those facilities, and improve the use of those facilities through cultivation of "smarter" users.

A shift in the automobile market from a commodity business to a technology innovation service business will have an impact on technological innovations. Infrastructure intervention will be intrinsically related to vehicle automation on the roadway network. Mesh and wireless networks will facilitate vehicle–roadway communications, which will improve traffic flow and reduce travel time variability. The vehicle–roadway system will operate as a mobile communications and information delivery "center" for users. Operation and maintenance of roadway agency communication devices will have to be well planned and structured to meet user (consumer) satisfaction. Innovative technologies will also affect how data sharing and agency cooperation are handled. Transmission of huge amounts of data such as video, audio, and large databases will happen in seconds. This speed will improve interagency cooperation, especially in dealing with incident management. Images and videos from incident locations will be sent to first responders before they reach the scene—helping them to better prepare for restoring traffic operations.

In addition to vehicle technology innovations, the integration of other technological innovations beyond transportation innovations will enhance travel time reliability. For example, the health conditions of travelers will be monitored by vehicles in the future. Breakdown points and specific locations that may threaten health (e.g., heart attacks) can be mapped and linked to traffic congestion patterns. A better understanding of the correlation of traffic and human factors will be achieved.

Transportation infrastructure innovations will also play a role in enhancing travel time reliability. These innovations are anticipated to occur in the three categories listed below.

1. Automation and infrastructure
   - Real-time control of transit arrivals, connections, and pretrip information;
   - Real-time road pricing;
   - Reliability and quality control with pricing;
   - VII implementation;
   - Instant automated incident detection and assessment;
   - Robotic deployment of visual screens;
   - Vehicle automation;
   - Automated, reliable detection of driving under the influence and intervention;
   - 3D video, 3D telepresence, haptic interfaces;
   - Automation in truck operations;
   - Resilient infrastructure; and
   - Wearable computers with augmented reality.
2. Information technology and data sharing
   - Comprehensive real-time information;
   - Video coverage of networks;

   - Reliance on roadside signs for driver information;
   - Weather detection and response systems;
   - Data from vehicle traces (e.g., using the Global Positioning System to track trucks and containers);
   - Data sharing; and
   - Predictive models for real-time systems operation.
3. Integration and cooperation
   - Customized, real-time routing;
   - Multimodal routing, schedules, and trip planning;
   - Real-time information on parking availability, roadway conditions, routing, and rerouting;
   - Rapid incident clearance;
   - Latest onboard technology;
   - Bus rapid transit and signal preemption;
   - Universal fare instruments for transit and road pricing;
   - Real-time condition monitoring to predict long-term infrastructure performance;
   - Combined sensors–computer–wireless link;
   - Advanced automated crash notification systems in all vehicles;
   - Next Generation 9-1-1 fully implemented; and
   - Hybrid wireless mesh networks.

Innovative technologies will support the following actions:

- Optimal routing and matching of supply and demand;
- Real-time knowledge of departures and arrivals and travel times and congestion;
- Dynamic, market-based pricing;
- Funding that more accurately matches network user choices;
- Improved relationship between land use and transportation;
- Understanding and measuring congestion externalities;
- Parking reductions;
- Carpooling initiatives;
- Improved dissemination and sharing of transportation information;
- Street design for multimodal use; and
- Increased transit, bicycle, and pedestrian amenities.

In addition to technological innovations, future concepts of “smart” and “compact” growth and transportation planning will emerge. Integrated technologies will support this ideal vision of the future. However, the integration of ideas and lifestyle rethinking will be the main drivers of this visionary future. Radical changes in land-use patterns will be observed. Commuters will live closer to job locations and related activities. With the full deployment of telecommuting capabilities, suburban areas will see more business centers at which workers who live nearby will work, regardless of their employers’ locations. Government may also support the concept of people living within a certain distance of their place of employment. All of these developments will have a positive impact on travel time reliability by dramatically reducing the miles traveled between jobs and housing.

Summary

Travel time reliability will improve through the collection and use of more and better information, together with agency integration and adoption of shared goals. The application of that information can be used to balance and manage demand and transportation system (multimodal) capacity more effectively. That means using information to actively expand capacity in those places where its value exceeds the cost of that expansion. At the same time, information can be provided to travelers so that they can make informed choices about the best travel option, given their own values of time and reliability.

That same information can be used to determine where best to spend limited resources on capacity expansion and to judge performance of the operational actions and infrastructure improvements that are selected and implemented. Results of those performance reviews would then be fed back into the management decisions that determine which actions to take under specific roadway conditions. That is, agencies would actively use the information that runs the management systems to continually assess the performance of those systems and then work to improve performance. The most-effective improvements to travel time reliability on our transportation network will occur by 2030 when market forces and accessible information allow travelers to plan trips more reliably.

CHAPTER 1

Introduction

The SHRP 2 Reliability Project L11, Evaluating Alternative Operations Strategies to Improve Travel Time Reliability, recognizes the imperative to maximize the value and capabilities of our existing transportation infrastructure; and it aims to do so in the context of a collaborative decision-making process that allows agencies and jurisdictions to make prudent decisions for investing scarce resources. The objectives of Project L11 are to identify and evaluate strategies and tactics to satisfy the travel time reliability requirements of users of the roadway network—those engaged in freight and person transport in urban and rural areas. The intent of this project is to provide a short-term perspective on system operations and travel time reliability and to produce a long-term view with innovative ideas that can be implemented in the future.

Travel Time Reliability

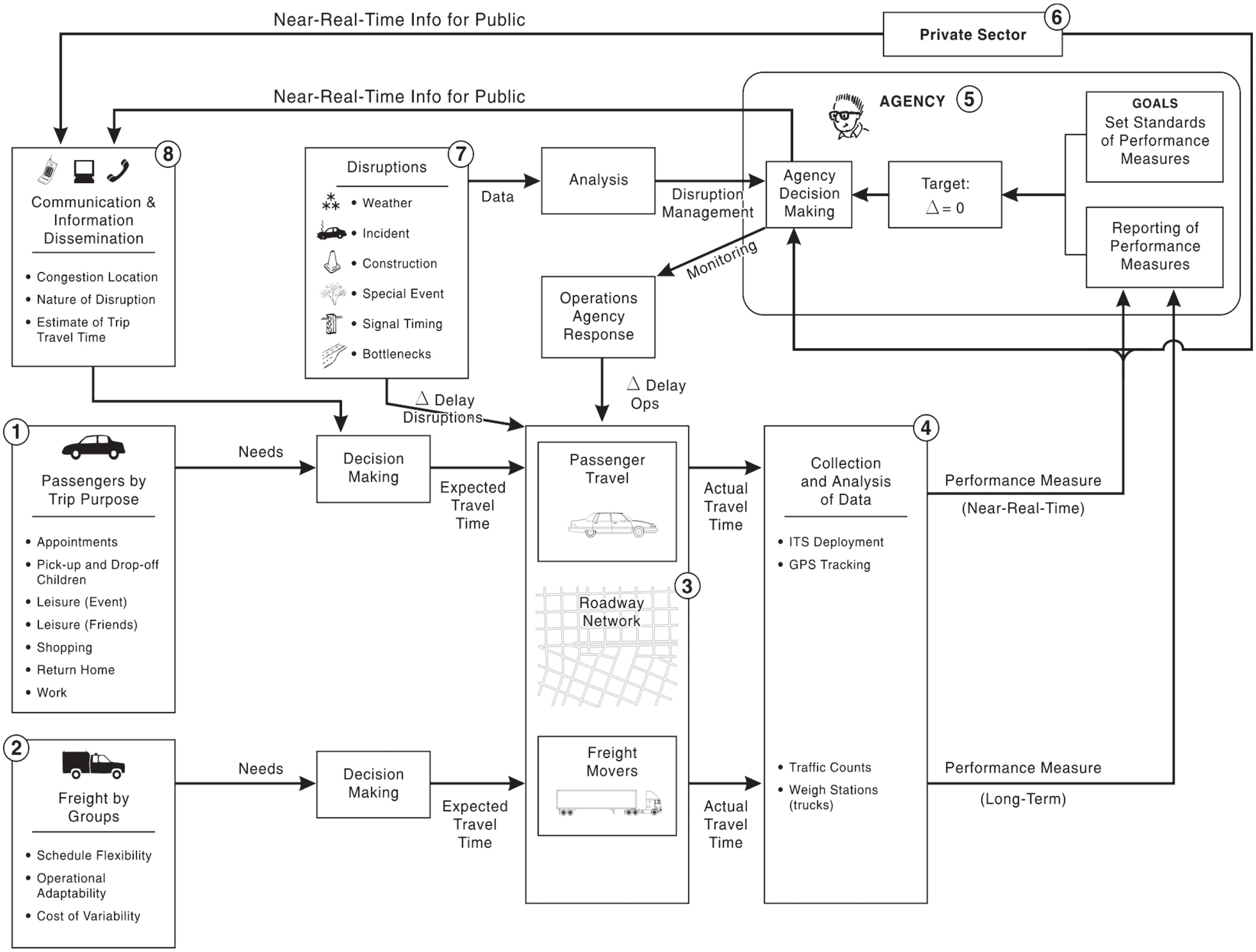
Travel time reliability is related to the uncertainty in travel times. It is defined as the variation in travel time for the same trip from day to day ("same trip" implies a trip made for the same purpose, from the same origin, to the same destination, at the same time of the day, using the same mode, and by the same route). If there is large variability, the travel time is considered to be unreliable. If there is little or no variability, the travel time is considered to be reliable.

The flow diagram in Figure 1.1 shows the travel time reliability interactions among roadway users, agencies, and the roadway network. This diagram illustrates the decision-making process used by passenger travelers and freight movers for travel on the basis of information on travel time reliability. In addition, it illustrates the agency decision-making process, given various disruptions and the agency's goals for performance measures.

The elements of this interaction are numbered in Figure 1.1 and are described in this paragraph. The two roadway user types—passenger travelers and freight movers—have transportation needs. According to these needs, these users make decisions on their trips and estimate an "expected travel time." Although both user types undertake their trips on the roadway network, the expected travel time is affected by delays from disruptions and from agency operational strategies. The actual travel time is collected through an intelligent transportation system (ITS) device or traffic counts. The roadway performance data are analyzed and translated to performance measures. The long-term performance measures are reported regularly and compared with agency goals. The near-real-time performance measures are a direct input for the real-time agency decision making. The disruptions directly affect the roadway network performance. Because the target of agencies is to reach their goals, agency response and monitoring of the roadway network is a process that considers the inputs from the performance measures and from the disruption measures. Another way to minimize the difference between actual and expected travel time is to disseminate information from the agency or from the private sector to passenger travelers and freight movers to assist them in their travel decision making.

Travel Time Reliability and Congestion

Travel time varies from one day to another because the traffic-influencing conditions differ from day to day. The original F-SHRP Reliability Research Plan identified seven sources that not only contribute to total congestion but also often result in unreliable travel times. Although, in general, higher congestion leads to higher unreliability in travel times, there may be instances when a facility is reliably congested but travel time, although high, can be predicted with a high degree of certainty. The results of the SHRP 2 Reliability Project L03 (Cambridge Systematics, Inc. et al. 2013) indicate that background traffic volume is the overriding factor affecting reliability. Therefore, strategies and treatments that mitigate congestion should be helpful in reducing variability in travel time. A brief summary of the seven sources of



Note: GPS = Global Positioning System; ITS = intelligent transportation system.

Figure 1.1. Travel time reliability interactions among roadway users, the agency, and the roadway network.

congestion and how they contribute to congestion (taken from the SHRP 2 L03 study) follows.

1. *Physical bottlenecks* (42%). Bottlenecks are sources of congestion that occur on short segments of roadway that exhibit lower capacity than do upstream segments of roadway, essentially resulting in unreliable travel. Bottlenecks commonly form either at changes in roadway geometry (e.g., lane drops), are caused by crashes, or occur when significant traffic movements reduce effective roadway capacity for a given number of roadway lanes (e.g., merge and weave sections).
2. *Traffic incidents* (39%). Traffic incidents are events that disrupt the normal flow of traffic, usually by physical impedance in the travel lanes. Events such as vehicular crashes, breakdowns, and debris in travel lanes are the most-common incidents.
3. *Weather* (18%). Environmental conditions can lead to changes in driver behavior that affect traffic flow. Weather events such as fog, snow, and heavy rain can negatively affect travel conditions and cause delays and congestion.
4. *Work zones* (1%). Construction activities on the roadway can result in physical changes to the highway environment. These changes may include a reduction in the number or width of travel lanes, lane “shifts,” lane diversions, reduction or elimination of shoulders, and even temporary roadway closures.
5. *Traffic-control devices* (not measured). Intermittent disruption of traffic flow by control devices, such as railroad grade crossings and poorly timed signals, also contribute to congestion and travel time variability.
6. *Fluctuations in normal traffic* (not measured). Variation in day-to-day demand leads to some days with higher traffic volumes than other days.

7. *Special events* (not measured). Special events are a special case of demand fluctuations whereby traffic flow in the vicinity of the event will be radically different from typical patterns. Special events occasionally cause "surges" in traffic demand that overwhelm the system.

Classification of User Categories

Roadway users can broadly be subdivided into passenger travelers and freight movers. Each of these two user groups can be further classified into several categories based on (*a*) their socioeconomic characteristics (in the case of passenger travel) or operational characteristics (in the case of freight) and (*b*) their context of travel. In the case of passenger travelers, the socioeconomic characteristics include attributes such as income, whereas the travel context may be defined by attributes such as trip purpose and mode. In the case of freight movers, the operational characteristics include factors such as size of the fleet and just-in-time delivery, whereas the travel context may be characterized in terms of international border crossings and long-haul trips compared with local travel.

Passenger Travelers

The classification of passenger travelers on the basis of their socioeconomic characteristics requires consideration of the following attributes:

- Income (low, medium, and high);
- Presence of children in the household (yes or no); and
- Employment (not employed, flexible work, inflexible work).

The classification of passenger travelers on the basis of the travel context requires consideration of these attributes:

- Travel purpose (such as work, child escort, appointments, shopping, return to home, and leisure);
- Trip frequency (daily or occasional);
- Flexibility (constrained or flexible);
- Mode (such as single-occupant auto, multi-occupant auto, transit, and walk or bike);
- Time of day (peak or off-peak);
- Trip length (short, medium, long);
- Facilities used (rural freeway, urban freeway, and arterials); and
- Weather (such as rain, snow, and clear weather).

An exhaustive classification scheme taking into account the combination of all factors identified above would result in thousands of categories. This situation would be neither manageable nor useful. Thus, the above categories are aggregated in different ways throughout the rest of this document. Further, the intent of the above classification scheme is to facilitate the analysis of the travel time reliability problem in terms of (*a*) measures of reliability, (*b*) importance, (*c*) severity, and (*d*) contributing factors. Thus, different types of aggregation are adopted that are most appropriate to the aspect of travel time reliability studied.

It was concluded that a broad classification, described in Table 1.1, would be useful for an analysis of the problem of travel time reliability for passenger travelers. Some unconstrained trips, such as visiting friends or shopping, can have "synchronization" constraints. (Note that not all of these trips have such constraints.) That is, unconstrained trips can take place within a fairly flexible time window, but unexpected congestion or the need to account for unreliable travel times has "downstream" implications on the traveler's daily schedule. Consequently, these synchronization effects alter the perceived value of time for otherwise unconstrained trips.

Freight Movers

Freight movers can generally be classified as shippers or carriers. A shipper is an entity or business (such as Walmart) that wants its goods shipped. Sometimes shippers fill their own transportation needs, but generally they contract their shipping needs to carriers. A carrier is in the business of moving freight or goods for shippers.

The extent to which freight movers are affected by and respond to variable travel times is a function of their operating environment. This includes the qualities of their fleet, the goods that they carry, the environment in which they work, and the requirements of the customers that they serve. To some extent, these are dependent. For example, a carrier that moves high-value goods will likely have customers (shippers) that demand narrow windows for delivery. Table 1.2 classifies freight movers by the quality of freight operations. These qualities determine how a particular carrier will respond to, and be affected by, variable travel times.

Table 1.1. Passenger Travelers by Trip Purpose

Broad Classification	Detailed Classification
Daily constrained trips	Work
	Pick up and drop off children
Daily unconstrained trips	Shopping (e.g., grocery)
	Return home
Occasional constrained trips	Appointments (e.g., medical, personal services)
	Leisure (e.g., movies, sports events)
Occasional unconstrained trips	Leisure (e.g., visits to friends)

Table 1.2. Classification of Freight Movers by Quality of Freight Operations

Classification by Quality of Freight Operations	Specific Level Considered Example
Nature of scheduling	Truck arrival scheduled tightly (less than 1-hour window)
	Truck arrival scheduled loosely (1- to 4-hour window)
	Truck arrival not scheduled
Level of contracting	Transportation contracted (inventory cost not incurred by carrier)
	Transportation in-house (inventory cost incurred by carrier)
Relative cost of inventory	Nonperishable or low-value goods
	Perishable or high-value goods
Travel time risk	Short range (many deliveries in 1 day)
	Medium range (two to three deliveries per day)
	Long haul (one delivery per day)
Driver pay	Driver paid by the hour
	Driver paid by the trip
Level of variability	Primarily highway driving
	Primarily arterial driving
Fleet size	Small vehicle fleet (single driver)
	Medium vehicle fleet (fewer than 25 vehicles)
	Large vehicle fleet (more than 25 vehicles)
Connectivity	Meeting connection (intermodal or cross-dock/terminal)
	Not meeting connection (intermodal or cross-dock/terminal)
Schedule flexibility	Trip occurs during peak periods with ability to shift to off peak
	Trip occurs during peak period with limited ability to shift to off peak
	Trip occurs off peak

The different combinations of the criteria listed in Table 1.2 were grouped into three general classifications of freight movers, outlined below.

1. Level of Schedule Flexibility
   - Flexible: Carrier can change schedule to less-congested times or widen time windows with few consequences.
   - Inflexible: Carrier must meet another outgoing vehicle, has limited timing flexibility, and has narrow windows.
2. Level of Operational Adaptability
   - Complete: Carrier can change route, has many deliveries, and has a large fleet of interchangeable vehicles.
   - None: Carrier has a small fleet, many deliveries, and few route choices.
3. Cost of Variability
   - High: Carrier experiences significant costs from travel time variability caused by high inventory and carries burden of variability.
   - Low: Carrier's cost of variable travel times is small.

With these more-general definitions, $2 * 2 * 2 = 8$, unique classifications of freight movers were defined, which are much more manageable and usable, and are shown in Table 1.3.

Travel Time Reliability Requirements

For each of the user categories developed above, there are corresponding requirements in terms of travel time reliability. To obtain an understanding of user needs, the research team conducted a review of literature dealing with travel time reliability. Subsequently, surveys in the form of focus group meetings of roadway users and stakeholders were conducted to supplement prior work done by the research team.

Passenger Travelers

Travelers may perceive the variability in travel time in different ways depending on the context of the trip. Thus, one may have to define measures of travel time reliability that are

Table 1.3. Classification of Freight Movers by Characteristics

Group	Level of Schedule Flexibility	Level of Operational Adaptability	Cost of Variability	Example Company
1	Flexible	Complete	High	Refrigerated carrier; carrier that operates in a very congested arterial network (e.g., grocery store deliveries by large company)
2	Flexible	None	High	Carrier that pays drivers by the hour
3	Inflexible	Complete	High	Carrier that must meet tight time windows for delivery (e.g., delivery companies such as FedEx, or residential moving company)
4	Inflexible	None	High	Carrier that moves air freight or fresh seafood and must deliver within tight time window
5	Flexible	Complete	Low	Carrier that moves natural resources
6	Flexible	None	Low	Carrier that has no delivery time windows
7	Inflexible	Complete	Low	Oversize or overweight specialty movers
8	Inflexible	None	Low	Drayage trucking company

appropriate for different types of trips. The following could serve as reliability measures for trips classified by frequency and flexibility:

- *Daily constrained trips:* The traveler perceives the day-to-day variability in travel time for these trips. Further, the traveler would like to arrive at the destination at a certain time. For these trips, reliability can be defined as the invariability in arrival time at destination from day to day.
- *Daily unconstrained trips:* The traveler perceives the day-to-day variability in travel time, but there is no fixed arrival-time requirement for these trips against which a measure of schedule delay can be calculated. For these trips, reliability can be defined as the invariability in travel time from day to day.
- *Occasional constrained trips:* The traveler does not perceive the day-to-day variability because the trips are not made daily. However, the variability affects the traveler's ability to reach the destination on time. (This is important as these are temporarily constrained trips.) For these trips, reliability can be defined as the ability to reach the destination on time.
- *Occasional unconstrained trips:* The traveler does not perceive the day-to-day variability because the trips are not made daily. Further, there is no fixed arrival-time requirement for these trips against which a measure of schedule delay can be calculated. However, the system reliability may affect how long the experienced travel time is relative to the expected travel time. For these trips, reliability can be defined in terms of how close the experienced travel time is to the expected travel time.

The surveys showed that travel time expectations were based on a combination of personal experience and information from online mapping utilities (such as MapQuest) and Global Positioning System devices. Further, if the trip was undertaken in a familiar area, travelers factored in congestion while estimating travel time. For some participants, reliability meant not encountering congestion. These people did not like "being stopped when they are supposed to be traveling." One participant indicated (in the context of freeway travel) that "if you are taking more than 2 minutes per mile (30 mph), you should probably be looking for an alternate route," which suggests that lower-than-anticipated speed is also a measure of unreliability.

Freight Movers

For freight movers with delivery windows of less than 30 minutes, reliability is related to the frequency that the experienced travel time is within ±15 minutes of the expected travel time. Therefore, it is fair to say that travel times do not need to be predicted with any more certainty than ±15 minutes. However, there are two main issues with this:

1. Narrower windows are not required, in part because they are currently unattainable, and carriers are not willing to promise delivery windows they know they cannot generally make.
2. For carriers that make many deliveries in one day, a series of longer-than-average travel times compound and make it difficult to identify how reliable an individual trip needs to be.

The focus group discussions suggest that travel time reliability is not an issue that has made it to the strategic level and, therefore, is not relayed to the shipper's activities in moving freight. This leaves carriers with little flexibility from the shipper and forces the carrier to manage travel time reliability. This is consistent with the responses from carriers. When asked about their primary transportation concerns, unlike the carriers, shippers mentioned oversize and overweight restrictions and railroads. For instance, Boeing is a manufacturer of very expensive goods that relies on skilled labor and has a long history of activity in the Puget Sound, Washington, area. Concerns about the lack of reliability in travel times have not become so problematic that they have been addressed at the strategic level within the company. Given their cost of goods and their just-in-time operations, they are willing to bear the relatively small cost of having trucks idle. They are driven by service and quality. This means that they will pay more for good service, such as shipping by FedEx. Solutions typically involve adding cost to the carrier in increased wait times.

Importance of Travel Time Reliability

This section depicts the importance (high, medium, low, or unclear) of travel time reliability for each user group according to the outcome of the focus group meetings.

Passenger Travelers

Research has shown that travel time reliability is very important to passengers. In fact, reliability (or consistency) in travel times appears to be even more important than the magnitude of the travel times. ("You expect that it will take 15 minutes and it takes 15 minutes—it does not matter that it was a mile for 15 minutes if you anticipated it.") If it is known in advance that the travel times are going to be long, then the users are able to plan for it. However, if the travel time turns out to be longer than expected, it could disrupt user plans in different ways depending on the nature of the trip. Finally, it is useful to note that people do not appear to be overly concerned about travel times being less than the anticipated values.

This research effort has demonstrated that the actions taken by travelers to deal with unreliability and the consequences when the travel time turns out to be greater than the anticipated value were discussed for seven trip purposes. The importance of travel time reliability for these different trip purposes (currently and in the future) can be inferred from Table 1.4. This table also presents a summary of the reported actions and consequences from the focus group interviews.

Freight Movers

The actions employed by various carriers to deal with unreliability are presented in Table 1.5.

The consequences of variability are different for various companies as a function of their ability to change their operations, their work environment, and the level of flexibility provided to them by shippers. This research effort has shown that shippers are relatively insensitive to the problem of reliability and provide carriers with little flexibility. Exposure to variability is greater in urban areas, areas with congestion, and for companies that rely primarily on arterial travel and those that need to make many scheduled deliveries in 1 day. To address travel time variability, carriers can either change their own operations or ask their customers to make changes (to delivery windows or to delivery times). A carrier's relative exposure to variability is affected by regional characteristics, for example:

- Quality of infrastructure
  - This describes (in general terms) the ability of regional infrastructure to accommodate variable conditions such as increased traffic volumes or severe weather.
    - Resilient infrastructure; and
    - Infrastructure on which service breaks down quickly with varying conditions.
- Environmental conditions
  - This describes the exposure to variability in travel times. For example, an urban region will typically experience more congestion than does a rural environment.
    - Urban; and
    - Rural.
- Weather conditions
  - This describes typical weather patterns in a region, which will affect the exposure to variability in travel times.
    - Frequent weather disruptions; and
    - Infrequent weather disruptions.

Carriers with greater exposure will exercise a stronger response to variability because of their increased frequency of disruption. However, these are not characteristics of the carrier but are characteristics of the region in which they operate.

Travel Time Reliability Performance Measures

It is important to identify travel time performance measures that are relevant to passenger travelers and freight movers with consideration of their respective needs. The following reliability measures, found to be the most relevant to the user categories, are most widely used by transportation agencies:

- *Planning time (95th percentile travel time).* Average trip duration in minutes and seconds for 95% or less of all trips. This measure estimates how bad the delay will be during the heaviest traffic days.
- *Buffer index.* The difference between the 95th percentile travel time and the average travel time, divided by the

Table 1.4. Actions and Consequences of Unreliability for Passenger Travelers

Trip Purpose	Importance of Reliability	Actions to Deal with Unreliability	Consequences of Unreliability
Appointments (e.g., medical, personal services)	High	Schedule appointments in off-peak periods. Allow more time for travel, especially for peak-period appointments and longer-distance trips. Organize day around appointment (medical). Change routes if experienced travel time is high.	Missed appointment and possible missed or late fee. Wait for next available opening; this affects travel for rest of day. Several days elapse before next appointment. Pressure on the travelers.
Pick up and drop off children	High	Allow more time than ideal for the trip. Ask someone else to escort child. May affect residential location and school choices.	Child may miss a class. Anxiety over keeping child waiting. School or day care may charge fee for late pick-up or even call police if lateness is consistent.
Leisure (e.g., movies, sports events)	Medium–low	Schedule during off-peak periods.	Experiencing stress for a trip meant for leisure. Missed event (for one-time events such as sports). Forfeit of money paid for tickets. More difficulty in finding parking.
Leisure (e.g., visit friends)	Low	Call and reschedule or meet somewhere else. Shorten planned visit to meet the start time for next scheduled event.	Guilt for wasting someone else's time.
Shopping	Low	None (especially if unplanned or short trip). Choose off-peak times. Abandon trip or go to a different store. Shorten shopping time and possibly limit number of items shopped for.	None (as long as groceries are not immediately needed). Affects the subsequent trips planned for the day. May miss the sale.
Return home	High–medium	Stop and take a break. Problematic as one may not be able to leave earlier to allow for unreliability in return-home trip. Choose travel time for trip *to* activity so that travel *from* the activity to home is reliable.	Fatigue and stress (especially if kids are traveling). Children at home needing attention. Pets at home needing attention. Ice cream bought at the grocery store can melt!
Work	High	Allow more time than ideal for travel (especially if work schedule is fixed). Prepare for day in advance and wake early. Affects the residential-location choice.	Loss in pay and other types of penalties. Poor reflection. A particular cause of concern in current economy.

Table 1.5. Actions of Unreliability for Freight Movers

Group	Level of Schedule Flexibility	Level of Operational Adaptability	Cost of Variability	Suggestions for Action
1	Flexible	Complete	Large	Move to times and routes when reliable travel is available; widen time windows.
2	Flexible	None	Large	Move to times and routes when reliable travel is available; widen time windows.
3	Inflexible	Complete	Large	Spread particularly congested deliveries across vehicles so that deliveries do not compound throughout the day.
4	Inflexible	None	Large	Increase price for services (because carrier has limited choices).
5	Flexible	Complete	Low	Undertake only cost-effective changes (because cost of variability is low).
6	Flexible	None	Low	Undertake only cost-effective changes (because cost of variability is low).
7	Inflexible	Complete	Low	Undertake only cost-effective changes (because cost of variability is low).
8	Inflexible	None	Low	Undertake only cost-effective changes (because cost of variability is low).

average travel time. This represents the extra time (in minutes or as a ratio) that travelers add to their average travel time when planning trips to ensure on-time arrival. The buffer index increases as reliability gets worse. The buffer index often produces counterintuitive results. When the average travel time decreases (a positive outcome) and the 95th percentile travel time remains high, the buffer index increases—indicating that reliability has become worse. Thus, the buffer index should be used with caution.

- *Planning-time index.* The 95th percentile travel time divided by the free-flow travel time index. The planning-time index can also be understood as the ratio of travel time on the worst day of the month over the time required to make the same trip at free-flow speeds. Consequently, the planning-time index represents the total travel time that should be planned when an adequate buffer time is included.

Although the buffer index shows the additional travel time that is necessary beyond the average travel time, the planning-time index shows the total travel time to complete a trip. The planning-time index is a useful measure during peak travel periods because it can be compared directly to the travel time index on a similar numerical scale.

All these performance measures provide different perspectives and provide additional insight when used with multiple time periods. For example, the 95th percentile travel time can be computed for an entire peak period or for each specific hour within that peak period. Comparing how these measures change over the course of a day illustrates how reliability changes during the day. Tracking changes in these measures by time of day describes whether peak spreading is occurring, what benefits travel demand management programs that change when employees come and go to work are likely to provide in terms of travel reliability improvements, and when incident-response resources are most needed.

In addition to the previously mentioned performance measures, the travel time index, which is the ratio of the travel time in the peak period to the free-flow, could also be used to compare measured travel time conditions to free-flow conditions. However, this index can represent a ratio for one or more trips and, therefore, is not necessarily a travel time reliability measure. A good practice for computing reliability performance is to base it on measurements taken over an extended period of time. The SHRP 2 Reliability Project L03 (Cambridge Systematics, Inc. et al. 2013) recommends that 6 months of data be collected for urban freeways on which winter weather is not a problem. When winter weather causes problems on a significant number of days, more data need to be collected for empirical studies of reliability.

CHAPTER 2

Effectiveness of Agencies

The purpose of this chapter is to describe the current effectiveness of transportation agencies (state, local, toll authorities, and metropolitan planning organizations with operations responsibility), incident responders, and other stakeholders in meeting travel time reliability requirements. This section first mentions existing measures used by agencies to assess travel time reliability or evaluate disruption events. It also describes the issues affecting the effectiveness of transportation agencies on the basis of a comprehensive literature review. Lastly, the effectiveness of agencies by transportation management infrastructure is analyzed.

Existing Agency Measures

In the *Research Results Digest 312* study (Margiotta 2007), interviews were conducted with 10 benchmarking agencies. The study provides an assessment of the state of practice in travel time mobility and reliability measures. For each agency, it provides an assessment of current practices and a determination of unmet needs. The process for applying freeway performance measures is related to decision making for (*a*) data collection, (*b*) operations application, and (*c*) planning application.

Considerable interest has been expressed at the national level in the use and reporting of more reliability-performance measures by these benchmarking agencies. In a number of states (e.g., Arizona with Proposition 400 and Washington with Initiative 900), specific reporting requirements are being adopted into law that require roadway performance reporting of various kinds with particular emphasis on ensuring that taxpayer dollars are spent effectively. At the same time, in the Safe Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), intelligent transportation systems (ITS) projects had to compete for scarce federal dollars along with traditional capacity and maintenance projects. As a result, some states are reporting more extensively on the performance of their roadway systems and on the benefits being obtained from a variety of programs. Information obtained through the Research and Innovative Technology Administration's ITS deployment program (RITA, U.S. Department of Transportation 2009) shows the types of transportation management infrastructure in use in each of the 50 states and in 105 major metropolitan areas. Appendix A contains a summary of the reliability performance measures available to agencies. These measures are necessarily aggregate measures, not personal perceptions or experiences. The measures are based on road segments rather than overall trip variability because the components of specific trips are not known to outside parties. There will necessarily be differences in the views taken of a given level of "reliability" as measured by external data and the views of individuals who value decreases in travel time variance and improvements in travel time reliability.

Current Performance Measures for Passenger Travelers

State roadway agencies have used "output" performance measures in some subject areas for many years. These measures indicate how well the agency is performing. However, the application of performance measurement to roadway reliability performance as perceived by the traveler (i.e., travel time and delay as "outcome" measures) has occurred only recently and is still not widespread.

Output Measures

Most of the performance measures actively collected and reported by roadway agencies relate to what actions are being taken by that agency and how well the agency is performing those actions. These are commonly called output measures. Output measures are excellent for responding to legislative and taxpayer concerns about governmental agency actions. They are also useful for managing personnel and other resources.

Examples of routinely reported output measures include the following:

- Number of variable message signs in place;
- Number of calls to a 511 system;
- Number of events that incident management systems responded to last month; and
- Average duration of an incident management system response.

Outcome Measures

Output measures do not report on the effect those agency actions have on overall changes in travel time or delay. Performance measures that report these conditions and that are more readily applicable to understanding travel time reliability are commonly called outcome measures. For those roadway agencies that have begun reporting outcome measures, the most commonly reported measures are the following:

- Total volume served;
- Truck volumes served;
- Mean travel time experienced;
- Buffer index;
- Planning-time index;
- Travel time index; and
- On-time percentage.

Current Performance Measures for Freight Movers

Many states are moving forward with developing roadway performance measures specifically targeted for freight. The truck-oriented freight performance measures most frequently used by states are roadway-based volume or usage statistics such as truck miles traveled, trucking tonnage carried on the roadway, and route miles usable by trucks. Such information is based on roadway inventories, vehicle volume, and vehicle classification counts that many transportation agencies already collect for a range of other planning and engineering reasons. Because of a lack of data, route-related measures, such as origin–destination patterns, travel-route information, and other factors that involve a truck's entire trip on the transportation network, are often not used. Many state agencies agree with the usefulness of measuring the reliability of freight deliveries but do not have the data to do it accurately. Several states are actively exploring ways to collect the necessary data to report on freight-delivery reliability. Although these programs are not yet fully operational, the measures being explored are discussed below.

One idea is that reliability could be measured as a statistical index derived from travel time, which could be a product of Global Positioning System data obtained from actual truck movements. Several roadway agencies suggest that the portion of trucks arriving on time is the best indicator of the reliability of a highway system from the freight mover's perspective. It was also suggested that the statistic "one standard deviation above an average travel time" could also serve this purpose. This measure is useful and easy to understand. However, it was noted that one major issue in implementing either of these measures is reluctance on the part of carriers to share information with governments. Several of the more-detailed efforts to analyze or develop freight performance measures (in New Jersey, Minnesota, and Texas) have stressed the need for measures that are directly applicable within their organization's institutional framework. In other words, the measures should be able to inform alternative approaches to how a state fosters freight mobility.

Issues Affecting Effectiveness of Agencies

States that are actively looking to report more performance measures for travel time reliability have described a number of concerns about their ability to develop and report reliability-related performance statistics. Staffs from several departments of transportation (DOTs) were interviewed about the issues encountered in gathering and using performance-reliability measures. The following are among their concerns:

- They lack consistent, accurate data, especially when considering their entire roadway systems.
- They lack the budgetary resources to significantly expand their current data collection programs.
- Travel times are affected by a wide variety of factors (e.g., weather, incidents, special events) not directly related to the roadway agency's actions, and some agencies are concerned that reporting performance measures can make an agency look bad when the factors that cause bad performance are beyond the agency's control.
- There is often only a modest link between the actions taken and the travel time reliability changes that occur. For example, adding one more incident-response vehicle to an existing team of 10 vehicles may not result in dramatic changes in travel time reliability, especially if traffic volumes grew during that same time period.
- There is resistance to the adoption of performance measures because of job concerns. As one DOT stated, "Everybody loves performance measures until it [*sic*] affects them."
- The lack of data means that states do not have a current baseline against which to set goals.

Issues affecting the effectiveness of transportation agencies in providing more reliable travel on the nation's transportation system can be divided into the following categories:

- Availability of resources;
- Ability to predict disruptions;
- Access to tools and procedures that remove disruptions quickly or supply additional, short-term capacity increases to compensate for capacity lost because of a disruption; and
- Knowledge of which tools work most effectively for given disruptions and the ability to get feedback on the performance of measures that are applied to improve travel reliability.

An evaluation of an agency involves determining the extent to which the agency has addressed each of these categories of issues.

It is also important to note that because specific agencies are rarely responsible for the roadway used throughout a specific trip, there is an organizational disconnect between how a traveler (person or freight mover) experiences travel reliability and how any given agency views reliability. By definition, agencies are concerned with the performance of their roadways, while travelers are concerned about the entire trip, which generally uses more than one agency's roads. Until agencies are provided with incentives to work together more effectively to manage disruptions and measure the effects of those disruptions on the combined roadway system, the organizational view of their effectiveness will remain somewhat different from that of the traveler and shipper.

Availability of Resources

Most highway operating agencies lack sufficient resources for operations. They may lack the infrastructure necessary to effectively monitor and control their systems or the personnel to operate and maintain their infrastructure. This lack of resources can be a result of operations falling behind other needs such as safety improvements, infrastructure preservation, and the addition of new capacity. It may also be due to a lack of awareness of the benefits of improved transportation operations.

Operational improvements, such as more efficient traffic-signal timing, are not as publicly visible as new construction and thus are not valued as highly as other public expenditures, even though the overall benefit-to-cost ratio might be higher for operational improvements. This lack of resources is a false savings made possible only by externalizing the cost of disruptions to the public in the form of increased delay. For example, many planned special events reimburse highway agencies for the costs of traffic control for those events. The costs of additional traffic operations measures on roadways leading to the event site are often borne by the roadway operating agency.

If an agency lacks the resources to implement these operational measures, the cost is borne by roadway users who experience additional delay and, possibly, accidents. This cost scenario is the same for unplanned special events and recurring congestion. Agencies are also hampered by regulations that discourage creative ways to use resources (staff and equipment) that could be available for incident-response or special events. Considerable improvement in access to equipment and staff could be gained if agencies were able to more effectively share resources (and otherwise cooperate) with other agencies.

Ability to Predict Disruptions

"Unreliable" conditions are caused by unusual events that reduce roadway capacity or increase traffic volumes. If these conditions can be predicted, steps can be taken to either mitigate or prevent the change in the conditions. This preparation often reduces the resources needed to respond to the disruption after the fact. Prediction of unusual conditions can be based on historical conditions that are predictable. For example, Memorial Day weekend has high traffic volumes, so placing incident-response vehicles on duty that weekend can dramatically reduce the effect of incidents on travel time reliability. Prediction of unusual conditions can also be based on (*a*) a network analysis of key locations where responses are most effective or (*b*) analytical factors extracted from other geographic areas that describe the conditions under which unreliable travel occurs.

Access to Tools and Techniques

Once an event or disruption occurs or is identified as "about to occur" (such as when a construction event is being planned), the ability to restore reliable travel conditions is a function of an agency's ability to quickly implement the appropriate response. This means that the agency needs to do the following:

- Understand the nature of the event or disruption;
- Understand what actions or resources are required to deal with that event or disruption;
- Have access to the necessary resources;
- Be able to take the necessary actions (permission is a big issue here); and
- Possess the appropriate management capabilities to apply the necessary resources and actions in the right places, at the right times, and in the right way.

The quality of execution matters as much as the actual effort expended. Keys to the above tasks are the existence of institutional arrangements that allow the following:

- Agencies to access and share resources;
- Functional multiagency protocols for working together;

- Interagency working arrangements that are regionwide, not simply limited to neighboring jurisdictions;
- Training for staff to ensure that these protocols work effectively (and feedback mechanisms to correct those that are ineffective);
- Surveillance and communications systems identifying problems;
- Decision support systems that help responders take the appropriate corrective actions;
- Control systems that either increase the available functional capacity of roadways, corridors, and networks or temporarily dampen travel demand within the affected area until the unreliable condition no longer exists; and
- Support for implementing significant control systems or actions (e.g., closing roadways or ramps) for short periods in response to unusual traffic conditions.

The current SHRP 2 L03 (Cambridge Systematics, Inc. et al. 2013) and SHRP 2 L06 (Parsons Brinckerhoff et al. 2012) projects focus on existing processes and techniques used by transportation agencies with respect to incorporating reliability and were also used as input to this effort.

Knowledge of Effectiveness of Available Tools

The resources necessary to massively overbuild the transportation system are and will continue to be lacking. Therefore, improving travel time reliability requires managing the transportation network at performance levels that are as close to optimum as possible. This management task cannot be accomplished without the ability to monitor the performance of the roadway system. This management task also includes an analysis function that can quantify the ongoing effectiveness (in near real-time and as a result of detailed performance analysis) of each of the operational programs adopted to create a more reliable transportation system. Thus, a key aspect of improving transportation network reliability is having underlying management support systems that describe the following:

- Status and performance of the transportation system;
- Causes of unreliable travel times;
- When and where these events and disruptions take place;
- Size of the impacts these events and disruptions have on travel times;
- Effectiveness of each action taken in response to these events and disruptions; and
- Management support to continually improve operational performance.

Reporting is a good way to be aware of the agency's performance in terms of a comparison from year to year or a comparison between peers to help evaluate and improve an agency's procedures. Including reliability measures and efficiency is a new trend.

CHAPTER 3

Goals and Performance Targets

Given the reliability needs of stakeholders and the ability to manage reliability by agencies, a set of agency goals and performance measures has been identified to improve travel time reliability. This section describes existing data issues and the need for developing goals and performance measures to improve travel time reliability. The section builds on the previous findings and is presented in three parts: (*a*) existing travel performance and disruption data, (*b*) potential performance measures for agency use, and (*c*) developing performance measures and setting goals.

Existing Travel Performance and Disruption Data

An understanding of how reliability of roadway operations affects stakeholders allows for the identification of statistics that track those attributes of roadway performance. However, those statistics are useful only if data can be collected to accurately populate those variables. The current state of the practice is described in terms of the collection of data that describe roadway performance travel time reliability and the factors that can adversely disrupt normal roadway operations and cause delay. This section is divided into (*a*) a summary of data availability, (*b*) roadway performance data, and (*c*) disruption data.

Summary of Data Availability

Because of the cost of collecting data and the relatively low priority of these data in relation to other agency needs, robust travel time reliability performance data are not commonly available throughout the United States. Staff members from several state departments of transportation (DOTs), who were interviewed for this project, indicated that one of the major reasons for a lack of reliability performance measures is their agencies' inability to afford the collection of consistent, accurate travel time and delay data over large geographic areas. Only a few congested urban areas, as well as certain high-profile rural corridors, have deployed traffic management and incident-response functions that supply the data necessary for travel time reliability performance monitoring. A large number of other urban areas, and much of the Interstate system, obtain performance information at a more modest level.

It is technologically possible to collect data on a large percentage of the disruptions to normal operations that cause unexpected travel delays. However, few agencies routinely collect these data, and even fewer make the data readily available for use in decision support systems that can be used to manage roadways to achieve better roadway operations. In large part, the lack of data is due to a combination of the cost of data collection and a lack of incentives to expend scarce resources on improving roadway operations at the expense of infrastructure repair and expansion.

Increasingly, private companies are collecting travel time data as a result of private-sector demand for this type of information. The most significant of these data collection efforts rely on vehicle probe data, currently from fleet tracking data sold to private-sector data aggregators. Several companies hope to be able to obtain Global Positioning System (GPS) information from cell phones for an even more-robust vehicle probe database in the near future. This has the potential for radically changing the availability of travel time and delay information. A number of states now purchase roadway speed data from private companies. These data are primarily available for Interstates and other major freeways. Similarly, increasing emphasis on incident response, roadway operations, and construction traffic management is likely to slowly increase the amount of data available on traffic disruptions. However, considerable improvement will be needed in most of these areas to fully deploy a performance reporting and management system that could improve travel time reliability.

Roadway Performance Data

The SHRP 2 L03 report (Cambridge Systematics, Inc. et al. 2013) provides information about the sources of and procedures related to performance data.

Existing and Future Performance Data

The current availability of travel time reliability and roadway performance information is highly variable across the country. Some performance statistics (e.g., traffic volumes) are widely available in almost all areas of the country but often describe only routine conditions (average annual daily traffic) and not the variation inherent in those conditions. Other statistics (e.g., average annual daily truck traffic) are generally available in all states but are often not available in specific geographic locations (e.g., core urban areas, especially on arterials). Data on the general patterns of traffic volume variation (time of day, day of week, seasonal) are available, but not on a site-specific basis. Other performance statistics (e.g., travel times and travel time variability) are not widely available but exist in great detail in a few selected locations—generally on instrumented freeways in major urban areas or on roads leading to major tourist venues.

However, modern technology is rapidly changing the availability of roadway-system performance data. Data availability is expected to change dramatically in the next 5 years as a variety of new data collection technologies become available and are adopted by transportation agencies. Examples of recent data technology include the following:

- Roadside infrared-sensing technology that allows the collection of detailed vehicle classification data (truck volumes) on high-volume urban roadways without the expense of manual data collection.
- A variety of new technologies (Bluetooth-based travel time computation, multiple cell phone–based vehicle probe tracking technologies, and GPS fleet tracking vehicle probes) show significant potential to dramatically reduce the cost of travel time, speed, and delay information.
- The I-95 Corridor Coalition recently completed acceptance testing of INRIX's near-real-time roadway speed data, which are primarily based on vehicle speed data obtained from a variety of fleet tracking systems. These acceptance tests apply to most of the major freeways on the Atlantic seaboard. The U.S. DOT is sponsoring efforts through the American Transportation Research Institute to collect similar types of data on major rural Interstates throughout the country.

The result of these recent technology improvements is that in the near future, data for travel time and speed could potentially be collected on most major freeway systems at a moderate cost if the data are not already available through existing sources. What is unknown is whether roadway agencies will have the discretionary funding to pay for the collection of these data. Similarly, although many trucking firms do not have data on travel time, some use vehicle-location technology to estimate point-to-point travel times for their vehicles on the basis of historical travel times and use those estimates in fleet and driver planning.

Collection of accurate performance data on urban arterials and smaller rural roadways will still be problematic in the near future, although the Bluetooth and GPS technology cited above offer the potential for significant improvements. On rural roads, data gathering will be most problematic because of the large number of centerline roadway miles and modest number of instrumented vehicles using those roadways at any given time of day, which does not allow for the estimation of travel times within statistically reliable boundaries. The large number of centerline miles means that infrastructure-based technologies, such as Bluetooth or automatic license plate readers, are prohibitively expensive to deploy because of the number of devices required to provide wide geographic coverage. The low volumes on roadways, particularly the low volumes of trucks, mean that an insufficient number of instrumented vehicles may be present to provide statistically valid travel time and delay information when vehicle probes are used for data collection.

Four additional factors complicate the collection of travel time reliability data on urban arterials. The first is the difficulty of accounting for midblock vehicle stops (e.g., short shopping trips and pickup and delivery stops) when vehicle probes are used. Short vehicle stops affect both point-based travel time systems, such as Bluetooth readers, and systems that aggregate spot speed data collected from GPS-equipped vehicle probes. The second difficulty is the effect of control delays on travel time estimates produced from spot speed data collected by vehicle probes. The third difficulty is that vehicles often take a variety of paths within an arterial network. This makes the placement and use of point-based travel time systems less effective (except on simple arterial corridors). Finally, arterial travel times are inherently variable, simply because of the variety of control delays that can affect any given trip. Therefore, a considerable number of travel time runs are required to collect sufficient data to determine statistically valid changes in travel time reliability.

Near-Real-Time Data Versus Long-Term Planning Data

It is important to note that there is a difference in the availability of data in near-real time (used for real-time decision making by travelers, shippers, carriers, and operating agencies) and the availability of long-term planning and reporting data (used for longer-term planning and agency management). The collection and dissemination of data in real-time or near-real time costs more than the collection and dissemination of data within a longer "planning time" horizon. As a result, much of the traffic and truck volume data available around the country are available only well after the fact. The systems that collect these data rely heavily on manual equipment placement and pickup. As a result, data are only available periodically. These data systems serve multiple purposes, are heavily budget constrained, and therefore collect data in the most cost-effective manner possible. The manual equipment placement allows a small number of pieces of data collection equipment and a small staff to collect data at a large number of geographically separated locations at a very modest cost. When collected properly and statistically manipulated, these data collection programs yield fairly good estimates of average facility use. However, the vast majority of data are not available in real time to improve the operational decision making necessary to increase travel time reliability.

Unlike volume data, the majority of travel time data are available in near-real time. This is because these data are primarily collected to improve operational decision making and to provide near-real-time traveler information to the traveling public. In most cases, these data are also stored so that they can be used for later analysis and performance reporting. Unfortunately, not all data that are currently collected and used in real time or near-real time are stored and made available for management and planning purposes. Older traffic management systems built in the 1980s and early 1990s often lack significant data storage and reporting capabilities. The data collected by traffic-signal systems are a primary example. The majority of modern traffic-signal systems have some level of detection on the approaches to intersections. However, most traffic-signal systems routinely discard the data collected at signals. The data are not stored for later use, and even signal systems with good data-collection capabilities often have limited reporting capabilities.

Before the current generation of computer and communications technologies, it was prohibitively expensive to transmit, store, and use these data to report signal and intersection performance. Although technology now makes these tasks much more cost-effective, limited budgets and a lack of incentive to conduct routine performance reporting on arterials has meant that the state of the practice has not changed appreciably, despite changes in costs and capabilities. This is an area in which considerable improvement could occur if priorities allowed the allocation of resources to address the problem.

Disruption Data

A second category of data required for performance reporting describes disruptions that cause nonrecurring travel delays. Without these data, it is impossible to determine whether changes in roadway performance are due to the actions of the operating agencies or changes outside of the control of those agencies. The data are needed for the following reasons:

- To improve roadway agencies' operational decision making in real time;
- To support traveler information services;
- To determine the causes of unreliable travel in planning time; and
- To evaluate the effectiveness of programs implemented to improve travel time reliability.

The availability of data on travel disruptions is similar to that of data on travel times. As a result, data are more commonly available for freeways in congested urban areas with significant operational improvement programs than they are for rural areas, smaller urban areas, and arterials.

Traffic Incidents

Accident data are routinely archived in state databases. Whether these data are available in near real time is a function of whether real-time traveler information or active traffic management activities are ongoing in the geographic region where an accident takes place.

In major urban areas, the private sector often does an excellent job of tracking accidents. These reports are used in private-sector-funded traveler information services funded by the private sector. However, the accuracy of private-sector databases is often not up to the standards desired by some roadway agencies. What may or may not be available along with the accident data (regardless of their public or private source) are statistics on the nature (e.g., size, severity, duration) of the accident, its disruption of roadway operations (e.g., the number of lanes closed), or the response to it. These data tend to be available only where specific incident-response programs have been implemented to collect them. Similarly, data on traffic incidents (stalled or disabled vehicles, debris) are also available only when such programs exist.

Weather

Basic weather data can be obtained from National Weather Service sources throughout the country. However, these data refer to specific geographic locations, and while they are extremely beneficial, they need to be used carefully when applied to other geographic locations. For example, a heavy thundershower occurring at the airport weather station had likely passed through the northern section of town 30 minutes earlier and will affect the southern portion of town 20 minutes from now, if it rains on the southern part of town at all.

Work Zones and Construction

Another major source of disruptions to normal travel time involves construction activities. Most states maintain simple databases that indicate when construction activity is scheduled. Few states have comprehensive, accurate databases that describe actual (as opposed to planned) construction traffic management activities. For example, there are often significant differences between the number of lanes planned for closure during construction and the actual number of lanes closed on a given day and time. While these data can be collected with relatively little technical difficulty, in reality the wide range of agencies, companies, and personnel involved make such data collection difficult to accomplish.

Fluctuations in Demand/Special Events

Fluctuations in demand, especially those caused by large special events, are the next source of traffic congestion. When events are large enough (such as major college or professional football games or Fourth of July fireworks displays) to generate significant traffic congestion, information is generally available that describes the nature of the changes in traffic demand that will occur. Similarly, the time and date of these events are often known well in advance, which allows traffic management plans to be developed to mitigate their effects.

However, a variety of other special events exist for which most agencies do not collect information. Work performed by a variety of researchers has shown how school schedules have a measurable influence on expected travel time performance: travel demand volume decreases during school holidays and increases during the first few days of school terms. When travel demand increases, as a result of these events, just enough to exceed roadway capacity, "unexpected" congestion occurs. The difficulty is in understanding which events are large enough to generate measurable increases in demand during periods when those increases are likely to cause congestion. Few data exist, and it would take considerable work to collect and make available the datasets necessary to develop or apply that information.

Traffic-Control Devices and Signal Timing

Signals and other traffic-control devices also disrupt traffic flow. These disruptions, unlike the disruptions described above are intentional, and they are designed to allow traffic to flow more smoothly more often (as in the case of signals at intersections) by separating conflicting movements by temporarily stopping one of them. The delay caused by stopping one traffic movement to allow another traffic movement to occur safely is commonly called "control delay." In ideal circumstances, these delays have been minimized as part of the design and implementation of the traffic-control system. In many cases, however, the traffic-control plan works less than optimally, because the control system does not adequately account for variations in the traffic volumes being served at that specific time. During times when the traffic-control system is not working as intended, significant decreases in travel time reliability may occur.

Considerable work has been performed in the past 30 years to make traffic-control systems more flexible to improve their performance. The most common of these changes is to allow signal-timing plans to change on the basis of observed traffic volumes. Two examples of such flexibility are the use of signal phases that only occur when vehicles are present to use them (traffic-actuated phases) and variable phase lengths, which change according to the traffic volumes present on conflicting movements (variable phase lengths). Similarly, many freeway ramp-metering algorithms change given a combination of traffic volumes and speeds on the freeway compared to ramp queue length.

Basic data on traffic-control plans, such as signal cycles, phase length, order, signal offsets, and base ramp-metering rates, are routinely available to all traffic agencies operating those traffic-control systems. What is rarely available are the specific timing plans implemented. That is, an agency in control of a signal-timing plan will know that a given green phase is designed to operate for between 30 and 50 seconds, depending on various factors (e.g., the presence of traffic on opposing movements or whether a pedestrian button has been activated). What the agency does not have is a record of exactly what phase length was actually operated over the course of a day, week, month, or year. Rarely (if ever) do agencies track exactly how their signal systems took advantage of the flexibility they have been given. As a result, most agencies do not have a direct means of confirming if their plans are working as intended or whether they could be improved by minor changes in these control parameters.

Bottlenecks

Bottlenecks are most commonly formed either at changes in roadway geometry (e.g., lane drops) or where significant traffic movements reduce effective roadway capacity for a given number of roadway lanes (e.g., merge and weave sections). A number of other causes for bottlenecks also occur. These include common visual disruptions (e.g., the sight of a mountain or lake that drivers encounter only periodically) or physical features such as uphill grades, which can reduce the effective capacity of a roadway.

All roadway agencies have good data on where significant geometric changes cause congestion to occur. Most roadway agencies also have a good understanding of where merges and other major traffic disruptions cause routine congestion, all of which are considered bottlenecks. Data on other types of minor changes in functional capacity that can form congestion routinely enough to be considered a bottleneck can also be obtained by most agencies. However, these less-significant bottlenecks are not as well documented. Those based on visual disruptions are particularly hard to record in that they result from factors not routinely recorded by roadway agencies (e.g., the weather conditions and visibility between a roadway and a distant mountain). The SHRP 2 L03 project (Cambridge Systematics, Inc. et al. 2013) includes information about the sources and procedures for disruption data.

Potential Performance Measures for Agency Use

On the basis of the current needs of highway users and the availability of roadway performance and disruption data, this section discusses the basic performance measures that roadway agencies could report. By combining the needs of individual travelers and freight movers, along with the needs and limitations of agencies, performance measures aimed at improving travel time reliability could be developed within the following three areas:

- Roadway performance: measures related to roadway performance (“outcome” measures).
- Disruption management: measures related to how an agency responds to disruptions in normal roadway operations (“output” measures).
- Information dissemination: measures related to how well an agency informs highway users about current and expected travel conditions to improve their ability to manage their lives and businesses.

Within each of these categories, a variety of measures are needed to understand the performance of the roadway and agency. A good performance-monitoring system will produce and use many performance measures. This report describes only the limited number of measures that could be reported for public presentation, since they are particularly useful in meeting stakeholder needs. It is expected that agencies that are actively managing their resources will produce and internally use a large number of additional measures to examine specific performance issues related to equipment and staff utilization and performance, as well as the performance of facilities with specific functions (e.g., high-occupancy toll [HOT] lanes or other managed lanes). The performance measures suggested within each of the categories listed above are discussed in the following subsections. The last subsection presents a summary of the most useful performance measures.

Roadway Performance Measures

Performance measures relate to the physical performance of a roadway. These measures consider travel demand and a variety of factors both within and outside of the roadway agency’s control. Within physical roadway performance measures, the primary focus is on the fluctuation of travel time across the year given the demand that occurs. Tracking demand and travel times on a continuous basis helps provide a comprehensive picture of the quality of service over time for a particular facility. The following five measures are aimed at characterizing roadway performance:

1. The mean travel time along defined segments of the roadway system at specified times of day, days of the week, and times of year.
2. The 80th percentile travel time of defined segments of the roadway system at specified times of day, days of the week, and times of year.
3. The 95th percentile travel time of defined segments of the roadway system at specified times of day, days of the week, and times of year.
4. The percentage of time or trips, or both, and trips when each of those defined segments of the roadway system operate at lower than a reporting standard adopted by the roadway agency.
5. The traffic volume on defined segments of the roadway system at a specified time of day, day of the week, and time of year.

For reporting purposes, the 95th percentile travel times can be reported as buffer time, planning time, buffer time indices, or planning time indices, depending on the specific question being answered. The 80th percentile travel times can also be presented in similar formats. The first three measures characterize the variability of travel occurring on the roadway system. Three different aspects of that travel (mean condition, 80th percentile, and 95th percentile) are tracked to describe the variability experienced on the roadway segment under study. Three statistics are needed rather than one because of the importance of travel time reliability changes (for both freight movers and passenger travel) from trip to trip, depending on the purpose of that trip. For some trips, arriving on time (before a deadline) is extremely important, and therefore, a traveler might plan with the 95th percentile travel time in mind. For other trips, on-time arrival is less important. A weekend trip to the mall is an example of a trip for which information about the mean travel time is adequate. In many commercial situations, when penalties for late delivery have to be balanced against the cost of unproductive use of labor and equipment, the 80th percentile travel time may be a more useful statistic. Of course, for trucking firms that deliver highly time-sensitive cargoes, the 95th percentile is more likely to be the travel time used for planning purposes.

In addition, the mean travel time is a function of the relationship between vehicular demand and basic roadway capacity. The 95th percentile is often a function of the occurrence and nature of significant travel disruptions (e.g., heavy snowfall, an accident involving large trucks, or significant vehicle fires). Preliminary findings from the SHRP 2 Reliability Project L03 (Cambridge Systematics, Inc. et al. 2013) indicate that on congested urban freeways, the 80th percentile travel time is often a function of the effectiveness of incident-response programs, while the 95th percentile travel time is fairly insensitive to the effects of most incident-response activities. Therefore, all three basic travel time statistics are important for developing comprehensive travel time reliability measures. Each represents a different, but significant, measure of performance.

The fourth suggested performance measure is the percentage of time that a roadway segment fails to operate at a desired level (an adopted performance standard or an adopted performance reporting standard). This statistic simulates an on-time performance measure. It allows the roadway agency to state that a facility should operate at a given level and then track performance against that goal. The difficulty with adopting an on-time performance measure is in setting the expected travel time (or speed) goal against which success will be measured. For general-purpose lanes, this may be free-flow speed, which is often appropriate for roads in uncongested rural areas. In some urban areas, agencies have adopted "speed at maximum vehicular throughput" (roughly 45 mph) as the standard. However, on heavily congested roadways, even this slower vehicle speed standard may result in a large number of "failures" because of high demand in comparison to available capacity. This results in the agency appearing to fail no matter what possible actions it can take within its financially constrained environment. In these cases, slower vehicle speed standards may be adopted.

The last proposed performance measure is of interest mostly to roadway facility managers. Volume (i.e., use) is a key indicator of how well measures to improve or maintain reliability are working. For example, if the implementation of an incident management or ramp-metering program results in a small reduction in the mean and 95th percentile travel times but traffic volumes on the facility double, the conclusion would be that these measures to improve reliability were successful. On the other hand, if the same increase occurred, but volume dropped by 20%, the agency may conclude that these programs were not effective in achieving the desired benefits. Table 3.1 is an example of the various performance measures that can be related to broad passenger traveler needs.

Table 3.2 is an example of the various performance measures that can be related to freight mover needs.

Note that the suggested performance measures only describe the performance of the system. They do not attribute that performance to any given activity or event. As a result, it is desirable to use these measures within the context of the external factors that affect roadway performance. For example, a small increase in mean and 95th percentile travel times is bad, but not if traffic volume on that roadway has doubled. Consequently, performance measures should always be viewed within the context of the larger operations-planning picture.

Travel Difference in Passenger Travelers and Freight Movers

As discussed in previous sections, when considering roadway performance, it is important to note that freight mover performance is likely to be different from passenger traveler performance on a given roadway at a given time. In some cases, this is because the speed limits for trucks are lower than the speed limits for cars. In congested conditions, trucks accelerate more slowly than cars and therefore have travel times that degrade more than those of cars. Work performed in Washington State, Freight Data from Intelligent Transportation System Devices, noted that even before congestion

Table 3.1. Example Performance Measures for Person Travel

Trip Purpose	Importance of Reliability	Performance Measure
Appointment (medical, personal services, etc.)	High	Mean and 95th percentile travel time
Pick up and drop off children	High	Mean and 95th percentile travel time
Leisure (movies, sports events, etc.)	Medium to low	80th percentile or mean travel time (for some leisure activities the 95th percentile is better)
Leisure (visit friends, etc.)	Low	Mean travel time
Shopping	Low	Mean travel time
Return home	High to medium	95th or 80th percentile
Work	High	95th percentile travel time

Table 3.2. Example Performance Measures for Freight Travel

Group	Schedule Flexibility	Operational Adaptability	Cost of Variability	Performance Measure
1	Flexible	Complete	Large	Mean and 80th percentile travel time
2	Flexible	None	Large	Mean and 80th percentile travel time
3	Inflexible	Complete	Large	Mean and 80th percentile travel time
4	Inflexible	None	Large	Mean and 95th percentile travel time
5	Flexible	Complete	Low	Mean and 80th percentile travel time
6	Flexible	None	Low	Mean and 80th percentile travel time
7	Inflexible	Complete	Low	Mean and 80th percentile travel time
8	Inflexible	None	Low	Mean and 95th percentile travel time

develops, trucks generally travel more slowly than cars and that speed difference increases when congestion develops. In addition, trucks often avoid certain roads or peak congestion periods, which makes point-to-point travel times different because the routes used for those trips may be different. In addition, the pickup and delivery schedules of trucks determine when they can travel. Similarly, work schedules define when travelers must leave home on the way to work, which provides for different levels of exposure to routinely congested time periods. It is unclear at this time whether freight mover reliability should be reported differently from passenger traveler reliability for the same roads. Table 3.3 provides example performance measures for roadway users (both passenger travelers and freight movers) as well as for agencies.

Table 3.3. Example Performance Measures for Roadway Users and Agencies

Stakeholder	Factors Related to Performance	Performance Measure	Performance Measure Depends Mainly On
Roadway users: passengers, travelers, freight movers	Travel time (point to point)	Mean travel time	Demand, capacity
		95th percentile travel time	Disruption occurrence, disruption nature, effectiveness of incident response
		80th percentile travel time Percentage centerline miles for which real-time travel information is available and the accuracy of that data Percentage of roadway miles for which disruption data are available Percentage of all disruptions for which a forecast of the effects of that disruption is available	Disruption occurrence, disruption nature, effectiveness of incident response
Agency	Congestion (on a specific roadway segment)	Mean, 80th percentile, 95th percentile travel times for defined roadway segments Percentages of time or trips, or both, during which a segment operates lower than an “on-time” standard adopted by the roadway agency	Demand, capacity “On-time” standards: • Rural: free-flow speed • Urban: “speed at maximum vehicular throughput” (~45 mph) or a slower standard if heavy congestion
		Traffic volume operating on a segment at specified times of day, days of the week, and times of year Percentage centerline miles for which real-time travel information is available and the accuracy of that data Percentage of roadway miles for which disruption data are available Percentage of all disruptions for which a forecast of the effects of that disruption is available	Travel demand Effectiveness of operational decisions and other management actions and policy decisions

Disruption Management

The second category of performance measures describes the number and nature of disruptions that occur on the roadway system and the management actions being taken in response to those disruptions. These measures are used to do the following:

- Define the nature and significance of the sources of congestion or traffic disruptions;
- Monitor the level of effort and the nature of effort committed in responding to the sources of congestion; and
- Monitor the impacts of managing disruptions.

These data also serve as independent variables. When combined with traffic demand, they define the causes of congestion and unreliable travel times. Therefore, to manage the roadway network and to improve reliability, data that describe these disruptions, as well as information on the agency's responses to these disruptions, are required. Other SHRP 2 research efforts and other projects that explore techniques to operate the roadway system more efficiently will define more-detailed ways to quantify disruptions and the responses to those disruptions. For example, SHRP 2 L01 (Kimley-Horn and Associates and PB Consult 2011), SHRP 2 L02 (Iteris/Berkeley Transportation Systems, Inc. et al. forthcoming), and SHRP 2 L13 Reliability Projects (Tao et al. 2011) will all contribute knowledge toward dealing with disruptions and the response programs to mitigate those disruptions. The following are a "first cut" of these independent variables:

Traffic Incidents

The key incident variables are as follows:

- The number and type of incident (crash, disabled vehicle, fire, debris, abandoned vehicle, injury severity if any, truck involvement, hazardous material spill) by time and location;
- A timeline for each incident (start of incident, detection, verification, on-scene arrival, lane or shoulder open, all clear); and
- The number of lanes blocked and the duration of each blockage.

These variables describe the basic scope of the roadway disruption caused by a given incident. A large number of additional variables are needed if the roadway agency expects to evaluate the performance of any response that is sent to the scene. Both NCHRP and the National Transportation Operations Coalition (AASHTO 2006) have published comprehensive guidance on the selection and use of these measures. NCHRP 20-07–Task 215, *Statewide Incident Reporting Systems* (Burgess et al. 2006), and the NCHRP 20-07–Task 202, *Guide to Benchmarking Operations Performance Measures* (Tarnoff et al. 2008), provide more definitive advice on the measures that could be collected and reported to manage and report on incident management systems. The intent, at a minimum, is to track and report two measures:

1. Roadway clearance time: the time between the first recordable awareness (detection, notification, verification) of an incident by a responsible agency and the first confirmation that all lanes are available for traffic flow; and
2. Incident clearance time: the time between the first recordable awareness and the time at which the last responder has left the scene.

Weather

The key weather variables define the following:

- Existence and intensity (amount) of precipitation;
- Existence and intensity (amount) of snow fall;
- Existence of winds strong enough to disrupt traffic flow;
- Existence of visibility restrictions; and
- Existence of temperatures low enough to cause ice formation, in combination with dew point and precipitation information, in order to predict (black) ice formation.

Strong consideration should be given to collecting these in the smallest time increments possible, but not less than hourly. Data as geographically precise as possible are most useful. That is, weather data from a local airport are good, but the weather occurring on a roadway 5 miles from the airport can be considerably different, especially with regard to the timing and amount of precipitation.

Work Zones and Construction

The key construction variables that affect reliability are as follows:

- Location of the construction event;
- Time and duration of lane and shoulder closures by extent of closure; and
- Time, duration, and nature of lane modifications and shifts made during construction activity.

These variables would ideally be reported in real time by staff working at the construction site. The data would then be posted to traveler information sites and broadcast to the traveling public. This rarely occurs, but construction traffic mitigation plans and construction schedules are usually available. These documents outline the planned modifications to the subject travel lanes during the scheduled construction activity and can present a clear picture if they describe both the times of day and the calendar days during which the lane closures will be put in place. Because actual construction activities will differ from these plans as a result of a variety of factors (such as weather and changes in construction plans), these data have limitations, but they are useful when the relative effectiveness of traffic management plans is assessed.

Special Events

The key special event variables are the following:

- Location of the event;
- Attendance at the event (vehicle demand); and
- Duration of the event.

Special events affect the performance of roadways in two ways: (*a*) they significantly increase traffic volumes before and after the event, and (*b*) they change the origin–destination travel pattern of trips by using roadways associated with those events. As a result, these events change the vehicle volume on roadways in the vicinity of the event venue and the parking lots that serve that venue. The above variables allow estimation of those traffic volume changes. The difficulty is in identifying special events. Some events are easy to identify (e.g., large college football games or traditional Fourth of July fireworks displays); but other events (e.g., large company gatherings occurring on weekdays at urban conference centers or stadia) can make identification and data collection difficult. Similarly, attendance at smaller venues may have significant effects near the venue itself but do not noticeably affect the freeways that serve the larger geographic area surrounding that venue. This makes it somewhat challenging to determine which event data to collect.

Traffic Control and Signal Timing

Data on traffic-control plans are needed to understand the level of roadway capacity that roadway agencies are providing. At a minimum, data desirable to maintain include the following:

- Location of all traffic-control mechanisms;
- Time that specific control plans or actions take effect;
- Descriptions of all signal-timing phases (as planned, and if possible, where executed); and
- Location, description, and timing of all non–signal control actions taken (e.g., what messages are placed on which dynamic message signs during which time periods, or what rates are charged on HOT or managed roadway lanes at specific times of the day).

These data allow actual performance of the roadway to be compared against the performance expected from the implemented traffic management plans in order to determine the performance of those control plans and the need for any changes.

Bottlenecks

Specific reporting statistics describing bottlenecks are not recommended in this report. However, the performance data of a roadway operating agency can help identify and understand the causes of bottleneck locations on the roadways.

Information Dissemination

The third category of performance measures deals with improving the passenger traveler and shipper experience and with decreasing the costs associated with unreliable travel conditions.

Regardless of how well an agency (or group of agencies) responds to disruptions of any kind, disruptions will continue to occur. Through the stakeholders meetings, it was confirmed that both passenger travelers and freight movers understand that some level of unreliability will exist on the roadway system as a result of unavoidable disruptions. However, there was near-unanimous agreement that having ready access to information on expected travel conditions is essential in reducing the actual costs imposed by those “slower than desired” conditions. Travelers would gain considerable benefit by having improved access to accurate descriptions of expected travel conditions. To improve their travel decisions and minimize the costs associated with unavoidable delays, both passenger travelers and freight movers require better access to accurate predictions of expected travel times and conditions.

The expected travel times can be calculated from the same data that are used to develop the performance statistics described previously. Once that has been done, the key is to use a variety of applicable mechanisms to make those predictions easily accessible to the public. Regardless of the accuracy of “average” expected conditions calculated from historical data, actual roadway performance will vary from the expected norm because of the occurrence of unexpected or unplanned disruptions (e.g., accidents). Having information about these disruptions and their expected effects on travel times is essential in improving both the decision making and the satisfaction levels of travelers. It also reduces (but does not eliminate) the costs that these disruptions impose on travelers. Therefore, a second key aspect of the traveler information system desired by all the stakeholder customers interviewed is a fast and accurate process for updating their knowledge of current travel conditions. This requires both an effective system for identifying travel disruptions as they occur and good predictive algorithms for estimating the effects that those disruptions will have on expected travel times. Once updated travel conditions are available, it is necessary to have a variety of effective delivery mechanisms for communicating the newly computed expected conditions to all interested travelers.

In response to stakeholder input, the following performance measures describe the types of information that are most useful:

- Percentage of freeway centerline miles for which real-time traveler information is available;
- Percentage of arterial centerline miles for which real-time traveler information is available;
- Percentage of freeway centerline miles for which travel times can be obtained for specific times of the day and days of the week; the accuracy of the information (actual in comparison to predicted);
- Percentage of arterial centerline miles for which travel times can be obtained for specific times of the day and days of the week; the accuracy of the information (actual in comparison to predicted);
- Percentage of urban area roadway miles for which real-time traffic disruption data (such as incidents, accidents, work zone closures, weather-related slowdowns) are available;
- Percentage of statewide rural roadway miles for which real-time traffic disruption data (incidents, accidents, work zone closures, weather-related slowdowns) are available; and
- Percentage of all disruptions for which forecasts of the effects of the disruption, based on the characteristics of the actual disruption, are available.

The private sector will likely play an important role in the dissemination of this information. It is also likely that the private sector will be responsible for the collection of a significant portion of the basic roadway performance (travel time and speed) data. However, the initial collection and preliminary dissemination of much of the disruption data (accidents, incidents, and construction traffic) will be the responsibility of the public sector in that public-sector agencies will be at the scenes of these events. For similar reasons, the public sector will need to supply the descriptive information necessary to predict the effects of those disruptions because the magnitude of the effects is a function of both the nature of the disruption and the response to that disruption. Only the public sector will know the applied response and be able to supply information related to planned work zones. Figure 3.1 presents a flow diagram showing the collection, analysis, and dissemination of performance and disruption information.

Developing Performance Measures and Setting Goals

Identifying performance measures is only the first step in setting performance goals. The second and more-challenging step involves identifying the points at which roadway performance meets the desired goals of transportation agencies, stakeholders, and decision makers. The act of developing performance measures and setting goals logically follows from the needs of stakeholders identified earlier in this report and takes into account the data limitations in developing statistics describing those performance characteristics.

Types of Goals

As noted previously, the challenge is not which measures to use but how to set the standards for judging performance.

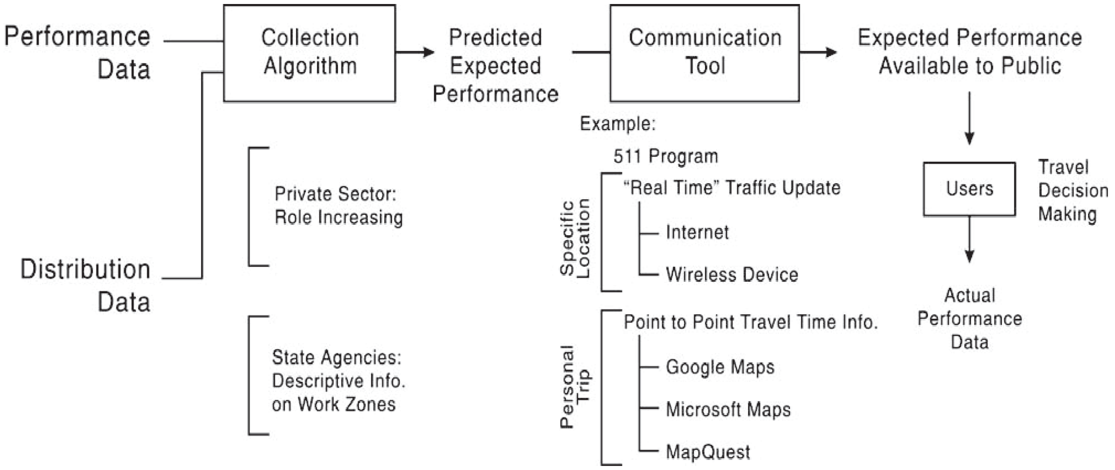


Figure 3.1. Collection, analysis, and dissemination of performance and disruption information.

To do that, it is important to clearly define and evaluate the intended outcome. After all, performance measures are developed to assist in achieving specific outcomes; that is, what are the types of outcomes desired by transportation agencies? A review of currently used transportation agency performance goals shows that intended outcomes can be grouped into three basic categories:

- Improve current performance to meet a technical standard of excellence or optimal level in important areas.
- Challenge an agency to stretch to make dramatic improvements in some area.
- Report current performance in areas for which truly good performance cannot be obtained because of circumstances beyond the control of the agency.

Engineering Optimal Goal

Initially, the first of these performance-goal categories would seem the obvious choice for engineers. For example, an agency might set a roadway reliability goal of having "roadways operate at the speed limit 95% of the time," given the obvious positive implications for both passenger and freight travel.

Unfortunately, the technical difficulties of meeting such a standard in currently congested urban areas make the adoption of such a goal infeasible. In economic terms, the cost of achieving such a goal is not worth the benefits obtained. This is why a more modest goal of "operating the freeways at no slower than the point at which they can carry maximum vehicle throughput" has been adopted in several metropolitan regions around the country. For example, in 2009–10 Executive Organizational Performance Measures and Targets the North Carolina DOT (2010) defines performance measure 2.5 as "percent reduction in expected growth of commuter generated vehicle miles traveled due to transportation options" as "greater than 25%". In other words, the North Carolina DOT decided that it could not expect to control growth and vehicle miles traveled, but it could potentially lower the expected increase. The Washington State DOT has adopted a congestion management guideline that uses maximum throughput productivity as a basis for congestion mitigation measures.

The major challenge of adopting "obvious" performance goals occurs when a goal that can be agreed to easily by users is unrealistic in terms of what the transportation system can provide. When this happens, the providing agency is placed in the very difficult position of publicly failing to achieve its goals or even to make substantial progress toward them. For a public agency that can be easily attacked in the news media, adopting a performance goal that makes the agency look bad, no matter what it does, is something to be avoided at all costs. Therefore, it is important that the performance goals be selected after considering whether the intended outcomes are reasonable.

Two examples of public agencies that had to retreat from their quantitative goals illustrate the challenges of goal setting. A recent one, which is probably also the best known, involved the Minnesota DOT. The Minnesota DOT deployed a large number of ramp meters in the Twin Cities area and operated them to give priority to freeway traffic flow in order to meet freeway performance goals. However, this operations strategy resulted in long ramp queues that generated motorist complaints. Then, public officials began questioning this operations policy. The result was a widely publicized shutoff of the ramp meters and a study of their effectiveness. Ultimately the meters were restored to operation, but a new operating strategy was implemented that balanced freeway performance with ramp-queue delays and impacts on adjacent streets. A legally mandated maximum approach queue setting of 4 minutes was a performance standard imposed on the operating agency by elected officials (Cambridge Systematics, Inc. et al. 2005).

In 1990, the California Air Resources Board (ARB) implemented regulations that required that 2% of vehicles for sale in California in 1998 be zero-emission vehicles. The percentage of zero-emission vehicles was required to increase by 2003 to 10% of vehicles for sale. In 1996 and 2001, ARB had to change these regulations because of the difficulty in implementation and the slow development of appropriate technology (Union of Concerned Scientists 2008).

Stretch Goals

The one exception to not setting "unreachable" goals is when the intent is obviously not to reach the goal but to change the entire concept of what is possible. For example, several states have adopted "target zero" goals of no fatal accidents as part of their safety management systems. The real objective of this second category of goals is not necessarily to achieve that outcome (although such an outcome would certainly be welcome) but to inspire a change in attitude about what is possible and to change the level of resources spent in the hope of producing more-dramatic reductions in the number of fatal accidents. These agreed-upon, but acknowledged as unreachable, goals constitute the second category of performance goals, called "stretch goals." These goals serve very useful purposes, primarily as rallying points around which resources and programs can be planned. The key is that all parties understand that success is not obtained by meeting (or even approaching) these goals but in dramatically changing the status quo, with the intent (and eventual outcome) of achieving a significant change in the performance measured, even if the absolute goal is never reached.

Improvement Goal

This third category of performance goals is often adopted when the desired outcome (e.g., no congestion) is not financially feasible, and when stretch goals are not appropriate, but agencies want to use the information they obtain from a performance monitoring effort to improve their activities. The process generally involves initially measuring performance (setting a baseline) and then setting goals to improve that baseline.

Selecting the Type of Goal

Service industries and most government agencies, which are in reality part of the service sector, have a difficult time setting quantitative performance standards. Manufacturers, in contrast, which have control over the supply of raw materials and produce an easily quantifiable product, can set quantitative performance standards. Transportation agencies, which provide an essential service, may be the industry that has the least control over inputs and operating parameters. Agencies responsible for transportation management have little or no control over the scheduling of both planned special events and unplanned events such as natural disasters. They have no accurate or reliable method to estimate latent demand for transportation facilities. They have no way of controlling what land-use changes will take place. And they have little or no control over how the changes in travel demand will affect the transportation system. For example, there is no way to know if a large family reunion is planned for the coming weekend, if there will be a massive warehouse fire during the next afternoon rush hour, or if someone will run out of gas on a road with no shoulders during the morning commute. As a result, agencies have avoided setting any kind of performance standard, particularly a quantitative one, that they know cannot be met.

The literature review and stakeholder interviews conducted for this project identified few instances in which roadway agencies have adopted policy goals or standards for travel time reliability. Exceptions to this are a limited number of cases involving high-occupancy vehicle lane or HOT lane performance and for which state DOTs have adopted general guidelines stating that urban freeways should operate at no slower than the speed of optimal vehicle throughput.

Another reason for not selecting specific roadway performance goals by the agencies interviewed for this project is that they do not have the necessary data to establish a baseline. As a result, these agencies are reluctant to set goals without knowing whether they can possibly meet them. Consequently, outside of managed lanes, performance goals acceptable to the general public are often stretch goals—even though this is not directly obvious to much of the public (whereas, “zero fatal accidents” is obviously a stretch goal to the public).

Instead of adopting stretch or specific performance goals, transportation agencies have begun adopting improvement goals. As data become available to define the current baseline conditions, agencies set goals to improve those conditions. In terms of travel time reliability, this means setting goals to decrease the current mean travel times and to reduce the frequency of occurrence of extreme travel times (improve travel time reliability) while also reducing the size of the travel time increases when significant disruptions occur—and still accommodating increasing use of the roadway system.

Because travel times differ by time of day (peak versus off peak) and location (large urban versus small urban versus rural), improvements are examined within the context of the current baseline conditions. Similarly, agency operations (e.g., the speed with which incidents are cleared or the number of centerline miles of roadway for which real-time traveler information is available) are compared against baseline conditions. In addition, once baseline conditions are well understood, more-definitive goals can be set for those measures that describe the performance of agency actions.

Suggested Actions for Goals and Targets

By setting goals and performance targets that fit the context of the current situation, agencies can report on the effectiveness of their programs (capacity increases, operational improvements, incident-response programs) for improving roadway performance without being held to a performance standard that assumes a volume-to-capacity ratio that is not attainable. This has the added benefit of keeping agencies from being unfairly singled out for not meeting national standards or for setting unrealistic goals. When publicly acceptable and realistic performance targets can be identified, they may be adopted. Good examples of these exist for managed lanes (e.g., HOT lanes that need to operate in free-flow conditions 95% of the time during peak periods) for which the public has accepted the volume control measures (pricing) and the operating agencies have devoted the incident management resources necessary to allow the goals to be met.

CHAPTER 4

Trends Affecting Travel Time Reliability

This chapter provides an overview of the trends that are anticipated to shape future roadway travel conditions, congestion, and reliability. Particular attention is paid to research documents and other literature related to these topics:

- Demographics, land use, and urbanization;
- Environment and climate change;
- Energy costs and availability;
- Technological innovation;
- Freight; and
- Finance, road pricing, and privatization.

The following sections provide a summary of the research related to future trends that will likely affect system reliability, the demand for roadway travel, and the ability to manage reliability.

Demographics, Land Use, and Urbanization

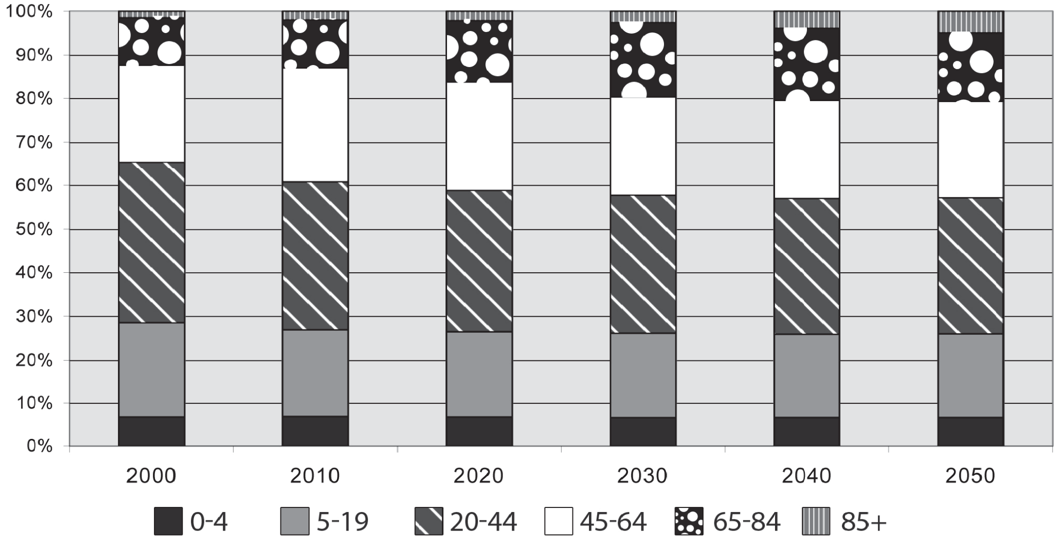
According to the Census Bureau, the U.S. population will increase to 438 million by 2050—a more than 40% increase from the 2008 population of 304 million. This will require more housing, employment, and services, which may lead to large impacts on travel patterns and demands. The United States will increase its population more than any country in the world, primarily because of immigration. And, as the baby boomers continue to enter retirement, the United States faces one of the most-dramatic demographic shifts in its history. The baby boom lasted from 1946 to 1960, during which time the fertility rate in the United States was nearly twice its 20th-century average. Because a high proportion of the current population was born in that period, their age has a strong influence on the average of the population. Accordingly, the U.S. population is, on average, growing older because of the baby boomers, as shown in Figure 4.1.

A U.S. Department of Transportation (DOT) study predicts that vehicle miles traveled (VMT) will grow between 1.91% and 2.26% annually during the next two decades—leading to a 62% total increase from 2001 to 2025. Other key factors that may influence travel and the opportunities to manage it include the following:

- Suburban seniors aging in place;
- Increasing performance capabilities of seniors, and thus, enabling more elderly drivers;
- Increasing percentage of the non-English-speaking population;
- Flattening of the growth in household income;
- Increasing motor-vehicle ownership;
- Increasing level of education;
- Increasing regentrification and densification of central cities; continued growth at the low-density edge of cities;
- Increasing number of multiworker families;
- Increasing prevalence of Internet usage and telecommuting;
- Increasing transit use;
- Decreasing average vehicle size; and
- Increasing level of ride sharing (increasing average vehicle occupancy).

Environment and Climate Change

The U.S. Environmental Protection Agency (EPA) website states: “Scientists are certain that human activities are changing the composition of the atmosphere, and that increasing the concentration of greenhouse gases will change the planet’s climate.” See Figure 4.2 for emissions allocated by economic sector from 1990 to 2005. One of the causes of climate change is the increase in CO_2 emissions, with transportation contributing 24% of the total U.S. greenhouse gases (GHG) in 2006. Furthermore, highway vehicles (passenger cars and trucks) accounted for 79% of transportation CO_2 emissions in 2006.



Source: U.S. Census Bureau.

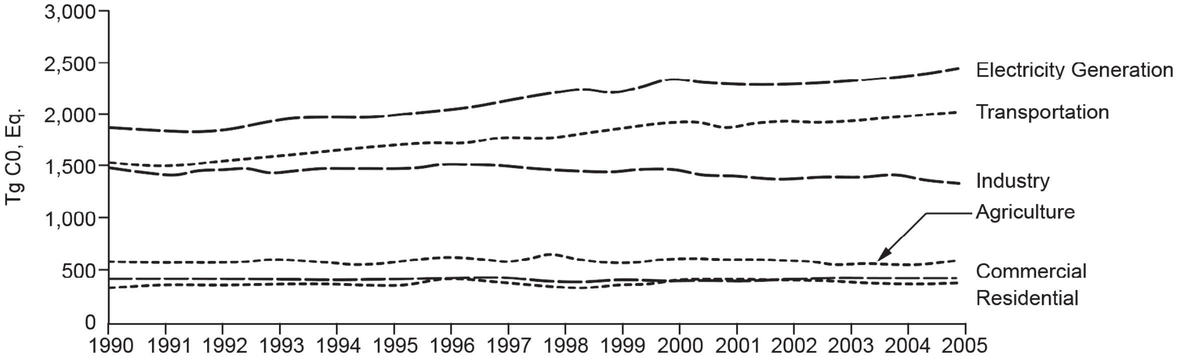
Figure 4.1. U.S. demographic changes.

The growth in GHG emissions is linked to the increase in VMT for the following vehicle categories:

- Light duty: +39% (1990–2006);
- Heavy duty: +58% (1990–2005); and
- Aircraft: +69% (1990–2005).

Climate change will alter weather patterns across the world and lead to an increased occurrence of significant weather events. The most-severe events will lead to major disruptions, including partial or complete evacuations and more-frequent instances of washouts, landslides, and flash flooding. Severe winds will topple trees and scatter debris across our transportation facilities. These events will lead to abrupt and unpredictable lane or road closures affecting passengers and freight on both rail and highways. Severe weather events in the Gulf Coast region may frequently damage oil refineries, causing spikes in motor vehicle fuel prices, such as the one that occurred after the 2005 hurricane season impaired several domestic refineries.

Adverse weather conditions pose a significant threat to the operation of the nation's roads. According to the National Research Council (2008), motorists endure more than 500 million hours of delay each year as a result of fog, snow, and ice. Rain, which occurs more frequently than snow, ice, and fog, leads to even greater delay. Under extreme conditions (such as snowstorms), travel times can increase by as much as 50%. Adverse weather not only degrades traffic flow and increases travel times, but also degrades transportation safety. Aside from these direct weather effects, climate change will lead to other trends that affect travel time reliability. Policy makers may begin to implement hardline measures to reduce GHG emissions. These measures could include adoption of zero-VMT growth policies, heavy taxation of oil, and increased



Source: U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990–2005 (April 2007) Fast Facts USEPA #430-F-07-004.

Figure 4.2. CO_2 emissions allocated to economic sector.

fuel economy standards. In these cases, the importance of integration—coordinating the use of shared resources among agencies and conflicting activities—will be critical at key locations in our transportation system, including intermodal transfer facilities.

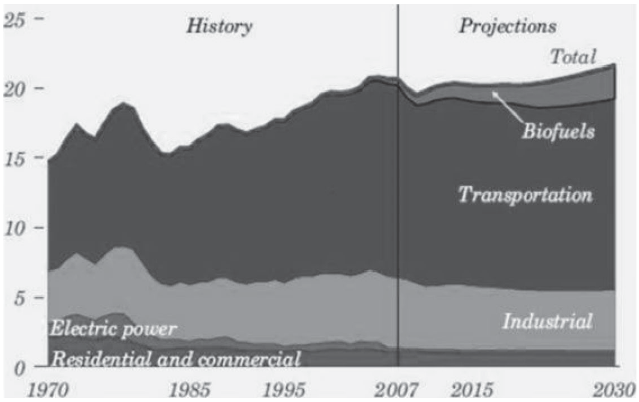
Energy Costs and Availability

The *Annual Energy Outlook 2009* (*AEO2009*) (Energy Information Administration 2009) presents long-term projections of energy supply, demand, and prices through 2030, based on results from EIA's National Energy Modeling System. The projections in *AEO2009* look beyond current economic and financial woes and focus on factors that drive U.S. energy markets in the long term. Key issues highlighted in *AEO2009* include the following:

- Higher but uncertain world oil prices;
- Growing concern about GHG emissions and their impacts on energy investment decisions;
- Increasing use of renewable fuels;
- Increasing production of unconventional natural gas (natural gas extracted from coal beds and other low-permeable sandstone and shale formations);
- Shift in the transportation fleet to more-efficient vehicles; and
- Improved efficiency in end-use appliances.

By using a reference case and a broad range of sensitivity cases, *AEO2009* illustrates these key energy market trends and explores important areas of uncertainty in the U.S. energy economy (Energy Information Administration 2009).

As shown in Figure 4.3, total U.S. demand for liquid fuels is anticipated to grow by 1 million barrels per day between 2007 and 2030 in the reference case, with no growth in oil consumption. Oil use is curbed in the projection by the combined effects of a rebounding oil price, more-stringent corporate average fuel economy standards, and requirements for the increased use of renewable fuels.



Source: Energy Information Administration 2009.

Figure 4.3. Total liquid fuels demand by sector (million barrels per day).

Some of the key projections in *AEO2009* include the following:

- World oil prices will rise to $130 per barrel (real 2007 dollars) in 2030.
- The use of renewable fuels will grow strongly, particularly in the liquid fuels and electricity markets.
- Overall consumption of marketed renewable fuels will grow by 3.3% per year. This includes wood, hydroelectricity, geothermal, municipal waste, biomass, solar, and wind for electric power generation; ethanol for gasoline blending; and biomass-based diesel.
- Significant increase in development and sales of unconventional vehicle technologies, such as flex fuel, hybrid, and diesel vehicles. Hybrid vehicle sales of all varieties will increase from 2% of new light-duty vehicle (LDV) sales in 2007 to 40% in 2030. Sales of plug-in hybrid electric vehicles will grow to almost 140,000 vehicles annually by 2015, supported by tax credits enacted in 2008. Diesel vehicles will account for 10% of new LDV sales in 2030 and flex fuel vehicles will account for 13%.
- The U.S. consumption of primary energy will grow from 101.9 quadrillion British thermal units (Btu) in 2007 to 113.6 quadrillion Btu in 2030, an increase of 0.5% per year (slower relative to history).

Technological Innovation

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) established a federal program to research, develop, and operationally test intelligent transportation systems (ITS) and to promote their implementation. The program was designed to facilitate deployment of technology to enhance the efficiency, safety, and convenience of surface transportation, resulting in improved access, saved lives and time, and increased productivity. Today, some of the common applications of ITS include the following:

- In-vehicle ITS;
- Traffic-signal optimization and retiming;
- Traveler information systems;
- Traffic-incident management;
- Safety service patrols;
- Surveillance and detection;
- Road weather information systems;
- Electronic toll systems and open road tolling;
- Ramp-metering systems;
- Electronic border crossing systems;

- High-occupancy toll facilities; and
- Work zone management systems.

Other key transportation-related technology trends that are anticipated include these:

- Sharp decrease in cost of advanced wireless condition and performance sensors;
- Increased pressure for efficiency of freight logistics, coming from increasing fuel prices or aggressive competition among markets and between modes (one aspect of this is the increased reliance on large-scale intermodal facilities);
- Substantial increases in vehicle fuel economy, either through evolution of the internal combustion engine, new fuels, or radically different energy systems (e.g., hydrogen fuel cells); and
- Increases in capabilities and decreases in costs of broadband communications technologies that support working, shopping, and learning at home.

Freight

The existing freight system is congested and brittle. As a result, even the smallest disruption in service causes great unreliability, congestion, and delay. According to the American Association of State Highway and Transportation Officials, a 90% increase is expected in tons moved domestically by 2035, resulting in approximately 25% of the traffic on the National Highway Systems to be trucks with 8% of this traffic having a high volume. Today, the average mile on an Interstate highway carries 10,500 trucks per day. This number is expected to increase by 2035 to approximately 22,700.

Truck traffic will increase proportionately more than passenger-vehicle traffic, with the most-dramatic growth in urban areas. This increase is due to long-term global growth and globalization, supply chain practices such as just-in-time delivery, and issues such as constrained rail infrastructure capacity, which may move goods from rail to trucks. The limited capacities of already congested port and road infrastructure in urban areas will eventually constrain urban freight growth and truck trips.

It is also expected that the continued shift to just-in-time delivery systems will result in more vehicles hauling smaller truck loads, with greater economic incentives to operate more-efficient light trucks, particularly in urban areas. The future will also see a countervailing trend toward larger trucks, particularly for intercity routes, because these routes will offer increased revenue per ton-mile. Freight paths will become more volatile as global trade patterns shift. Freight and passenger traffic will continue to share the same network for the most part, and hence a future increase in passenger congestion will adversely affect freight traffic and vice-versa. With inadequate funds for new infrastructure along with growth in freight and passenger traffic, conditions are expected to deteriorate, and freight system disruption will be more common. Some of the key freight trends noted by Hillestad et al. (2009) include the following:

- Speed and reliability have deteriorated in the past few years in all freight-transportation modes. Reliability was judged by most users as a key attribute in their transportation choices, sometimes as more important than speed.
- Congestion in urban areas is a factor that significantly degrades freight-system performance.
- Operational improvements that increase efficiency (and reduce cost and environmental impacts) are the most-effective near-term source of increased capacity.
- Potential operational improvements vary from new labor agreements and changed regulations to various information technology applications to increased visibility and control of the system.

Finance, Road Pricing, and Innovation

The current U.S. road pricing and investment policies are such that a gap will continue between available funds and infrastructure investment needs. As a result, increasing levels of congestion and unreliable travel during peak periods will be likely. Pavement and structural deterioration will probably continue throughout the roadway system, especially on lightly built streets and roads. A frequently suggested option is the development of integrated variable pricing and corridor investment policies. Such an approach would allow for a better match between funding and the need for cost-beneficial improvements. Under such a pricing and investment scheme, there is likely to be less of a perceived need for new capacity. The existing capacity of the roadway system can be better utilized through policies such as congestion pricing. Regardless of the specific approach for closing the gap between available funds and infrastructure needs, government will probably have to leverage its resources to obtain private-sector funding through some type of public–private partnership.

The National Transportation Infrastructure Financing Commission has recommended a series of measures to expand the ability of states and localities to fund infrastructure investments. Prominent among the recommended options are measures allowing for the tolling of existing Interstate roadways in large metropolitan areas, facilitation of public–private partnerships to leverage private capital, expansion of Transportation Infrastructure Finance and Innovation Act credit and private activity bond programs, and recapitalization of State Infrastructure Banks.

CHAPTER 5

Alternative Futures

Using Alternative Futures to Identify Trends

The objective of crafting alternative futures is to group the current and potential range of trends and scenarios described in Chapter 1 to identify the following:

- A range of cumulative impacts on the operation of the transportation system and the demands placed on it;
- Frequency of nonrecurring congestion;
- Priorities likely to be placed on mitigating such congestion;
- Technologies that may either exacerbate the problem or facilitate effective responses to it; and
- Broader social and environmental contexts within which the future transportation system is managed.

These alternative futures are not forecasts but rather an attempt to bound the trends that might affect congestion and reliability. To capture the range of possible impacts, these trends were combined to produce a set of three possible future scenarios:

- Alternative 1: The Optimistic Scenario;
- Alternative 2: The Mediocre Scenario; and
- Alternative 3: The Pessimistic Scenario.

Global climate change, the economy, and energy were considered to be the defining variables within each alternative scenario. The first alternative (Optimistic Scenario) features minimal change in severe weather events, strong economic growth (including rapid technology innovation), and stable energy prices. The second alternative (Mediocre Scenario) features typical (historical) weather-related events, moderate economic growth and advancement in technology, and some increases in energy prices. The third alternative (Pessimistic Scenario) describes a future that brings an increase in severe weather, continued economic contraction coupled with little technology growth, and escalating energy costs. For each of the alternative scenarios, likely influences on the other known trends and on the operation of the transportation system and travel behavior are described. In addition, the potential effects of these trends on the sources of congestion are noted.

As the future gets closer, the attributes of the highway system naturally become clearer, and strategies can be adapted to meet more-specific challenges and needs. The immediate task is to develop the strategies and treatments (in the context of a concept of operations) that can be used to ensure the satisfactory performance of the transportation system under any and all of these possible outcomes.

Alternative Future 1: The Optimistic Scenario

The Optimistic Scenario assumes a positive outlook on the future as it relates to climate change, the economy, and energy. A key assumption of this scenario is that technological advances in energy will provide alternative sources of energy at an expense comparable to today's levels. New technology will also dramatically reduce the contribution of transportation to greenhouse gas (GHG) emissions, achieving a 75% reduction in GHG emissions relative to year 2000 levels by 2030. The impacts from climate change are also less severe than expected. In addition to new technology providing a solution to anticipated escalating energy prices and climate change, economic growth is stimulated with a steady increase in employment and population in the United States. The demand for reliable transportation will increase because of (*a*) increased travel demand as a result of strong economic, population, and employment growth and (*b*) new technology making more-reliable transportation systems feasible.

Scenario Drivers

The following subsections provide a summary of the assumptions for the scenario drivers related to Alternative Future 1.

Climate

In addition to addressing greenhouse gas emissions at lower than expected costs through new energy technologies, the impacts of weather trends associated with climate change are not as severe as expected. Occurrence of rare events, such as extreme rains and snow, hurricanes, and tornadoes, will remain consistent with historical patterns.

Economy

Technological advances and relatively stable energy prices lead to strong economic growth, during which gross domestic product (GDP) will increase at 3% to 4% annually over the next 20 years. A new "clean" energy industry will result in population and employment growth coupled with a drop in unemployment to below normal levels (4% to 5%). These demographic trends will increase travel demand, measured in vehicle miles of travel (VMT), 2% annually.

Energy

Innovative and alternative clean-energy technologies will be developed and rapidly adopted to address global energy needs. As a result, energy prices will stabilize, and the cost of addressing climate change is less than expected.

Responding Trends

The secondary effects of this scenario are determined by assessing how current trends and factors will be affected and how they will respond to a moderate climate, strong economic growth, and stable energy prices.

Demographics and Land Use

As a result of stronger economic growth, population growth will remain high, particularly through immigration.

The aging population will phase out of the labor force and into retirement, continuing the aging-in-place phenomenon. Economic growth will have a positive effect on retirees' wealth, resulting in stable VMT per capita for the aging population. Furthermore, advances in medical technology, including both prosthetic and genetic technologies, are likely to increase both life spans and human performance as a function of age. This would keep more single-occupant vehicles on the road and put a floor under demand because the total driving population will be growing.

Through affordable travel and a continued trend of urbanization with population growth occurring in metropolitan areas, spreading of cities and settlement in rural areas will continue. This trend will be supported by communications technologies that facilitate telecommuting and e-commerce.

Technology

Considerable increases in the capability and application of imbedded sensors in all aspects of life are anticipated. For the transportation system, this means access to low-cost, high-accuracy data on component performance and condition. These data would enable a complete understanding of network conditions, congestion, and incidents. The rapid advancement of communications technology will make it possible to deliver performance, route guidance, and rerouting information to travelers wherever they are located. Over time, travelers will learn to use this comprehensive information on the transportation system to adapt their travel choices in terms of cost, time of travel, destination, mode, and route to maximize their own benefits.

There will be continuing and expanded deployment of available intelligent transportation systems (ITS) technologies for incident detection and management, signal coordination, and freeway corridor management. These will include current and emerging technologies as well as new technologies that will see widespread application. Best-practice incident management techniques will become pervasive, and all of these technology deployments will reduce delays and increase reliability.

The vehicle fleet will see notably less dependence on fossil fuels. Unconventional vehicles (vehicles that can use alternative fuels, electric motors and advanced electricity storage, advanced engine controls, or other new technologies) will account for 70% of new light-duty vehicle (LDV) sales in 2020. Hybrids (including standard hybrids and plug-in hybrids) will account for 65% of all new LDV sales, while microhybrids, which allow the vehicle's gasoline engine to turn off by switching to battery power when the vehicle is idling, will have the second largest share, at 25% of unconventional LDV sales. Hybrid and pure-battery technology will be common in heavy vehicles used in short-range travel (e.g., delivery trucks), but most long-distance trucks will be powered by cleaner diesel engines.

Passenger vehicles will be smaller than they are today. In-vehicle ITS technologies will be standard in all new vehicles. These include integrated navigation devices, speed monitors, lane-changing warning devices, radar braking, and so on. These technologies will make driving easier, more efficient, and safer. As a result, there will be a continued reduction in both crash rates and severity. Over-the-road trucks may grow in size because of pressures for increased efficiency. The near-ubiquitous availability of accurate, real-time travel information will influence travel behavior, including departure times, mode, and route choice. This will soften peak periods and increase user expectations for reliable transportation services. Improved technologies and reduced costs will facilitate substitution of telecommuting and teleconference for some travel, thus reducing peak demands on all modes of passenger transportation.

The information revolution will change the characteristics of transit services, not only providing travelers with a broader range of choices, but also supporting management of tight service integration, vehicle meets, and overall end-to-end service connectivity. All fare collection will be electronic, seamless, and will not create boarding and alighting delays. Information and integration will make mixing travel modes, within trips and from day to day, the norm rather than the exception. The result will be higher quality of service for travelers, and as a result, the demand for still more reliability.

There will be substantial improvements in transportation systems integration that smooth the interfaces between modes for both freight and passenger travel. This will effectively reduce the cost of travel and promote multimodal travel. Travel activities around intermodal terminals will increase.

Policy and Institutional Trends

By 2030, through the development and rapid adoption of new technologies, the United States will achieve a 75% reduction in GHG emissions relative to year 2000 levels. Attainment of emission targets made possible by technological advances obviates or reduces the need for regulatory policies restricting energy use and VMT.

Freight Trends

Economic growth and increasing population will result in a rapidly increased demand for freight and freight movements. Congestion due to higher passenger VMT growth and infrastructure capacity limitations will lead to freight mode shifts from truck to rail, water, and (to a lesser extent) air.

Financing Trends

Because of the switch to alternative or highly fuel-efficient vehicles, this future will see extensive application of vehicle-use charges based on location, VMT, and time of day. These charges will become the dominant source of funding for federal highway projects. States and regions will also rely on this funding source. A revenue-neutral VMT user charge, indexed to inflation, will therefore stabilize agency funding.

Public–private partnerships (PPPs) will continue to play a role in financing the highway system through construction and operations of tolled new capacity in urban areas and high-demand intercity corridors. High-occupancy toll lanes and express toll lanes with dynamic pricing will be common.

Effects on Sources of Congestion

The expected travel behavior and the impact that the scenario drivers described for the Optimistic Scenario could have on transportation system reliability are shown in Table 5.1.

Table 5.1. Optimistic Scenario Effects on Sources of Congestion

Source of Congestion	Effects of Scenario Drivers
Traffic incidents	• Possible increase in traffic incidents caused by increased VMT will be offset by safety gains through technological advancements related to ○ Congestion; ○ Run-off-the-road crashes; ○ Weather management; and ○ Incident management.
Weather	• Stable impact of weather on congestion. • Technological advancements.
Work zones and construction	• Comprehensive, accurate data related to construction management activities will provide pretrip information. • Economic growth and technological advancements will allow better integration between various aspects of construction activities; this will allow optimization of construction activities and allow fewer disruptions and congestion for road users. • Automated enforcement of speeds through work zones improves safety.
Fluctuations in demand and special events	• Comprehensive, accurate data related to special event activities will provide pretrip information.
Traffic-control devices and signal timing	• Technological advancements will allow for improved system management (TSM&O). • Widespread automated red-light enforcement improves safety.
Bottlenecks	• Severity of bottlenecks will increase. • Freight-related bottlenecks will increase at modal facilities and transfer centers.

Note: TSM&O = transportation systems management and operations.

Alternative Future 2: The Mediocre Scenario

The driving variables—climate change, the economy, and energy—will be in a range that supports moderate economic growth as well as the deployment of advanced technologies for transportation systems and operations. Energy prices will continue to increase, but supply, in the form of traditional and alternative fuel sources, will be fairly reliable. The demand for reliable transportation will increase because of (*a*) a stronger economy and increased employment, (*b*) pressure for efficiency coming from climate change and energy constraints and regulations, and (*c*) emerging technologies making more-reliable transportation systems feasible.

Scenario Drivers

The following subsections provide a summary of the assumptions of the scenario drivers related to Alternative Future 2.

Climate

Global warming will continue, bringing slightly higher temperatures, rising sea levels, and some coastal flooding. Rare events, such as heavy rains and snows, hurricanes, and tornadoes will become more frequent. These events will affect transportation infrastructure, which will bring about more unexpected failures and service interruptions. Interruptions in electric power will be more common (until transmission infrastructure is renewed and protected). This will affect traffic management systems and the ability to recharge electric vehicles. Under this scenario, the climate is not expected to reach a tipping point, but it may be on or near the borderline.

Economy

The economy will gradually rebound from the current recession and enter a period of moderate economic growth, during which GDP will increase at 2% to 3% annually over the next 20 years. Employment will grow, and the unemployment rate will return to normal levels (5% to 7%). Mostly through immigration, the population will increase at about 0.9% annually. Together, these demographic trends will lead to increased travel demand, measured in VMT. VMT will increase annually at a rate of about 1.5%, as a result of population growth, moderate energy prices, and reasonable transportation services.

Energy

Energy costs will increase slowly after 2010, with much of this increase caused by declining shares of foreign petroleum reaching American shores. Gasoline will be in the range $3 to $5 per gallon. Electricity prices will also rise gradually, pressured in part by the gradual shift toward more electrically powered vehicles.

Responding Trends

The secondary effects of this scenario are determined by assessing how current trends and factors will be affected and how they will respond to increasing rare-weather events, moderate increases in employment and population, and an increase in energy prices.

Demographics and Land Use

Future growth will be dominated by more-compact urban development, infill, downtown regentrification, and revitalization. These trends will be supported by social services and public infrastructure investments to make cities more livable. However, as long as travel service and prices are reasonable, some spreading of cities and settlement in rural areas will continue. The trend toward spreading of cities will be supported by communications technologies in the form of telecommuting and e-commerce. These trends will result in more reliability in cities and less reliability in rural areas.

Technology

There will be continuing deployment of available ITS technologies for incident detection and management, signal coordination, and freeway corridor management. These will primarily be current and emerging technologies that will see widespread application.

Continued deterioration of transportation infrastructure will result in increasing failures. These will interrupt transportation services and decrease reliability. At the same time, there will be widespread deployment of continuous remote monitoring technology to track the condition of surface transportation infrastructure, which will provide more-accurate and more-timely information to guide reinvestment and renewal choices. In the long term, the effect on infrastructure will be positive.

The vehicle fleet will see notably less dependence on fossil fuels. Unconventional vehicles (vehicles that can use alternative fuels, electric motors, advanced electricity storage, advanced engine controls, or other new technologies) will account for 50% of new LDV sales in 2020. Hybrids (including standard hybrids and plug-in hybrids) will account for 65% of all new LDV sales, while microhybrids, which allow the vehicle's gasoline engine to turn off by switching to battery power when the vehicle is idling, will have the second largest share, at 25% of unconventional LDV sales. Hybrid technology will continue to spread to intermediate-duty vehicles used in short-range travel (e.g., delivery trucks), but most long-distance trucks will be powered by cleaner diesel engines.

Similar to the Optimistic Scenario, passenger vehicles will, on average, be smaller than they are today. In-vehicle ITS technologies will become increasingly common. These technologies will make driving easier, more efficient, and safer. As a result, there will be a continued gradual reduction in both crash rates and severity. Over-the-road trucks may grow in size because of pressure for increased efficiency. The availability of accurate, real-time travel information will influence travel behavior, including departure times, mode, and route choice. This will soften peak periods and increase user expectations for reliable transportation services. Improved technologies and reduced costs will facilitate substitution of telecommuting and teleconference for some travel, reducing peak demands on all modes of passenger transportation.

There will be moderate improvements in transportation systems integration smoothing the interfaces between modes for both freight and passenger travel. This will effectively reduce the cost of travel and promote multimodal travel. Travel activities around intermodal terminals will increase.

Policy and Institutional Trends

VMT charges, incentives, and rules to require vehicles to be more efficient will become more common—particularly if pressures from the European Union and elsewhere in the world force U.S. compliance with global regulations. Investment priorities will continue to focus on renewal and rehabilitation, with capacity additions coming mainly through operational, integration, and pricing improvements. Those infrastructure expansions that are implemented will primarily be for providing access to new activities, congestion relief and reliability improvements, service to high-occupancy vehicles, or transit improvements (especially bus rapid transit). Funding will still be scarce. So, not all transportation problems will be solved. There will still be a gap in terms of infrastructure needs. More and better real-time information on system performance and condition and more effective data integration will support more open and better-informed investment decision making.

Freight Trends

Continued economic and population growth will result in a growing demand for freight and freight movements. As energy prices increase the cost of moving freight, the manufacturing of some goods will shift from overseas to the United States, thereby increasing roadway congestion and shifting some freight traffic away from trucks and onto rail and water. Congestion and infrastructure capacity limitations will lead to occasional freight system disruptions.

Finance

A broader application of vehicle-use charges will occur that is based on location and time of day. This will become the dominant source of funding for federal highway projects, and some states and regions will rely on this funding source as well. Charges will be common for separable facilities and for privatized and franchised facilities. These mileage charges will be used, sometimes only lightly, to manage travel demand and thereby reduce congestion. The barrier of interoperability of electronic charging mechanisms will be solved through standardization, but the barriers will remain, and it will not be easy to shift to mileage-based fees during this interval.

PPPs will continue to penetrate the transportation market because of the potential for increasing efficiency and generating profits. All stakeholders in PPPs (franchise holders, lenders, public agencies, users, and the general public) will have a vested interest in objective measurement of facility performance and condition. Travel time reliability will almost certainly be one of these measures. This will increase the demand for good reliability measures and the data to support them.

Effects on the Sources of Congestion

The expected travel behavior and the impact that the scenario drivers described for the Mediocre Scenario could have on transportation system reliability are shown in Table 5.2.

Alternative Future 3: The Pessimistic Scenario

The driving variables—climate change, the economy, and energy—will be in a range that does not support economic growth because of, among other influences, more-frequent rare events and increasing energy prices. In particular, it is assumed that the drivers of change result in worst-case outcomes, such as an increasing rate of climate change, a worsening of economic conditions, and increasing energy prices.

This scenario focuses on the effect of exogenous variables on travel costs and provides the basis for an overall assessment. In this scenario, the demand for reliable transportation will increase because of policies and goals focused on (*a*) reducing fuel consumption, (*b*) decreasing greenhouse gas emissions, and (c) supporting economic growth. With the high value of travel cost, delays become a much stronger economic constraint, so strategies aimed at reducing delays and travel variability become an important component of state and regional transportation strategies to improve system performance.

Table 5.2. Mediocre Scenario Effects on Sources of Congestion

Source of Congestion	Effects of Scenario Drivers
Traffic incidents	• Improvements in in-vehicle detection and control technology, along with reductions in vehicle size, will lead to fewer crashes and reductions in severity related to ○ Congestion; ○ Run-off-the-road crashes; ○ Weather management; and ○ Incident management.
Weather	• Increased frequency of rare events such as tornados, heavy rain and snow storms, flooding, and so on, will cause service interruptions and decrease travel time reliability. • Technological advancements will allow for better system integration and weather management.
Work zones and construction	• Work zones will become more common because of both infrastructure failures and infrastructure maintenance and renewal activities. • Stresses on the aging electrical grid will lead to failures and the need for street and lane closures for utility repairs. • Many jurisdictions will use ITS technologies and more-comprehensive analyses to minimize delays in work zones, but the overall outcome will be decreased travel time reliability.
Fluctuations in demand and special events	• Increasing variations in day-to-day travel demand will result from growing population and relaxation of economic constraints on travel. • Better information dissemination will result in peak spreading, which may improve reliability. • Application of ITS technologies to help plan and manage special events will improve network reliability.
Traffic-control devices and signal timing	• Available technologies will be deployed to interconnect traffic-control devices and make them more adaptable or available to more locations; surveillance technologies and speed smoothing (variable speed limits) will contribute to increase network reliability. • More-effective use of responsive technologies to monitor network performance and condition will contribute to enhanced flow management; these and other technologies will enable collection, analysis, and dissemination of detailed performance and condition data that will support better decisions by system owners, operators, and users to make trips smoother and more reliable.
Bottlenecks	• Some maintenance and renewal funding will be available to address bottlenecks (persistent capacity limitations). • Less funding for infrastructure will retard the pace of resolution of such problems.

Large-scale applications of technology, financial tools, and institutional arrangements will be needed to support this focus on system reliability.

Scenario Drivers

The following subsections provide a summary of the assumptions of the scenario drivers related to Alternative Future 3.

Climate

Expected changes in weather that are to occur over a 40- to 60-year timeframe will occur much sooner. Some of these changes and likely impacts are shown in Table 5.3.

The best scientific evidence suggests that the annual frequency of serious hurricanes along the Atlantic and Gulf coasts will be seven to nine hurricanes by 2030. This scenario assumes

Table 5.3. Pessimistic Scenario Climate Change Impacts

Category	Impact
Precipitation	• Accelerated asset deterioration • Increased incidence of flooding events • Water scarcity and loss of winter snowpack • Increased incidence of wildfires • Shift in ranges of endangered species
Temperature	• Arctic asset and foundation deterioration • Increase in the frequency and severity of heat events • Reduction in frequency of severe cold
Ocean levels	• Inundation of infrastructure • Increase in storm surge intensities
Intense weather events	• Damage to assets • Increased frequency of road traffic disruption, including interruption of emergency routes

nine to 11 hurricanes. The expected increase in average temperature by 2030 is 1°C above current temperatures. Sea-level rise is not likely to show significant change over the next 20 years, and it is assumed that it will not be a dominant factor in defining the climatic condition in 2030. Finally, precipitation intensity and patterns are expected to change over the next 20 years, but not significantly. Over the longer term (40 to 60 years), some parts of the country are expected to experience more droughts, whereas others will be experiencing higher rainfall.

Economy

Recessionary forces will continue to keep growth in GDP low (less than 2% of the annual growth rate), with the possibility of inflation eroding the purchasing power of the American consumer. The federal and many state government debts will remain high, resulting in greater difficulties in borrowing in the bond market. Although governments have used economic stimulus packages aimed at investing in job-intensive projects, few jobs will be created, and the unemployment rate will be around 10%. Low economic growth will result in a decline in disposable income for the average American household, which will lead to a stagnant housing market and continuing decline in international trade. Key industries, such as manufacturing and energy, will lose economic strength. Along with the dismal economic picture, immigration will slow, and overall population growth will not reach the expected value of 325 million by 2030.

Energy

Energy costs will increase significantly, with much of this increase caused by declining shares of foreign petroleum reaching American shores. In some cases, the fuel supply will be interrupted because of unrest in source countries as well as targeted foreign attacks against pipelines and other parts of the distribution system. Even with the increasing cost of energy, average household energy consumption will decline negligibly. However, the cost of transportation will increase significantly, both for the individual traveler, as well as for industry, which will see transportation costs becoming a much greater share of the production cost.

Responding Trends

The secondary effects in this scenario are determined by assessing how current trends and factors will be affected and how they will respond to an increasing rate of climate change, a worsening of economic conditions, and increasing energy prices.

Demographics and Land Use

With increasing travel costs, there will be increased pressure for lifestyles that minimize the amount of income that goes toward transportation. This could mean more mixed-use developments, more-dense development through land-use and zoning regulations, more urban concentration, and more emphasis on safer and better infrastructure for pedestrians and bicyclists.

Technology

Substitution technologies for transportation will be used more often by transportation users. This usage will primarily be due to the high cost of travel and the convenience and affordability provided by telecommunications. Such technologies also represent an opportunity for transportation agencies to convey information in a more-ubiquitous and cost-effective manner.

There will likely be more applications for advanced traveler information services through ITS technologies. Information such as weather information systems, alternate route and mode selection services, and carpooling services will be readily available to permit travelers to determine their desired objective (routes that minimize cost, routes that minimize GHG emissions, and so forth).

In-vehicle hazard identification technologies will be available on a large portion of the vehicle fleet, and strategies such as speed management will be used by transportation agencies to manage system performance.

Policy and Institutional Trends

Government policies will likely be adopted to reduce GHG emissions and to prepare for climate adaptation challenges (such as aggressive policies on fuel consumption and targeted CO_2 reductions). Greater coordination among transportation agencies will occur in order to provide more-efficient, cost-effective transportation, especially across jurisdictional boundaries. More-aggressive policies will be adopted to improve management of the system, such as incident management systems, speed enforcement and management, active traffic management, and so on. Government policy could very well be to provide dollars aimed at stimulating the economy, with much of this investment aimed at transportation systems. Government incentives might be provided to encourage more-efficient freight movement.

Freight Trends

The demand for freight and freight movements will grow modestly. Infrastructure capacity limitation will affect just-in-time (JIT) manufacturing, resulting in more trucking activity to support time-critical business processes. Growing energy prices will increase the cost of moving freight, and the manufacturing of many goods will shift from overseas to the United States. This will shift some freight traffic away from ports, which will increase the use of trucks and contribute to roadway congestion.

Table 5.4. Pessimistic Scenario Effects on Sources of Congestion

Source of Congestion	Effects of Scenario Drivers
Traffic incidents	• With a reduction in VMT, total crashes will decline. • Weather-related crashes will increase and represent a higher proportion of total crashes. • Nature of crashes might change as follows: ○ Congestion-related crashes decrease, and ○ Run-off-the-road crashes increase because of extreme weather.
Weather	• Increased frequency of rare events, such as tornadoes, heavy rain and snow storms, flooding, will cause service interruptions and decrease travel time reliability.
Work zones and construction	• Work zones will become more common because of the following: ○ Infrastructure failures and infrastructure maintenance and renewal activities due to adverse weather, and ○ Government policies to stimulate the economy through public works programs. • Stresses on the aging electrical grid will lead to failures and the need for street and lane closure for utility repairs.
Fluctuations in demand and special events	• With less disposable household income, there will be fewer visits to special events, thus reducing their overall number. • Lower demand for travel will reduce roadway volumes and most likely reduce large fluctuations in demand as well.
Traffic-control devices and signal timing	• Weather-related disruptions will disable traffic-control devices on more occasions. • Higher energy costs could affect the ability of operating agencies to operate signal systems or any other system requiring energy consumption.
Bottlenecks	• Weather-related bottlenecks will increase in number and severity. • Given reduced travel volumes, the severity of existing bottlenecks will decline for both passenger and freight movements.

Finance

The national government may take steps to use technology to enhance revenue collection (e.g., VMT tax). With economic stimulus a national or state goal, there will likely be more government funding for capital investment and operations/management (although this funding will likely come from non–gas tax revenues).

Given the declining road revenues from gas tax receipts (due to declining VMT, use of higher-efficiency vehicles, and mode shifts), there may be increased interest in PPPs.

Effects on Sources of Congestion

The expected travel behavior and the impact that the scenario drivers described for the Pessimistic Scenario could have on transportation system reliability are shown in Table 5.4.

Summary of Alternative Futures

The possible range of future outcomes for the three scenarios is summarized in Table 5.5. These three scenarios help to define the possible range of impacts. This summary spans the set of reasonable predictions that are taken from a variety of studies. It provides a basis for developing a robust set of concepts of operations for the future. These future scenarios also highlight the significant changes that may unfold in the future and may help departments of transportation, metropolitan planning organizations, and members of the transportation industry to ensure that our infrastructure, both physical and institutional, is prepared to address transportation needs during the next 20 years.

In response to the scenario drivers and responding trends that are shown in Table 5.5, agencies and the private sector have an opportunity to begin implementing strategies and treatments that can help mitigate a reduction in travel time reliability. The effects on sources of congestion described at the bottom of Table 5.5 present the range of future outcomes that may occur.

The outcomes that are most important to consider in defining future concepts of operations include some events from the Optimistic Scenario (increased travel demand and explosion of technologies), as well as some events from the Pessimistic Scenario (much-higher energy prices, more-severe weather events, and deterioration of infrastructure). The challenge will be to define strategies to prepare for and cope with these extremes in the future.

Table 5.5. Alternative Futures Summary

	Alternative 1: Optimistic Scenario	Alternative 2: Mediocre Scenario	Alternative 3: Pessimistic Scenario
Scenario Drivers			
Environment and climate change	Rare-weather events insignificant	Moderate increase in rare-weather events	Significant increase in rare-weather events
Economy	Strong annual GDP growth (3%–4%), VMT (2%)	Moderate annual GDP growth (2%–3%), VMT (1.5%)	Slow annual GDP growth (<2%)
Energy cost and availability	Significant development of alternative clean-energy technologies; Stable energy prices	Development of alternative clean-energy technologies; Increasing energy prices	Development of alternative clean-energy technologies; Significant increase in energy prices
Responding Trends			
Demographics and land use	Strong population growth; Spreading of cities and settlement of rural areas continue	Moderate population growth; Dense development, downtown regentrification and revitalization	Slow population growth; Dense development to minimize transportation costs
Technology	Considerable increase in energy and transportation technologies; Increased expectations for reliability	Increase in energy and transportation technologies; Decrease in reliability because of deterioration of transportation infrastructure	Increase in energy and transportation technology; Increase in cost of travel
Policy and institutional	GHG emission targets met	GHG emission targets not met	GHG emission targets not met
Freight	Increase in demand for freight on highways, rail, air, water	Modest growth in freight demand; shifting some demand for freight onto rail and water	Modest growth in freight demand; shifting manufacturing to United States and moving freight away from ports to highways, rail, water
Financing	Extensive application of VMT charges, increasing role of PPPs	Broader application of VMT charges, increasing role of PPPs	Developing applications of VMT charges, increasing role of PPPs
Effects on Sources of Congestion			
Traffic incidents	Increase in incidents offset by safety gains through ITS	Safety gains through ITS	Reduction in overall incidents but increase in weather-related incidents
Weather	Negligible impact	Moderate impact	Significant impact
Work zones and construction	Improved through ITS Better system integration	Work zones more common; ITS able to minimize delays and improve safety	Work zones more common because of infrastructure failing
Fluctuations in demand and special events	Information dissemination spreading peak demand through accurate real-time data	Information dissemination spreading peak demand	Lower demand reducing fluctuations in demand
Traffic-control devices and signal timing	Increase in network reliability through various ITS measures and improved systems management (TSM&O)	Increase in network reliability through various ITS measures and improved systems management (TSM&O)	Weather events disabling traffic devices more frequently; Higher energy costs affecting operations of signal systems
Bottlenecks	Increase due to demand	Remains consistent	Decrease due to weak demand

CHAPTER 6

Operations Strategies and Treatments to Improve Travel Time Reliability

This chapter identifies a list of key strategies and their strengths, weaknesses, threats, and opportunities for improving travel time reliability under the baseline and three future scenarios developed in Chapter 5. To identify the strategies and treatments most likely to have the greatest impact, a literature review focused on previous and current work of several SHRP 2 Reliability and Capacity projects, including L03, L06, L07, and C05, was conducted. In addition to SHRP 2 projects, information from the FHWA, state departments of transportation (DOTs), universities, and other countries were reviewed to ensure a broad assessment of strategies and treatments. Innovative technologies that may affect travel time reliability in the future were also reviewed and are presented at the end of this chapter.

Sources of Congestion and Unreliability

Congestion occurs when the traffic volume on a roadway exceeds the available capacity. However, roadway capacity is not a constant and is influenced by a variety of factors that reduce effective or operational roadway capacity from the "baseline" capacity computed through *Highway Capacity Manual* procedures. Previous research has identified seven sources of congestion, which are briefly summarized as follows (Cambridge Systematics, Inc. and Texas Transportation Institute 2005):

- *Physical bottlenecks.* Bottlenecks are sources of congestion that occur on short segments of roadway that exhibit lower capacity than do upstream segments of roadway, essentially resulting in unreliable travel. Bottlenecks commonly form either at changes in roadway geometry (e.g., lane drops) or where significant traffic movements reduce effective roadway capacity for a given number of roadway lanes (e.g., merge and weave sections).
- *Traffic incidents.* Traffic incidents are events that disrupt the normal flow of traffic, usually by physical impedance in the travel lanes. Events such as vehicular crashes, breakdowns, and debris in travel lanes are the most-common form of incidents.
- *Weather.* Environmental conditions can lead to changes in driver behavior that affect traffic flow. Weather events such as fog, snow, and heavy rain can negatively affect travel conditions, causing delays and congestion.
- *Work zones.* Construction activities on the roadway can result in physical changes to the highway environment. These changes may include a reduction in the number or width of travel lanes, lane "shifts," lane diversions, reduction or elimination of shoulders, and even temporary roadway closures.
- *Traffic-control devices.* Intermittent disruption of traffic flow by control devices such as railroad grade crossings and poorly timed signals also contribute to congestion and travel time variability.
- *Fluctuations in normal traffic.* Variation in day-to-day demand leads to some days with higher traffic volumes than other days.
- *Special events.* Special events lead to unusual demand fluctuations whereby traffic flow in the vicinity of the event will be radically different from typical patterns. Special events occasionally cause "surges" in traffic demand that overwhelm the system.

The FHWA website (2009) provides national estimates of the amount of delay caused by each of the sources of congestion noted above. The SHRP 2 Reliability Project L03 (Cambridge Systematics, Inc. et al. 2013) further quantifies these estimates by using real-time traffic data from Atlanta, Georgia, and Seattle, Washington. The fundamental objective of the L03 project was to develop predictive relationships between highway improvements and travel time reliability. An overall finding from the L03 research was that all forms of improvements, including capacity expansions, affect both average congestion and reliability in a positive way (i.e., average congestion is reduced and reliability is improved). The following are other key findings of the SHRP 2 L03 study:

- Traditional capacity projects significantly improve reliability, not just capacity.
- Demand management strategies such as congestion pricing will lead to improvements in reliability.
- Accounting for traffic volume as a factor of available capacity can provide valuable input for efficiently allocating operations strategies, particularly incident management.

The SHRP 2 L03 study documents the fact that travel time reliability is largely influenced by the degree to which recurring congestion occurs. That is, on a congested roadway segment, travel quickly becomes unreliable when nonrecurring events take place (such as incidents, inclement weather, crashes, or special events). Conversely, when a road segment is uncongested, travel time can often remain stable—even when nonrecurring events happen because of the ability of the roadway to "absorb" these events.

Classification of Strategies and Treatments to Improve Travel Time Reliability

This section introduces the organizational structure of strategies and treatments that can be applied to improve travel time reliability. For the purposes of this report, the following definitions apply:

- *Strategy:* A group of related activities that might include different intelligent transportation systems (ITS) technologies, operational improvements, and management techniques that are aimed at achieving an improvement in travel time reliability (e.g., improve incident response).
- *Treatment:* A specific activity or action that improves travel time reliability (e.g., Global Positioning System [GPS] technology to measure the variation in travel times). The application of one or more treatments constitutes a strategy.

These strategies and treatments were identified through a literature review of SHRP 2 L03 (Cambridge Systematics, Inc. et al. 2013), L06 (Parsons Brinckerhoff et al. 2012), L07 (Potts et al. forthcoming), and C05 (Kittelson & Associates et al. 2013). In addition, FHWA publications and international research documents were reviewed. These sources are listed in the References.

Classification of Strategies

On the basis of their general focus area, the strategies are grouped into six major categories as follows:

1. Agency management, organization, and resource allocation;
2. Information collection and dissemination;
3. Vehicle technologies;
4. Incident and special event management;
5. Infrastructure improvements and demand optimization; and
6. Technology innovations.

Table 6.1 provides an outline of the organization of strategies (in the first five categories) that could improve travel time reliability. The sixth category, technological innovations, is discussed at the end of this chapter.

Each category in Table 6.1 is further subdivided into strategies and treatments. This chapter provides detailed information about key strategies and treatments that can be applied to improve travel time reliability.

Appendix E describes a framework for strategies that are related to agency management, organization, and resource allocation.

Appendix F provides additional description and quantitative benefits for the strategies listed in Table 6.1 (excluding agency management and technology innovations). It should be noted that no quantitative benefits specific to travel time reliability were identified. However, information related to other performance measures, such as reduced delay, travel time savings, increased safety, and increased capacity, that could have an indirect impact on travel time reliability are quantified in Appendix F.

Appendix G presents information on capital and operational costs for the strategies that exclude agency management strategies and technology innovations. General cost information highlighting some example applications in the United States is also presented in Appendix G.

Agency Management, Organization, and Resource Allocation

It is important for public agencies to reassess internal procedures, management, and resource allocation to manage the transportation system in terms of travel time reliability. Best practice indicates that important improvements in system reliability depend largely on the noncapital, noncapacity measures that are at the core of systems operations and management (SO&M). Therefore, agencies need to institutionalize a commitment to delivering reliable services first and have the right, motivated people with the necessary resources to manage for reliability.

Table 6.1. Organization of Strategies

Category	Strategy
Agency management, organization, and resource allocation	SO&M awareness
	SO&M structure
	SO&M as high-priority budget item
	Public and private partnerships
Information collection and dissemination	Surveillance and detection (remote verification [CCTV])
	Probe vehicles and point detection (GPS, video detection, microwave radar, transponders, Bluetooth MAC readers)
	Pretrip information
	Real-time information
	Roadside messages
Vehicle technologies	Vehicle–infrastructure integration
	Driver assistance products
Incident and special event management	Pre-event strategies
	Postevent strategies
Infrastructure improvements and demand optimization	Geometric design treatments
	Access management
	Signal timing and ITS
	Traffic demand metering
	Variable speed limits
	Congestion pricing
	Lane treatments
	Multimodal travel
	Travel reduction

Note: SO&M = systems operations and management; CCTV = closed-circuit television; MAC = mobile access code.

Systems operations and management (SO&M) refers to the broad concept that transportation agencies can apply a set of known strategy applications to maintain and improve highway service in the face of recurring peak-period congestion and nonrecurring events. There are several best-practice examples of SO&M applications on the part of state DOTs in a few major metropolitan areas in the United States. These examples include highly integrated incident management systems, well-managed work zone control, and innovative traveler information programs. However, these examples obscure a more-general reality: at the statewide level (even in states with well-known examples), best practice is confined to only a few congested metropolitan areas. Even in those areas, only a narrow range of strategies is applied. Therefore, this generally low level of implementation offers significant opportunities for improvement.

Agencies are currently more likely to be organized to handle infrastructure improvements as the bulk of their work. With an SO&M structure in place, implementing and managing the various strategies and treatments discussed below is much more doable. Agencies with more-comprehensive strategy applications that are increasingly integrated, standardized, and comprehensive are distinguished from agencies with less-developed SO&M activities through four key institutional features (Parsons Brinckerhoff et al. 2012): (*a*) SO&M awareness, (*b*) SO&M structure, (*c*) SO&M as a high-priority budget item, and (*d*) identified opportunities for public–private partnerships. The purpose of these strategies is to support transportation agency management in moving toward an institutional framework that increases and encourages the capability of supporting more-effective management, organizational, and resource-allocation structures. These strategies are specifically aimed at managing nonrecurring congestion.

On the freight side, the literature (Hassall et al. 2003) shows that the effective adoption of in-vehicle transportation technology is accompanied by a system of regulation. Government often provides policy guidance to allow industry to make decisions to invest in technology. Significant productivity gains can be achieved from government-supported performance-based standards for trucks that allow truckers to respond more flexibly to business needs.

Table 6.2 provides a summary of the key strategies for examples presented in this section. Note that all the strategies within this category are essential for managing the sources of congestion.

Agencies need to monitor travel time reliability problems as they arise and to prepare to respond. Problems can be addressed by tracking travel trends, identifying innovative solutions, and acting to implement those solutions. Smart

Table 6.2. Key Agency Management, Organization, and Resources Allocation Strategies

Strategy	Treatments	Possible Impact on Reliability	Barriers to Institutional Change
Create SO&M awareness	Undertake educational program about SO&M as customer service	Awareness provides a platform from which managing for travel reliability can be established as a sustainable agency activity.	Limited public and elected leader support
	Exert visible senior leadership		Limited internal middle-management support
	Establish formal core program		Significant capacity construction program
	More effectively use, and rationalize, as necessary, state DOT authority		Limited internal middle-management support
	Internalize continuous improvement as agency mode or ethic		Fuzzy legislative authority
Establish SO&M structure	Establish top-level SO&M executive structure	Dedicated structure allows for interrelated sequence of planning, systems engineering, resource allocation, procurement, project development and implementation, procedural coordination, etc.	Absence of experienced SO&M managers
	Establish appropriate organizational structure		Staffing level constraints
	Identify core capacities		Shortfall and turnover in qualified staff
	Determine and allocate responsibility, accountability, and incentives		Staffing level constraints
Establish SO&M as high-priority budget item.	Develop program-level budget estimate.	A dedicated budget will ensure that agencies have funds on hand to implement the various strategies and treatments available to improve travel time reliability.	Ineligibility of state funding for SO&M
	Introduce SO&M as a top-level agency budget line item.		Competition for resources from other program backlogs
	Develop acceptance of sustainable resourcing from state funds.		Ineligibility of state funding for SO&M
	Develop methodology for trade-offs.		No performance outcome measures
Identify opportunities for public–private partnerships.	Agree on operational roles and procedures with professional services agreement (PSA).	Bringing together the functional or geographic priorities of various agencies will allow for cooperative efforts to apply strategies and treatments effectively, with key roles played by several parties.	Conflicting partner priorities
	Identify opportunities for joint operations activities with local governments and MPOs.		Conflicting partner priorities
	Develop procedures that accommodate partner goals and maximize mobility (minimum disruption) MOUs.		Conflicting partner priorities
	Rationalize assignment of staff and outsourced activities, responsibilities, and oversight.		Conflicting partner priorities

Note: MPOs = metropolitan planning organizations; MOUs = memoranda of understanding.

use of resources, driven by good information and the ability to decide and act, are all part of the solution. Agencies may wish to make a case for increasing transportation funding levels that promote economic development and safety. Agencies may also train and elevate a new cadre of professionals who are focused on service quality, system management, and technology innovation.

Information Collection and Dissemination

Agencies need to know how the system is performing and can benefit from access to real-time information that would allow them to detect and respond to reliability problems. Data feedback allows agencies to select or adjust appropriate strategies to better manage the system.

Many of the services that are possible through arterial and freeway management systems are enabled by traffic surveillance and detection strategies, such as sensors or cameras that monitor traffic flow. These strategies relate to both information collection and information dissemination as follows:

- Information collection includes traffic data collection (e.g., speed, flow, and incidents) as well as demand-related data collection (traveler preferences and perceptions, route choice, and mode choice). Such strategies would also include traveler satisfaction and preferences surveys.
- Information dissemination relates to projected and real-time traveler information. These strategies might include work zone closure information, planned special events, real-time incident information, projected travel times, and real-time bus location. Strategies may also include information required by important stakeholders such as freight companies, airports, rail, and ports.

Table 6.3 provides a summary of the key strategies and examples presented in this section. The possible impact on reliability; strengths, weaknesses, opportunities, and threats (SWOT); the level of technology involved with each strategy application; and the possible application to the sources of congestion are noted.

The challenge is to encourage the public sector to open the doors to new information technologies, to become more service and market oriented, and to collaborate with the private sector so that the benefits of both public and private information systems are achieved. Information technologies are available today and are rapidly expanding because of market demand for them. Travelers and transportation managers can access better information on current and predicted transportation system performance. Improved information gives travelers travel options and the ability to choose among them, which will result in better system performance.

Vehicle Technologies

Another set of strategies involves in-vehicle driver assistance systems. The Vehicle Infrastructure Integration (VII) program is a research program focused on enabling wireless communications among motor vehicles and between motor vehicles and roadside infrastructures. Researchers, automobile manufacturers, and federal and state transportation officials are currently working together to make that vision a reality. By enabling wireless connectivity with and between vehicles, between vehicles and the roadway, and with devices such as consumer electronics, VII has the potential to transform roadway user safety, mobility, and environmental impacts in the near future.

Table 6.4 provides a summary of the key strategies and examples presented in this section. The possible impacts on reliability, SWOT (strengths, weaknesses, opportunities, threats), the level of technology involved with each strategy application, and the possible application to the sources of congestion are noted.

Vehicle controls, propulsion systems, fuels, and safety equipment will improve because the private sector will respond to consumer demand. The safety equipment will include vehicle information; front, side, and rear object detection; and crash protection devices. The challenge will be to integrate onboard information with traffic controls, toll collection (real-time pricing), multimodal information, and treatments that expedite freight deliveries.

Incident and Special Event Management

Incidents and special events are significant sources of unreliability. Incident management systems can reduce the effects of incident-related congestion by decreasing the time needed to detect incidents, the time it takes an emergency response to arrive, and the time required to restore traffic to normal conditions. Disruption management deals with incident prevention (pre-event) and incident clearance (postevent). Similarly, strategies that address special events related to traffic management before and during such events could include signal control, ramp metering, and ramp closures. Incident management systems make use of a variety of surveillance technologies as well as enhanced communications and other technologies that facilitate coordinated responses to incidents. Strategies such as service patrols shorten the response time for incidents.

Table 6.5 provides a summary of the key strategies and the examples presented in this section. The possible impact on reliability, SWOT, the level of technology involved with each strategy application, and the possible application to the sources of congestion are noted.

Incident detection can be rapid and accurate if agencies act to enable this to occur. Transportation management systems can be regional or even statewide, depending on the degree

Table 6.3. Key Information Collection and Dissemination Strategies

Strategy	Treatments	SWOT				Technology (Low, Medium, High)	Status (Current, Emerging, New)	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats			
Surveillance and detection	Remote verification (closed-circuit television)	Improves mobility because of quick response to incidents		Good portion of roadway networks can be covered due to decreasing costs of technology		Low	Current and emerging	Traffic-control devices, special events, weather incidents
	Driver qualification	Improves safety, adds convenience, and reduces congestion; impartial	Cost, needs public acceptance	Can be self-sustaining	Resistance in public acceptance	Medium	Current and emerging	Traffic Incidents
	Automated enforcement (speed, red light, toll, HOV)	Improves safety and reduces congestion; levels the playing field for drivers	Cost, needs public acceptance	Implemented by private contractors	Resistance in public acceptance	Medium	Current and emerging	Traffic incidents, bottlenecks
Probe vehicles and point detection	GPS, video detection, microwave radar, transponders, Bluetooth MAC readers	Improves travel time estimation by capturing real-time information	Needs further testing and research	Good portion of roadway networks can be covered because of decreasing costs of technology		High	New	Traffic-control devices
Pretrip information	National Traffic and Road Closure Information	Improves reliability and mobility	Accuracy, variability in traffic conditions not quickly reflected by the system	Simple improvements to remedy accuracy		Medium	Current	Weather, work zones
	Planned special events management	Improves reliability and mobility	Lack of coordination between event and transportation agencies		Diversity (size, location, purpose)	Medium	Current	Special events

(continued on next page)

Table 6.3. Key Information Collection and Dissemination Strategies (continued)

Strategy	Treatments	SWOT				Technology (Low, Medium, High)	Status (Current, Emerging, New)	Application to Sources of Congestion
		Strengths	**Weaknesses**	**Opportunities**	**Threats**			
Real-time information	Pretrip information by 511, websites, subscription alerts, real-time navigation systems	Improves reliability and mobility	Accuracy, variability in traffic conditions not quickly reflected by the system	Public demand	Other technologies (vehicle integrated)	High	Emerging	All but traffic-control devices
	Road weather information systems	Improves reliability and mobility	Variability in traffic conditions not quickly reflected by the system	Implementation in remote areas where weather information is critical to drivers	Other technologies (vehicle integrated)	Low–medium	Current	Weather
	Freight shipper congestion information, commercial vehicle operations, border technology systems, smart freight, weigh-in-motion	Improves reliability and mobility	Cost, needs driver acceptance, multiple agency cooperation required	Implementation in remote areas where weather information is critical to drivers; increased freight activity	Other freight modes, may require sharing private company information, lack of standards	Medium	Current and emerging	All
Roadside messages	Travel time message signs for travelers (dynamic message signs), queue warning systems	Improves reliability and mobility	Variability in traffic conditions not quickly reflected by the system	Integration with other ITS technologies for faster information update	Other technologies (vehicle integrated)	High	Emerging	All

Note: HOV = high-occupancy vehicle.

Table 6.4. Key Vehicle Technologies Strategies

Strategy	Treatments	SWOT				Technology (Low, Medium, High)	Status (Current, Emerging, New)	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats			
Vehicle infrastructure integration	Vehicle infrastructure integration	Improves travel time estimation by capturing real-time information	Cost	System implementation would not only help with real-time travel time estimation but also with transportation planning (e.g., origin–destination estimations).	Driver privacy	High	New	Traffic-control devices, traffic incidents, weather fluctuation in normal traffic
Driver assistance products	Electronic stability control, obstacle detection systems, lane change assistance systems, lane departure warning systems, rollover warning systems, road departure warning systems, forward collision warning systems	Improves safety, adds convenience, reduces congestion	Cost	Products are desired by customers, and implemented by auto manufacturers.		High	New	Traffic incidents

Table 6.5. Key Incident and Special Event Management Strategies

Strategy	Treatments	SWOT				Technology (Low, Medium, High)	Status (Current, Emerging, New)	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats			
Pre-event	Service patrols	Improves mobility and safety	Cost	Faster response to incidents in remote areas	Requires a priority budget item	Low	Current and emerging	Traffic incidents, work zones
Postevent	On-scene incident management (incident responder relationship, high-visibility garments, clear buffer zones, incident screens)	Improves mobility and safety	Cost	Faster response to incidents in remote areas; extension of existing technology; supported by agencies and public		Medium–high	Current and emerging	Traffic incidents
	Work zone management	Improves mobility and safety	Medium cost	Work zone management becoming fundamental as work zones tend to increase nationwide	Significant increase in costs if infrastructure needs to be added	Medium	Current and emerging	Work zones

of congestion and the level of coordination that is achieved among agencies. The key challenge in managing incidents will be in consolidating control and fostering coordination among jurisdictions. By addressing this challenge, emergency responders will be able to clear incidents more quickly, and infrastructure investments can be shared among agencies—allowing innovations to be implemented sooner.

Infrastructure Improvements and Demand Optimization

Numerous capacity improvements are available to enhance travel time reliability. These actions increase capacity and reduce the sensitivity of the facility to reliability problems. As noted earlier, on a congested roadway segment, travel time quickly becomes unreliable when nonrecurring events happen (such as incidents, inclement weather, crashes, and special events). Conversely, when a road segment is uncongested, travel time can often remain stable—even when nonrecurring events take place (because of the ability of the roadway to "absorb" these events).

This set of strategies focuses on improvements applied to the roadway environment and to optimizing travel demand. Physical capacity improvements include link additions, lane additions, roadway widening, access management, and pavement resurfacing. Traffic operations improvements include signal-timing optimization, deployment of intelligent transportation systems, traffic-demand metering, and the application of variable speed limits. Strategies related to agency intervention or guidance include travel pricing and travel demand management measures, which focus on reducing vehicular travel and promoting alternative travel modes—all measures that are inclined to improve nonrecurring congestion.

Some of the strategies that fall into this category are also considered part of the emerging concept called active traffic management (ATM). FHWA defines ATM as

> the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing traffic conditions. Focusing on trip reliability, it maximizes the effectiveness and efficiency of the facility. It increases throughput and safety through the use of integrated systems with new technology, including the automation of dynamic deployment to optimize performance quickly and without the delay that occurs when operators must deploy operational strategies manually. (FHWA, U.S. Department of Transportation 2013a)

The ATM approach to congestion management, which has been well developed in Europe, consists of a combination of operational strategies that when implemented in concert, fully optimize the existing infrastructure and provide measurable benefits to the transportation network and the motoring public. These strategies include speed harmonization, temporary shoulder use, junction control, and dynamic signing and rerouting. Managed lanes, as applied in the United States, are an obvious addition to this collection. In addition, various institutional issues essential to the successful implementation of ATM include a customer orientation; the priority of operations in planning, programming, and funding processes; cost-effective investment decisions; public–private partnerships; and a desire for consistency across borders (Mirshahi et al. 2007).

Table 6.6 summarizes the key strategies and examples presented in this section. The possible impact on reliability, SWOT, and the level of technology involved with each strategy application, and the possible application to the sources of congestion are noted.

Economic principles suggest that to improve travel time reliability, travel demand and capacity need to be balanced. So, removing bottlenecks eliminates capacity constraints and managing demand smoothes out surges in traffic. To accomplish these two objectives, the mission of transportation agencies may have to be enlarged. In addition to the mission of economic development and social access of many transportation agencies, it is likely that demand management will have to be fully embraced. This will not be an easy task, but it may be a pillar of support under any scenario to effectively address reliability problems.

Effectiveness of Strategies and Areas of Application

The references listed in Appendix F note the literature reviewed to quantify the benefits of each strategy and treatment. No quantitative benefits related to travel time reliability were identified in the reviewed documents. However, other measures such as travel time savings, improved safety, and increased capacity were quantified. It is assumed that these improvements have a direct relationship with travel time reliability. Thus, the strategies and treatments listed in this section were ranked on the basis of the following general levels:

Level 1: Delay reduction of up to 50%;
Level 2: Delay reduction of up to 20%;
Level 3: Delay reduction of up to 10%;
Level 4: Other improvements (such as safety, capacity); and
Level 5: Unknown benefits to date.

Tables 6.7 through 6.11 present the strategies that fall into each of the five levels noted above. In addition, the overall cost ranges for implementing the strategies and treatments are also provided. An effectiveness rank that considers both the key quantitative benefits of the treatment (1 through 5) and its overall cost range (A through F) is also provided for each strategy and treatment.

As shown in Table 6.7, the treatments with the greatest delay reduction potential include the FHWA National Traffic and

Table 6.6. Key Infrastructure Improvements and Demand Optimization Strategies

		SWOT						
Strategy	**Treatments**	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**	**Technology (Low, Medium, High)**	**Status (Current, Emerging, New)**	**Application to Sources of Congestion**
Geometric design treatments	Bottleneck removal (weaving, alignment)	Reduced congestion	Cost		Difficulty of post-construction	NA	Current	Physical bottlenecks
	Geometric improvements (interchange, ramp, intersections, narrow lanes, temporary shoulder use)	Improved mobility	Difficulty of post-construction	Sustainability		Low	Current	Physical bottlenecks, traffic incidents
Access management	Access management (driveway location, raised medians, channelization, frontage road)	Improved mobility and safety	Cost	Incorporated into regional planning or land-use programs	Difficult to implement in post-development stage	Low	Current	Traffic incidents
Signal timing, ITS	Transportation management center	More-efficient coordination and operation of various transportation systems	Cost	Potential reduction in installation costs due to technology development and deployment		Medium	Current and emerging	All but bottlenecks
	Signal retiming and optimization	Improved mobility and reduced fuel consumption	Cost, corridor implementation	Overall networkwide optimization		Low	Current	Traffic-control devices
	Traffic-signal preemption at grade crossings	Reduced delay and improved safety	Highway and railroad interagency cooperation	Better traffic management strategy due to the interconnection of highway and rail signal systems	Increasing highway and rail traffic volumes	Medium	Emerging	Traffic-control devices
Signal timing, ITS	Traffic adaptive signal control and advanced signal systems	Improved mobility	Cost	Possible connection with low-cost technologies instead of using loop detectors		Medium	Emerging	Traffic-control devices
	Advanced transportation automation systems, signal priority and AVL (transit, CVO, and truck)	Improved transit, freight, CVO mobility	Cost	Application to multimodal corridors and potential to reduce auto use with reliable transit services; potential reduction in cost of fuel consumption and gas emissions due to improvement to freight operations	Lack of support and funding	High	Emerging	Traffic-control devices

(continued on next page)

Table 6.6. Key Infrastructure Improvements and Demand Optimization Strategies (continued)

Strategy	Treatments	SWOT				Technology (Low, Medium, High)	Status (Current, Emerging, New)	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats			
Traffic demand metering	Ramp metering, ramp closure	Improved mobility and safety	Impact on arterials (relocate congestion)	Application on freeways that have reached their saturation points	Public acceptance	Medium	Emerging	All but weather and work zones
Variable speed limits	Variable speed limits	Improved mobility and traffic flow	New concept to U.S. drivers; needs research and advertising	Low-cost application; integration with other ITS technologies	Public acceptance	Low	Emerging	Physical bottlenecks
Congestion pricing	Electronic toll collection	Increased capacity and reduced delays	Cost	Replace old open toll roads	Driver noncompliance, resistance to paying tolls, concerns about equity	High	Emerging	Physical bottlenecks
	Cordon pricing (areawide)	Capacity preserved and improved mobility	Needs public acceptance	Deployment in areas with no room to construct new lanes or roads	Right-of-way issues	Low	Emerging	Physical bottlenecks, fluctuation in normal traffic, special events
Lane treatments	Managed lanes: HOV, HOT, truck-only, and TOT lanes, and HOV bypass ramps	Optimized capacity and reduced congestion	Needs public acceptance	Can be viewed as new source of funding	Right-of-way issues	Low	Current and emerging	Physical bottlenecks, fluctuation in normal traffic, traffic incidents
	Changeable lane assignments (reversible, variable)	Optimized capacity and reduced congestion	Cost	Deployment in areas with no room to construct new lanes or roads	Interagency cooperation and driver awareness required	Low	Emerging	Traffic-control devices
Multimodal travel	Integrated multimodal corridors	Reduced congestion and Improved mobility	Cost	Application to large urban corridors	Difficult to implement	High	Emerging	Fluctuation in normal traffic, special conditions, physical bottlenecks
Travel reduction	Travel alternatives or diversion to other times (ride-share programs, telecommuting, home office, video conferences)	Reduced congestion and Improved mobility	Needs public acceptance, requires technology and agency buy-in			Low	Current and emerging	Fluctuation in normal traffic, special conditions, physical bottlenecks

Note: NA = not available; CVO = commercial vehicle operations.

Table 6.7. Level 1 Strategies: Delay Reduction of Up to 50%

Category	Strategy	Treatment	Application to Sources of Congestion	Key Quantitative Benefit	Overall Cost Range[a]	Effectiveness–Cost Rank
Information collection and dissemination	Pretrip information	National Traffic and Road Closure Information	Weather, work zones	Reduces delays (early and late arrivals) by 50%	Low–medium	1-B
Incident and special event management	Pre-event assistance	Service patrols	Traffic incidents	Can reduce incident response by 19% to 77% and incident clearance time by 8 min	High	1-E
	Post-event assistance	On-scene incident management (incident responder relationship, high-visibility garments, clear buffer zones, incident screens)	Traffic Incidents	Traffic incident management programs have reported reductions in incident duration from 15% to 65%	Low	1-A
		Work zone management	Work zones	Reduces work zone–related delays by 50% to 55%	Variable (depends on addition of infrastructure)	1-D
Infrastructure improvements and demand optimization	Signal timing, ITS	TMC	Traffic-control devices, special events, weather, work zones, traffic incidents	Reduces delay by 10% to 50%	High	1-E
		Traffic adaptive signal control, advanced signal systems	Traffic-control devices	Adaptive signal control systems have been shown to reduce peak period travel times by 6% to 53%	Medium–high	1-C
	Congestion pricing	Electronic toll collection (ETC)	Physical bottlenecks	Electronic toll collection (ETC) reduces delay by 50% for manual-cash customers and by 55% for automatic-coin-machine customers, and increases speed by 57% in the express lanes	High	1-E

[a] Overall cost range applies to the application of a treatment in roadway segment or corridor. For example, several dynamic message signs can be installed along an important route. The designations of overall cost range correspond to the following values: low = <$200,000, medium = >$200,000 but <$1 million, and high = >$1 million.

Road Closure Information program, service patrols, on-scene incident and work zone management, transportation management centers (TMCs), and traffic adaptive signal control. These treatments have been proven to reduce traffic delays by up to 50%. Although these treatments have a high potential for reducing delay, the costs associated with them are relatively high when compared with the strategies and treatments in the other four categories.

An important aspect of these treatments is the need for interagency cooperation. For example, the National Traffic and Road Closure Information program may have to obtain data from weather-related agencies to make them available to roadway users. In the same fashion, TMCs may have to be interconnected with emergency responders and law-enforcement authorities to address any roadway disruptions quickly. In addition, the intent of these treatments is to cover a large portion of roadway networks to benefit roadways across multiple jurisdictions. The following sections provide a brief overview of the application of the strategies that fall within the category of reducing delay by up to 50%.

National Traffic and Road Closure Information

The context in which this treatment would apply varies depending upon whether motorists use it on a national basis when they are seeking information on real-time delay conditions and causes (i.e., weather, work zone, etc.) that may be encountered on a particular roadway. This information is made available for pretrip planning purposes through the FHWA National Traffic and Road Closure Information website, which contains links to local websites with similar information by state. Thus, the affected area is larger than the area that would be affected by other treatments and would apply mostly to urban and suburban areas where large volumes of traffic would benefit from this type of information. The treatment could apply to facilities operated with or without tolls and would more likely involve the dissemination of traffic and road-closure information related to freeway or major arterial facility types. In addition, the treatment provides information to motorists about both recurring and nonrecurring congestion conditions (e.g., road closures).

Service Patrols

Service patrols are commonly applied in urban and suburban settings to detect, respond to, and clear incidents. They are an effective component of work zone management systems, especially for long-duration work zones. However, given the dynamic response nature of this treatment, service patrols can also be applied in more-remote areas. They typically serve within a regional context that crosses jurisdictional boundaries as needed. Service patrols are most commonly applied to freeway facilities (both tolled and nontolled) but are also applied to arterials in some regions. They primarily address a nonrecurring congestion need to restore traffic flow to normal conditions safely and efficiently.

On-Scene Incident Management (Incident Responder Relationship, High-Visibility Garments, Clear Buffer Zones, Incident Screens)

On-scene incident management deals with the coordination of the work of public safety agencies (police, fire and rescue, emergency medical services) and transportation agencies to ensure rapid and appropriate incident detection, response, traffic control, and clearance. As such, the application of this treatment is spread over all area and facility types and can be localized for a particular community or provided regionally across multiple communities. The treatment is also typically applied in a nonrecurring congestion environment in response to traffic incidents, with public safety agencies playing a primary role and transportation agencies playing a supportive role.

Work Zone Management

Work zone management is a treatment that can be applied locally (such as on smaller construction projects) or regionally for larger construction projects that cross jurisdictional boundaries. This treatment can be applied within all area types (urban, suburban, and rural) and facility types and operations (i.e., tolled and nontolled). Work zone management is used for reducing sources of nonrecurring congestion. It has the objective of safely moving traffic through working areas with as little delay as possible while protecting the safety of the workers.

Transportation Management Centers

As a treatment, TMCs can be applied either locally or within a regional context. Application of a regional TMC is typically the case in larger urban areas where individual TMCs share information back and forth with regional TMCs. Given the cost of installing this treatment, it is typically applied in urbanized areas and statewide. However, smaller traffic operations centers would also be applicable in rural settings. TMCs rely on the availability of field ITS devices to relay information back to a centralized location, so the application of this treatment is confined to roadways with these devices, which are more commonly freeways and arterials. In addition, this treatment is applied in both recurring and nonrecurring congestion situations, given that the infrastructure to view both exists at all times with this treatment type.

Traffic Adaptive Signal Control, Advanced Signal Systems

The use of adaptive or advanced signal systems is a treatment that would be more commonly applied on a local basis with the need for similar control system types among the signalized intersections that make up the traffic adaptive signal control system. This treatment is more challenging to apply at jurisdictional boundaries where different signal-control equipment types exist. The complexity of operations related to adaptive signal control is a limiting factor for rural areas where traffic operations staffing is limited. Also, this treatment is limited to arterials with both recurring and nonrecurring congestion management needs.

Electronic Toll Collection

Electronic toll collection (ETC) treatments have a limited application area that includes tolled freeway facilities. The high installation costs of this treatment are another limiting factor. Thus, ETC is usually confined to facilities in larger urban areas that serve regional travel needs. ETC is also a treatment that can be applied in areas where the objective is to reduce recurring congestion by expediting transactions at toll booths via tag readers, license plate recognition, cell phones, or GPS units. It should be noted that as costs decrease for ITS technologies in the future, the deployment of ETC may become more widespread.

Table 6.8 shows the second-most-effective group of strategies and treatments found in the literature review. The treatments contained in this group include closed-circuit television (CCTV), pretrip information, road weather information systems (RWIS), dynamic message signs, geometric design treatments, signal retiming, automated vehicle location (AVL), ramp metering, congestion pricing, and managed lanes. Interestingly, these treatments have lower costs in comparison to the costs of Level 1 treatments. A common characteristic of these treatments is that they address local congestion sources, and their benefits may not be seen in

Table 6.8. Level 2 Strategies: Delay Reduction of Up to 20%

Category	Strategy	Treatment	Application to Sources of Congestion	Key Quantitative Benefit	Overall Cost Range[a]	Effectiveness–Cost Rank
Information collection and dissemination	Surveillance and detection	Remote verification (CCTV)	Traffic-control devices, special events, weather, traffic incidents	5% reduction in travel times in nonrecurring congestion; overall 18% reduction in travel times	Medium	2-C
	Real-time information	Pretrip information by 511, websites, subscription alerts, radio	Traffic-control devices, special events, weather, work zones, traffic incidents	Potential reduction in travel time from 5% to 20%	Variable	2-E
		Road weather information systems	Weather	Reduces delays by up to 12%	Low–medium	2-B
	Roadside messages	Travel time message signs for travelers (DMS, VMS)	All	Improves trip-time reliability, with delay reductions ranging from 1% to 22%	High	2-F
Infrastructure improvements and demand optimization	Geometric design treatments	Bottleneck removal (weaving, alignment)	Physical bottlenecks	Reduces travel time by 5% to 15%.	Medium–high	2-D
	Signal timing, ITS	Signal retiming, optimization	Traffic-control devices	Reduction in travel time and delay of 5% to 20% when traffic-signal retiming was used	Low	2-A
		Advanced transportation automation systems, signal priority, and AVL	Traffic-control devices	Reduces transit delays by 12% to 21%	Low–medium	2-B
	Traffic demand metering	Ramp metering, ramp closure	All	An increase of mainline peak-period flows from 2% to 14% because of on-ramp metering, according to a study of ramp meters in North America	Low–medium	2-B
	Congestion pricing	Cordon pricing (areawide)	Physical bottlenecks, fluctuation in normal traffic, special events	A decrease in inner city traffic by about 20% from congestion pricing in London	Low–medium	2-B
	Lane treatments	Managed lanes: HOV, HOT, and TOT lanes	Physical bottlenecks, fluctuation in normal traffic, traffic incidents	Reduces travel times up to 16%	Medium–high	2-D

Note: CCTV = closed-circuit television; VMS = variable message signs; HOV = high-occupancy vehicle; HOT = high-occupancy toll; TOT = truck-only toll.

[a] Overall cost range applies to the application of a treatment in roadway segment or corridor. For example, several dynamic message signs can be installed along an important route. The designations of overall cost range correspond to the following values: low = <$200,000, medium = >$200,000 but <$1 million, and high = >$1 million.

other parts of the roadway network. The context in which each treatment associated with Table 6.8 could be applied was also considered as described below.

Remote Verification

Remote verification has a localized use associated with its application given the relatively limited viewing areas around CCTV devices. As a result, a series of CCTV cameras are typically deployed to widen the coverage area along a facility. The setting in which this treatment can be applied is varied and includes the monitoring of urban area networks (e.g., central business districts), suburban arterials, and freeways. The lack of available communication infrastructure is a common controlling factor for the application of this treatment in rural areas and along local roads. This treatment type can also be applied in areas with both recurring and nonrecurring congestion and can be used to monitor the status of either (typically via a TMC).

Pretrip Information by 511, Websites, Subscription Alerts, Radio

This treatment type provides pretrip information to motorists through the Internet, television, or radio in close to real time. The source of this information is typically CCTV cameras and eye-witness traffic reports that are then relayed to the public through a variety of media outlets. This treatment can be applied on a local or regional basis for any area (urban, suburban, and rural) and facility type. The treatment provides valuable information during both recurring and nonrecurring congestion conditions that can be used by motorists when planning a trip.

Road Weather Information Systems

This treatment has application to the many areas throughout the country that experience weather-related disruptive impacts on the transportation system. RWIS can be installed in all area and facility types when a significant threat to the operation is posed by weather. Moreover, this treatment can be interconnected with local and regional TMCs.

Dynamic Message Signs

Dynamic message signs (DMSs) play an important role in travel time reliability as one of the main sources of travel time reliability information for en route roadway users. Permanently mounted DMSs that provide real-time traffic information, such as travel times, incidents, weather, construction, safety, and special events, are mostly applied to freeways and arterials, given the need for good communication throughout an area. The application of DMSs is more common in urban areas but can also be found in suburban and rural areas. In addition, DMSs are used to disseminate information when both recurring and nonrecurring congestion conditions exist.

Temporary signs are often used in work zones to update travelers on ongoing or expected changes in normal travel conditions.

Geometric Design Treatments

Geometric design treatments primarily apply to facilities with existing weaving sections and horizontal or vertical alignment deficiencies. In the case of weaving sections, these treatments apply primarily to freeways. The improvement to or removal of weaving sections can be applied in any area (urban, suburban, and rural) where recurring congestion occurs. It can also be applied to a facility in need of higher safety performance—where crashes have been known to create nonrecurring congestion conditions. The improvement of horizontal and vertical alignments is most often applied in the case of older facilities of all types and settings.

Signal Retiming and Optimization

This treatment can be applied at multiple intersections along arterials, on local roads, or at individual intersections. Because traffic signals can be found in urban, suburban, and rural settings, this treatment can be applied in all setting types. Typically, this treatment is applied to address recurring congestion issues, but it has the flexibility to also be applied in nonrecurring congestion situations to temporarily improve the flow of traffic (for example, through the implementation of a special-events timing plan).

Advanced Transportation Automation Systems, Signal Priority, and Automated Vehicle Location

These three treatments have a variety of applications associated with them. In the case of an advanced transportation automation system, the application would be limited to those facilities instrumented to automate all or part of the driving task for private automobiles, public transportation vehicles, commercial vehicles, and maintenance vehicles through cooperation with an intelligent infrastructure. Given the costs of instrumentation, this treatment is likely to include localized operations before regional operations are achieved. Signal priority and AVL can be applied locally or regionally depending on the institutional frameworks in which they are deployed. Signal priority applications are typically limited to transit vehicle operations while AVL is commonly applied to a wider range of vehicle types that include transit, fire, and emergency response vehicles.

Ramp Metering and Ramp Closure

The application of ramp metering is limited to freeway facilities and is most commonly applied in larger urban areas. This treatment can be applied at locations where there is a need to control the manner and rate in which vehicles are allowed to enter a freeway. It also can overcome issues with safety and geometric design at merging sections on a freeway. Ramp closures are limited to freeway facilities in most cases and are applicable in all areas (urban, suburban, and rural) where an operational benefit could be achieved through closing a ramp.

Congestion Pricing (Areawide)

Congestion pricing is a treatment with limited applications. Internationally, it has been applied only in large urban areas such as Singapore, London, and Stockholm, Sweden. Given that this treatment requires tolling of vehicles as they enter a central area street network, its application is required on the major travel routes (i.e., freeways and arterials) that provide access to the area. It can be considered as an alternative to expensive and infeasible infrastructure expansions in large metropolitan areas.

Managed Lanes: High-Occupancy Vehicles Lanes, High-Occupancy Toll Lanes, and Truck-Only Toll Lanes

Managed lanes are applied on a variety of freeway facilities, including concurrent-flow, barrier-separated, contra-flow, shoulder-lane, and ramp-bypass metered lanes. Within a freeway context, managed lanes operate next to unrestricted general-purpose lanes, and they are also used on some arterial roadways. Managed lanes can be operated either as tolled or nontolled facilities. Managed lanes are most commonly found in urban areas. In urban areas, these lanes are used to increase the person-moving capacity of a corridor by offering incentives for improvements in travel time and reliability. The dynamic and proactive traffic management provided by this treatment can help agencies respond more quickly to daily fluctuations in traffic demand.

The third-most-effective group of strategies for improving travel time reliability is shown in Table 6.9. This group has the potential to reduce delays by up to 20%. The treatments that make up this group include planned special events management, freight shipper congestion information, driver assistance systems, and traffic-signal preemption at grade crossings. This group of treatments is aimed at specific traffic events and user groups. For example, traffic-signal preemption at grade crossings is focused on reducing delays for highway traffic caused by railroad movements. The context

Table 6.9. Level 3 Strategies: Delay Reduction of Up to 10%

Category	Strategy	Treatment	Application to Sources of Congestion	Key Quantitative Benefit	Overall Cost Range[a]	Effectiveness–Cost Rank
Information collection and dissemination	Pretrip information	Planned special events management	Special events	Reduces delay caused by special events	Low–medium	3-B
	Real-time information	Freight shipper congestion information, commercial vehicle operations	Traffic-control devices, special events, weather, work zones, traffic incidents	Reduces freight travel time by up to 10% and screening time by up to 50%	Low	3-A
Vehicle technologies	Driver-assistance products	Electronic stability control; obstacle detection systems; lane-departure warning systems; road-departure warning systems	Traffic incidents	Reduces accidents involving vehicles by up to 50%; reduces travel times by 4% to 10%	Low	3-A
Infrastructure improvements and demand optimization	Signal timing, ITS	Traffic-signal preemption at grade crossings	Traffic-control devices	Reduces delays by up to 8% at grade crossings, according to simulation models	Medium	3-C

[a] Overall cost range applies to the application of a treatment in roadway segment or corridor. For example, several dynamic message signs can be installed along an important route. The designations of overall cost range correspond to the following values: low = <$200,000, medium = >$200,000 but <$1 million, and high = >$1 million.

in which each of the treatments could be applied is described in the following section.

Planned Special Events Management

Planned special events management is a treatment applied in urban, suburban, or rural locations where special events cause nonrecurring congestion and unexpected delays for travelers. The facility types where this treatment is most commonly applied are arterials and freeways that provide access to and from the location associated with the special event. Because of the magnitude of certain special events (i.e., Olympic Games), the need for planning and managing events will become critical in the future.

Freight Shipper Congestion Information and Commercial Vehicle Operations

Freight shipper congestion information is a treatment that involves disseminating real-time travel time information along significant freight corridors to freight operators using ITS technologies such as DMS and variable message signs, GPS, and weigh-in-motion. The treatment can be applied along corridors instrumented with these types of ITS technologies. Border crossings are another application of this treatment.

Driver Assistance Systems

Driver assistance systems, such as electronic stability control, obstacle detection systems, lane-departure warning systems, and road-departure warning systems, are a treatment applied within a vehicle rather than on a particular facility type. In the future, the number of automobiles with these safety capabilities will become increasingly common.

Traffic-Signal Preemption at Grade Crossings

Traffic-signal preemption is a treatment applied at locations where highway–railroad grade crossings exist. They are applied in any urban, suburban, and rural area type and along arterials and local roads. New technologies and improved interagency communications will increase the deployment of this treatment. The focus is often most desirable at locations with high daily volumes and a high number of crashes involving vehicles and trains.

Table 6.10 shows the treatments identified in Level 4 at which the quantified improvements are mainly related to increased safety and capacity. These treatments include driver qualification, automated enforcement, probe vehicles, geometric design improvements, and variable speed limits. The focus of this group is to apply active traffic management strategies. The impact of these strategies is maximized

Table 6.10. Level 4 Strategies: Other Improvements

Category	Strategy	Treatment	Application to Sources of Congestion	Key Quantitative Benefit	Overall Cost Range[a]	Effectiveness–Cost Rank
Information collection and dissemination	Surveillance and detection	Driver qualification	Traffic incidents	Reduces nonrecurring congestion by reducing accidents	Low	4-A
		Automated enforcement	Traffic incidents, bottlenecks	Reduces travel time and improves safety	Variable (high if done by agencies, low if by contractors)	4-D
	Probe vehicles and point detection	GPS, video detection, microwave radar, Bluetooth MAC Readers	Traffic-control devices	No direct benefit to reducing congestion	Low	4-A
Infrastructure improvements and demand optimization	Geometric design treatments	Geometric improvements (interchange, ramp, intersections, narrow lanes, temporary shoulder use)	Physical bottlenecks, traffic incidents	An increase in overall capacity by 7% to 22% from geometric improvements	Medium	4-C
	Variable speed limits	Variable speed limits	Physical bottlenecks, special events	Increases throughput by 3% to 5%	Low–medium	4-B

Note: MAC = mobile access code.

[a] Overall cost range applies to the application of a treatment in roadway segment or corridor. For example, several dynamic message signs can be installed along an important route. The designations of overall cost range correspond to the following values: low = <$200,000, medium = >$200,000 but <$1 million, and high = >$1 million.

Table 6.11. Level 5 Strategies: Unknown Benefits

Category	Strategy	Treatment	Application to Sources of Congestion	Key Quantitative Benefit	Overall Cost Range[a]	Effectiveness–Cost Rank
Vehicle technologies	Vehicle–infrastructure integration	Vehicle–infrastructure integration	Traffic-control devices, traffic incidents, weather, fluctuation in normal traffic	Unknown benefit for reducing congestion	Low–high	5-B
Infrastructure improvements and demand optimization	Access management	Access management (driveway location, raised medians, channelization, frontage road)	Physical bottlenecks, traffic incidents	Unknown benefit for reducing congestion	Low	5-A
	Lane treatments	Changeable lane assignments (reversible, variable)	Traffic-control devices	Unknown benefit for reducing congestion	Medium–high	5-C
	Multimodal travel	Integrated multimodal corridors	Fluctuation in normal traffic, special conditions, physical bottlenecks	Unknown benefit for reducing congestion	High	5-D
	Travel reduction	Travel alternatives (ride-share programs, telecommuting, home office, videoconferences)	Fluctuation in normal traffic, special conditions, physical bottlenecks	Unknown benefit for reducing congestion	Low	5-A

[a] Overall cost range applies to the application of a treatment in roadway segment or corridor. For example, several dynamic message signs can be installed along an important route. The designations of overall cost range correspond to the following values: low = <$200,000, medium = >$200,000 but <$1 million, and high = >$1 million.

if they are implemented together. The European experience has shown that when variable speed limit (VSL) systems and temporary shoulder use lanes were deployed together, significant improvements to capacity were achieved. Another key point about this group is the safety focus. Driver qualification and automated enforcement are strategies that deal strictly with drivers' abilities to operate a motor vehicle and comply with traffic laws. Crash reductions were observed where these strategies were put into place. The context in which each of the treatments associated with Table 6.11 could be applied was also considered as described in the section below.

Driver Qualification

Driver qualification is a treatment that involves the prior training of drivers. Thus, it is not a treatment applied to a particular facility type. The safety aspect of this treatment could improve travel time reliability by reducing traffic disruptions caused by impaired drivers.

Automated Enforcement

Automated enforcement involves the use of speed-enforcement cameras along arterial and local roads and red-light-running cameras at signalized intersections. These cameras can be applied in a variety of area types (urban, suburban, and rural) to reduce speeds and to reduce red-light running.

Probe Vehicles

Probe vehicles and point detection treatments such as GPS, video detection, microwave radar, and Bluetooth MAC Readers are treatments used by agencies for vehicle detection as a means to provide near-real-time travel time estimation. These treatments can be applied in a variety of different area and facility types. Assessing congestion (and changes in travel time reliability) in busy corridors and exploring alternative routes are some of the possible applications.

Geometric Design Improvements

Geometric design improvements involve spot reconstruction or minor geometric widening within existing paved areas of all facility types. This treatment can be applied within a relatively small section of roadway or at an intersection and includes such features as auxiliary lanes, flyovers, interchange modifications, narrow lanes, temporary shoulder use, and minor alignment changes. Many major metropolitan areas in the United States have examples of spot geometric design treatments being used to address freeway bottlenecks (Parsons Brinckerhoff et al. 2012, Potts et al. forthcoming).

Variable Speed Limits

This treatment is applied to freeway facilities to vary the speed limit on the facility as it approaches capacity at a bottleneck. Its use has predominantly been seen in larger urban areas and is in widespread use on freeways in the Netherlands and Germany. VSLs can also be applied in work zones to homogenize traffic flow.

The last group of strategies and treatments (identified as Level 5) is shown in Table 6.11. These strategies and treatments are not necessarily less effective than the previous groups, but their benefits were not quantified in the literature. Such treatments include vehicle–infrastructure integration (VII), access management, changeable lane assignments, integrated multimodal corridors, and travel alternatives. One reason that information on benefits was not found is that some of these treatments are relatively new and their potential effectiveness is under evaluation. Despite this, strategies such as access management and lane treatments are well documented in terms of standards and implementation, but there is a lack of information regarding their performance. The context in which each treatment associated with Table 6.11 could be applied was also considered as described in the section below.

VII is a treatment currently undergoing testing in several locations, such as California and Michigan. The treatment provides full communication between vehicle and infrastructure by combining technologies, such as advanced wireless communications, onboard computer processing, advanced vehicle sensors, GPS navigation, smart infrastructure, and others, to enable vehicles to identify threats and hazards on the roadway and communicate this information over wireless networks to alert and warn drivers. As such, the application of this treatment will be limited to those facilities (freeways and arterials) instrumented with an infrastructure that supports this technology.

Access Management (Driveway Location, Raised Medians, Channelization, Frontage Roads)

Access management is mostly applicable to arterial roadways and is intended to provide access to land development while still maintaining a safe and efficient transportation system. In most cases, access management techniques are applied in urban and suburban areas to improve capacity and performance.

Changeable Lane Assignments (Reversible, Variable)

Changeable lanes are applicable on arterial roadways, freeways, bridges, and tunnels to increase capacity for facilities that have directional peak traffic flows. On freeway facilities, most reversible-lane applications are implemented by constructing a separated set of lanes in the center of the freeway with gate controls on both ends. Temporary shoulders are another form of this treatment that are applied on freeways to reduce congestion levels.

On arterial facilities, a movable barrier can be applied to separate opposing directions of traffic flow physically, or overhead lane-control signs can be applied to inform drivers of the current status of a changeable lane. In addition, variable lanes can be applied at intersections with variable-lane-use control signs that change the assignment of turning movements to accommodate variations in traffic flow.

Integrated Multimodal Corridors

These corridors are a treatment that can be applied on arterial roadways in urban and suburban areas to help mitigate bottlenecks, manage congestion, and empower travelers to make more-informed travel choices. This is achieved most effectively when multiple agencies are managing the transportation corridor as a system rather than through the traditional approach of managing individual assets.

Travel Alternatives (Ride-Share Programs, Telecommuting, Home Office, Videoconferencing)

Of the travel alternatives treatment types, ride-share programs (i.e., carpools and vanpools) are the only ones that can be applied on a particular transportation system. Given the flexibility of this treatment type, these programs can be applied within all area and facility types.

Future Technological Innovations

The development of technological innovations is usually not a priority for agencies. Nevertheless, agencies and, ultimately, road users will benefit from evaluating the positive impacts that technological innovations may have on travel time reliability. Mobile applications are at the core of cutting-edge technologies that will have a large impact on travel time reliability. The widespread dissemination of user-customized traffic information with temporal and spatial multimodal integration will change the behavior of commuters in the next 20 years. As these mobile applications are being developed and integrated with traffic data, more information on the following will be available:

- Carpool and carsharing programs;
- Transit information;
- Safety applications (e.g., automated accident notification);
- Emergency ride programs;
- Parking information;
- Dynamic routing integrated with ridership programs; and
- Multimodal travel options with cost and time information.

With future pricing strategies, the transportation system will likely see full integration of transportation options across mode, time, and space. Similar to deciding on what to have for breakfast, commuters will have the option to choose the most efficient or cost-effective travel option in real time after considering total travel time and cost across various modes of travel. The price that users pay will directly reflect the true costs associated with the selected travel mode. As such, user choices will provide insight on market preferences, while system use will provide a continuous stream of revenue to support the program and innovation. Therefore, unlike today, the price of travel will be tied directly to the value of time as well as the value of service received. For example, if a user wishes to drive at a certain time of day, the user will have information about the time it would take to complete that trip and the associated cost. The system will also provide cost and travel time information for different times of the day. With user knowledge about the true cost of travel by mode, time, and space, demand will likely be more even across the day, which would support better system reliability.

Overview of Future Travel Opportunities

Travelers will experience the advance of current applications in an integrated fashion in order to improve operations. GPS will be used in conjunction with congestion pricing and tolling schemes. As the manufacturing cost of GPS units decreases and their data communication capabilities with dedicated short-range communication (DSRC) networks increase, agencies will be able to better implement variable congestion pricing plans and also collect real-time information on travel time reliability. This information can then be displayed in DMSs and converted into performance measures so that an analysis of the effectiveness of implemented operational strategies can be evaluated.

Another existing technology that will have widespread application is smart cards and radio frequency identification (RFID) tags. The market penetration for this technology will become a reality, and privacy issues will be overcome. As a result, electronic toll collection will make cash toll booths disappear and result in less-disrupted traffic flow. In addition, accurate origin–destination information will be available, and better planning models will be developed. RFID tags will also support better dynamic pricing strategies.

On the other end of technological innovations, “telecommuting collaborative technologies” will finally turn telecommuting into a practice part of major business activities. Videoconferencing systems allied with the next generation of 100 Gb/s networks and high-speed wireless networks will provide superior video- and data-stream quality, regardless of where employers are (e.g., at home, in the air, or in another city).

Microsensors and nanosensors will be part of infrastructure-monitoring programs. Information concerning bridge and pavement conditions will be fed to agencies that will allow them to better manage construction and rehabilitation projects. Also, development of innovative practices in construction techniques and development of faster-curing pavement (such as rapid-curing concrete) will reduce the work zone disruptions to traffic flow. As to weather, heated roadway surfaces (particularly through the use of solar energy) could prevent the accumulation of snow or reduce the effect of snowfall on traffic flow.

Automated cars and highway systems are other concepts that have been around for decades but have never been widely accepted. With the advances in research of VII applications and DSRC networks, these concepts have gained a new boost. One of the main focuses of the 2010–2014 U.S. Department of Transportation ITS Strategic Research Plan (U.S. Department of Transportation and Booz Allen Hamilton 2009) is to fully develop the capabilities of VII. Existing applications are mostly based on the need to survive a crash, whereas future applications will focus on the ability to avoid a crash. Future vehicles will supplement or override driver control when necessary. The integration of several technologies will make the communication of vehicles and infrastructure possible.

In the same line of technologies, the concept of shared smart cars will also be part of most urban areas and large-scale trip-attracting developments such as airports and amusement parks. In these applications, shared smart cars will make carpooling and conventional transit more effective, by solving the “last mile” problem.

As for renewable fuel sources, the increase in electric and hybrid vehicles will follow the changes in funding sources. The additional cost associated with toll roads and congestion pricing on top of gas taxes will lead to a shift from fossil-based vehicles. Hydrogen fuel will appear as an environmentally friendly alternative to fossil-based fuels, especially in Europe and Asia. In North America, biodiesel consumption will be widespread and will help offset the pricing costs for roadway users.

In addition to technological innovations, future concepts of "smart" and "compact" growth and transportation planning will emerge. Integrated technologies will support this vision of the future, but the integration of ideas and lifestyle rethinking will be the main drivers of this visionary future. As noted earlier, web and mobile applications will be the roadway user's comprehensive data and information center. Radical changes in land-use patterns will be observed. Commuters will live closer to their jobs and other activities. With the full deployment of telecommuting capabilities, suburban areas will see more business centers where workers who live nearby will be employed, regardless of their employer location. Government will also support the concept of people living within a certain distance of their place of employment. With these developments, miles traveled between jobs and housing will reduce dramatically, having a positive impact on travel time reliability.

The least-sustainable suburban communities will be redesigned into work–leisure areas where community "gathering spaces" will be created near residential neighborhoods. Walk-to social activities will transform old, cheap land in the suburbs. The actionable future needs to combine multimodal transit, telecommuting, ride sharing, demand management, land use, market forces, pricing policies, technology, and a mind shift in roadway users' approaches to traveling.

In the future, ITS will need to inform and assist all trips imaginable on all roads and by all modes of travel. All of the elements needed to make driverless cars—radar, automatic pilot software, computing power, wireless communications, and of course, navigation systems that know travelers' destinations—are technologically feasible and, in many cases, are even available commercially. Even without collective action, driverless technology will advance. The reason is that decades of experience have shown that drivers will pay for car safety. It is not hard to envision a gradual evolution as computers stealthily take on more and more driving chores (Morris 2010, Freakonomics 2010).

In the future, bicycles will play an important role in improving mobility. Dynamic routing, bike sharing, and distributed data sensing are some of the innovations that will develop to give roadway users comparable technology and information available across different modes. A trip to the grocery shop will no longer involve only one mode of transportation. Shared use of different modes will allow shoppers to use public transportation or lighter personal transportation (scooters, bicycles, etc.) to go shopping and then use a smart car to bring bags back home. The following path will be a reality:

$$\begin{aligned}&\text{home} \rightarrow \text{public transit/bike} \rightarrow \text{grocery shopping}\\&\qquad\rightarrow \text{smart car/CityCar/Zipcar} \rightarrow \text{home}\end{aligned}$$

In the future, every roadway user will be a decision maker, with the power of deciding where, how and when to make every trip in a cost-efficient way.

In an effort to identify potential new and emerging strategies, an extensive review was conducted. Sources for this review are listed in the reference section of this chapter. The most-promising strategies that could positively influence travel time reliability are described in the following sections on (*a*) automation and infrastructure, (*b*) information technology and data sharing, and (*c*) integration and cooperation.

Automation and Infrastructure

Imagine automated cars capable of picking up elderly or disabled people in residential areas and taking them to nearby supermarkets, doctor's appointments, and wherever else they might want to go. This will be possible because of the improved communication capabilities between vehicles and roadway. In the next decade, we will see a new type of infrastructure intervention. Mesh networks are transforming the automotive industry, morphing cars into sophisticated network nodes that will offer highly customizable services and be virtually self-regulating. Automated cars will also solve the localness problem because cars will come to the driver. In a way, this also solves the lateness problem; because there is no need to reserve a specific car for a specific window, any unused fleet car can be dispatched (Levinson and Nexus Research Group 2008).

Not far from this concept is the revolutionary in-wheel traction and steering system of the CityCar from the Massachusetts Institute of Technology, a stackable, all-electric, two-passenger vehicle that could radically alter personal urban transportation. CityCars work as shopping carts, stacking on each other. They are intended to have an efficient shared use. Another innovation is that the CityCar spins on its own axis, which avoids U-turns and conflicting turning movements. In the same way, the development of rechargeable motorcycles and bicycles equipped with communication devices capable of providing a variety of information to riders will complement the use of automated cars.

A shift on the automobile market from commodity business to technology-innovation service business will also be seen as an impact of technological innovations. Collaborative computing and telecommunications services will be delivering voice and data more efficiently through fiber-optic and wireless mesh networks. The idea of the vehicle as a mobile information center will be widespread with the addition of increasing electronic intermediation of vehicle control (*North American Intelligent Transportation Systems* 2009).

Table 6.12 presents additional innovative technologies related to automation and infrastructure and their possible impact on travel time reliability.

Table 6.12. Automation and Infrastructure Strategies

Strategy	Description or Application	Modes Affected	Impact on Reliability
Real-time control of transit arrivals, connections, and pretrip information	Advanced transit operation strategies	Transit	Medium
Real-time road pricing	Broadly applied, broadly accepted	Passenger vehicles and freight	Medium
Reliability and quality control with pricing	Permits reservation systems; guaranteed arrival times at a price	Passenger vehicles and freight	High
Vehicle–infrastructure integration implementations	Will make crashes on limited access roadways rare; greatly affects reliability	All (passenger vehicles, freight, transit, bikes, pedestrians)	High
Instant automated incident detection and assessment	Information to first responders and rerouting algorithms	Passenger vehicles	Medium
Robotic deployment of visual screens	Eliminates “gaper’s block”	All (passenger vehicles, freight, transit, bikes, pedestrians)	Medium
Vehicle automation	Crash reduction and smoothing traffic flow, including onboard VSL	Passenger vehicles	High
Automated, reliable DUI detection and intervention	Crash and intervention reduction	Passenger vehicles and freight	Medium
3D video, 3D telepresence, and haptic (touch-based) interfaces	Makes telecommuting a real option (because of advanced communication technologies and general acceptance of this family friendly, environmentally soft work style)	All (passenger vehicles, freight, transit, bikes, pedestrians)	High
Automated in-truck operations	Exclusive, tolled, automated lanes; reduces crashes and driver fatigue; increases reliability	Freight	High
Resilient infrastructure	Works well even when weather is a problem	All (infrastructure)	High
Wearable computers with augmented reality	Use of full AACN data in biomechanical models to predict specific occupant injuries in real time	All (passenger vehicles, freight, transit, bikes, pedestrians)	Medium

Note: DUI = driving under the influence; AACN = advanced automated crash notification system.

Information Technology and Data Sharing

Forecasters say that by 2030 video calling will be pervasive and will be generating 400 exabytes of data—the equivalent of 20 million Libraries of Congress. The phone, web, e-mail, photos, and music will explode to generate 50 exabytes of data. As a result, improved wireless telecommunications services will be observed, such as video distribution and messaging, innovative service offerings, packages tailored to niche groups regionally, and instantaneous transmission of large amounts of data (*North American Intelligent Transportation Systems* 2009, Tech Vibes 2010, Impact Lab 2010). This overwhelming amount of information will challenge agencies’ capability of handling and making good use of so much data. Information sharing across agencies is a key factor in overcoming this issue by promoting a strong basis for collaboration and coordination in managing incidents.

Today, one of the challenges in identifying operational performance benefits is generally related to a lack of baseline performance data from which to measure. With improved data quality and amount, electronic data collection (particularly in recording the incident start and stop times) will have significantly improved overall data usefulness. This communications enhancement will ultimately provide a more-accurate measure of the benefit of implemented tactics to the traveling public and the media (Houston et al. 2010).

Paired with electronic data collection, information related to exact modes of transportation (rail, car, bus), time of day, walking routes, origins, and destinations, all tracked in real time, will be readily available to the public. Cost information dissemination also will be a reality, providing a basis for users to decide how to use the different available modes. In addition, the use of wireless telephones and other devices equipped with cameras to capture and deliver traffic incident imagery and

Table 6.13. Information Technology and Data Sharing Strategies

Strategy	Description or Application	Modes Affected	Impact on Reliability
Comprehensive real-time information	Real-time information available to all modes in an integrated fashion; pedestrians, bikes, and vehicles will have relevant information and options on how to proceed with trips	All (passenger vehicles, freight, transit, bikes, pedestrians)	High
Video coverage of networks	Can see picture of the road ahead in car, on phone, in TMC	All (passenger vehicles, freight, transit, bikes, pedestrians)	High
Reliance on roadside signs for driver information	Real-time messages directly to vehicles for information, routing, traffic management, incident management, etc.	Passenger vehicles, freight, transit	Medium
Weather detection and response systems	Snow and ice management through chemical and nanotechnology applications; reduce reliability problems due to weather despite increasing extreme events	All (infrastructure)	Medium
Data from vehicle traces (e.g., GPS tracking of trucks and containers)	Powerful source of reliability data; vastly improved ability to measure reliability makes it feasible to manage for reliability, to guard against performance degradation, to guarantee performance, etc.	Passenger vehicles, freight, transit	Medium
Data sharing	Barriers overcome through creative confidentiality agreements, technologies, and algorithms	na	Medium
Predictive models for real-time systems operation	Forecasting models supporting real-time systems operations and preventing possible breakdowns on the network	na	Medium

Note: na = not applicable.

audio that is useful to first responders will become common and will reduce traffic incident clearance times (RITA, U.S. Department of Transportation 2010).

Another change related to information technology will be the increased use of social networks related to carpooling, bikes, and transit. Agencies will provide support to social network activities. Once information is widely spread, people will be using their transportation social networks as they use Facebook today. Table 6.13 provides additional information on strategies related to information technology and data sharing.

Integration and Cooperation

It is known that more fuel-efficient cars, more public transportation, more ride sharing, and more telecommuting are needed steps—but they are not enough. Some of the technological examples described earlier include changes to signal timings, dynamic toll adjustments, incentives to change mode of travel, and incentives for changing the time of travel (*The Globalization of Traffic Congestion* 2010). The key for significantly improving reliable traffic flow, reduced emissions, and reduced delays is the integration of such strategies. Below, some new ideas are addressed.

The Washington State DOT is using high-tech message signs that deliver real-time traffic information to drivers and adjusted speed limits based on traffic conditions. Using real-time traffic speed and volume data gathered from pavement sensors, Washington DOT has deployed 97 electronic overhead signs stationed every half mile along I-5. Depending on traffic conditions, drivers will see variable speed limits, lane status alerts, and real-time information about traffic incidents, backups, and alternate routes. In addition, the signs provide advance notice of lane merges and closures, allowing drivers to change lanes ahead of time or exit the highway to avoid traffic congestion (ITS America 2010).

The future of technology integration will not only provide the benefit of combining well-known ITS strategies but will also provide resources to support the on-demand urban mobility concept with the emergence of urban facilities schemes such as carsharing and bikesharing. Alternative market models involving small electric cars, scooters, and electric bikes—all cooperatively owned and working together—will drastically reduce congestion and improve day-to-day mobility. Thus, ITS will, of necessity, be more strategic and integrated. ITS will better demonstrate, through performance metrics and evaluation, the return on investment (*North American Intelligent Transportation Systems* 2009). We will see the continued evolution and integration of previously separate information and safety systems. The establishment of more-strategic approaches and the effective use of performance measurements will be critical for evaluating the efficiency of integrated strategies.

Field tests have been conducted to integrate the information systems of the Utah Highway Patrol, the Utah Department of Transportation, the Salt Lake City Fire and Police Departments, the Utah Transit Authority, and the Valley Emergency Communications Center to enable the real-time exchange of incident data. These tests have revealed the importance of involving agency information technology staff early in the development of the integrated system and the importance of developing close working relationships among the agencies involved in this effort (Houston et al. 2010).

Another important aspect of integration comes when different transportation modes compete for the same space on the roadway network. The future of transportation will rely on integrated systems working harmoniously at the same and different surface levels. For example, passenger vehicles and transit will have a complementary effort in such a way that public transportation will move people and goods in long urban commutes while shared vehicles will help people to reach their final destinations. Modes at different levels such as subways, buses, and airplanes will have synchronized and integrated departure and arrival times—optimizing network use. The integration of systems also goes beyond transportation applications. For example, health conditions will be monitored by vehicles in the future. Breakdown points and specific locations that may be a threat to health can be mapped and linked to congestion patterns. A better understanding of the correlation of traffic and human factors will be achieved (Flanigan et al. 2010).

Table 6.14 summarizes additional strategies related to integration and cooperation that will significantly affect travel time reliability in the next 20 years.

Table 6.14. Integration and Cooperation Strategies

Strategy	Description or Application	Modes Affected	Impact on Reliability
Customized real-time routing	Tuned to driver preferences and driven by real-time congestion and reliability data, with predictive capability; what conditions will be at arrival	Passenger vehicles, freight, transit	High
Multimodal routing, schedules, trip planning	Gives people travel options; same for freight (though to a large degree, this exists for freight through 3PL)	All (passenger vehicles, freight, transit, bikes, pedestrians)	Medium
Real-time information on parking availability, roadway conditions, routing, rerouting	Time spent on parking significantly reduced; drivers will know parking availability ahead of time	Passenger vehicles	High
Rapid incident clearance	Automated scene assessment, damage assessment through total stations and digital imaging, rapid removal of damaged vehicles; ability to do on-scene accident investigation in minutes, not hours, with automated imaging technology	All (passenger vehicles, freight, transit, bikes, pedestrians)	High
Latest onboard technology	Fleet turnover inertia overcome with software upgrades rather than new vehicle purchases	Passenger vehicles, freight, transit	Medium
Bus rapid transit and signal preemption	Vastly improved transit as a serious option	Transit	Medium
Universal fare instruments for transit and road pricing	Highly controlled to minimize transfer and waiting time; elimination of dwell times caused by fare collection	Passenger vehicles, freight, transit	High
Real-time condition monitoring to predict long-term infrastructure performance	Major elements self-monitoring on real-time basis; reports problems in advance	All (infrastructure)	High

(continued on next page)

Table 6.14. Integration and Cooperation Strategies (continued)

Strategy	Description or Application	Modes Affected	Impact on Reliability
Combined sensors–computer–wireless link	Multiple information fusion methods combining data from multiple sensors and databases; data fusion nodes communicating on ad hoc wireless network	na	Medium
AACN systems in all vehicles	Crash notification within 1 min for all crashes; network of sensors in infrastructure to detect imminent or actual events or hazards	All (passenger vehicles, freight, transit, bikes, pedestrians)	High
Fully implemented NG9-1-1	Full AACN telemetry data in actionable form pushed into NG9-1-1 system; image from inside vehicle automatically received at public-safety answering point after crash	All (passenger vehicles, freight, transit, bikes, pedestrians)	High
Hybrid wireless mesh networks	Mesh networks facilitating communication of VII and improving mobile interconnection; vehicle-to-vehicle and vehicle-to-infrastructure networks a reality	All (passenger vehicles, freight, transit, bikes, pedestrians)	High

Note: 3PL = third-party logistics; BRT = bus rapid transit; na = not applicable, AACN = advanced automated crash notification; NG9-1-1 = Next Generation 9-1-1.

CHAPTER 7

Concept of Operations

Definition

According to the U.S. Department of Transportation (DOT), a concept of operations (ConOps) describes the roles and responsibilities of stakeholders with regard to systems and transportation operations within a region. Because of the complexity of the transportation system, as well as stakeholder involvement, a typical ConOps is intended to be a high-level document. In fact, the depth of information of a ConOps will likely rely heavily upon the quantity and variety of systems and the likely scenarios within a region. To that end, many regional intelligent transportation systems (ITS) architectures use high-level operational scenarios to engage stakeholders and to better define their roles and responsibilities. For example, these scenarios may describe what happens during a major weather incident, hazardous material spill, or long-term construction project. As stakeholders assess these scenarios and document their ConOps, the significance of their roles and responsibilities is readily apparent, and they can identify and prepare for gaps or challenges in regional operations. The resulting documentation can be a series of statements that an agency or group of entities may wish to adopt that are binding and simply stated facts or that establish a goal or direction.

Travel Time Reliability ConOps Purpose

The intent of this document is to define the roles and responsibilities of participating agencies in applying strategies and treatments to improve travel time reliability. The agencies that can contribute to improving travel time reliability include those responsible for transportation systems (at the federal, state, and local levels), law enforcement, freight movement, emergency response, and vehicle manufacturers. If agencies are to achieve the vision of improving travel time reliability, they will have to work individually, and in collaboration, to implement the strategies most relevant to their region and be able to measure the performance of each strategy. The purpose of this document is to do the following:

- Establish a baseline set of conditions that describes strategies employed today.
- Describe strategies that could be implemented over the next 20 years to enhance travel time reliability for both passenger and freight vehicles. Strategies were developed to address the three alternative scenarios that span the range of possibilities that could develop by the year 2030.

The questions to answer are who, what, where, why, and how to implement these strategies. By anticipating changes in transportation services and travel characteristics, transportation agencies will be positioned to maintain or improve reliability and mobility in the context of increasing levels of demand.

Travel Time Reliability Performance Measures

Performance measures describe the physical performance of a roadway with regard to travel demand and a variety of other factors both within and outside of the transportation agency's control. Within physical roadway performance measures, the primary focus is on the fluctuation of travel time across the year given recurring and nonrecurring changes in demand. To develop a comprehensive picture of the quality of service along a particular facility means tracking demand and travel times on a continuous basis.

It is important to identify travel time performance measures that are relevant to travelers and freight carriers. The performance measures presented below are focused on travel time, which is influenced by fluctuations in both demand and supply (i.e., maintenance, utility work, snow and ice). The following five reliability measures were found to be most relevant to the user categories and are most widely used by transportation agencies:

1. *Planning time (95th percentile travel time).* This is the length of a particular trip in minutes that a traveler can use in planning to ensure arrival as scheduled (required) 95% of the time. It is calculated by computing the 95th percentile travel time for a specific trip measured over a given time period (i.e., 6 months or 1 year). This measure estimates how large delay will be during the heaviest traffic days.
2. *Buffer index.* This is the difference between the 95th percentile travel time and the average travel time, divided by the average travel time for specific trips. (The median travel time is often used.) The buffer index represents the extra time (as a multiplier of average time) that travelers must add to their average travel time when planning trips to ensure on-time arrival 95% of the time.
3. *Planning-time index.* This is the 95th percentile travel time divided by the free-flow travel time index. The planning-time index can also be understood as the ratio of travel time on the worst workday of the month over the time required to make the same trip at free-flow speeds. Consequently, the planning-time index represents the factor to multiply free-flow travel time to ensure on-time arrival with high probability (19 workdays out of 20 workdays per month would yield a 95th percentile measure).
4. *Travel time index.* This is the ratio of the average travel time in the peak period to the travel time at free-flow conditions. It is a measure of average congestion rather than of travel time reliability. Nevertheless, it is an important measure because it can be directly compared to the planning-time index.
5. *Percentage on-time arrival.* This is the percentage of trips that are completed within a given target schedule. This measure is best suited for tracking the performance of scheduled trips (such as buses and light rail).

As suggested by the SHRP 2 L03 report (Cambridge Systematics, Inc. et al. 2013), the buffer index often produces counterintuitive results. When the average travel time decreases (a positive outcome) and the 95th percentile travel time remains high, the buffer index increases—indicating that reliability has become worse. Thus, the buffer index should be used with caution. While the buffer index shows the multiplier of the *average* travel time necessary to achieve high probability of on-time arrival (high reliability), the planning-time index shows the multiplier of free-flow travel time to ensure high probability of on-time arrival. The planning-time index is a useful measure during peak travel periods because it can be directly compared to the travel time index on a similar numerical scale. The travel time index is a measure of average conditions that indicates how much longer, on average, travel times are during peak periods compared to base periods when traffic is light.

The need for the five measures noted above, rather than just one, is important because travel conditions change (for both freight movers and passenger travel) from trip to trip, depending on the purpose and time of the trip. Roadway users are able to easily understand the meaning of planning time because it gives them specific guidance on how to adjust their trip plans to deal with unreliability. It is desirable if agencies focus on reporting and evaluating the planning-time index because this measure is better understood by engineers.

Travel time reliability performance measures also play a key role in evaluating the effectiveness of ITS strategies used to provide traveler information and reduce congestion. In a funding-restricted environment, it is important that agencies wisely invest their scarce resources on ITS technologies that will improve the system performance and capacity at a minimum cost. With the performance measure indexes, and effective tools to forecast them, agencies will be able to quantify the impact of the deployed ITS technologies and, therefore, prioritize investments in the future.

Appendices B and C present an approach to determining the economic value of improving travel time reliability. In this approach, uncertainty is converted to a certainty-equivalent measure in order to use conventional evaluation methods to place a value on the cost of unreliability. The certainty-equivalent measure is a method that allows for expressing the value of reliability in terms of the increase in the average travel time a person would accept to eliminate uncertainty. The value of reliability can be derived for multiple user groups or market segments by applying a separate value of time that corresponds to each user group along with the observed average volume for each user group on the roadway segment. The total value of reliability is then computed as the sum of the reliability values for each user group on the highway segment. The concept for calculating the value of travel time reliability is illustrated in Figure 7.1.

Appendix D provides an example of this methodology based on actual data from Seattle, Washington. This example determines the economic benefits of improving travel time reliability through the implementation of ramp meters under recurring congestion. In this example, the uncertainty arising from recurring congestion is converted to a certainty-equivalent measure in order to use conventional evaluation methods to place a value on the cost of unreliability.

Existing Stakeholder Roles and Responsibilities

The following is an overview of the various stakeholders and what they are currently doing to improve travel time reliability.

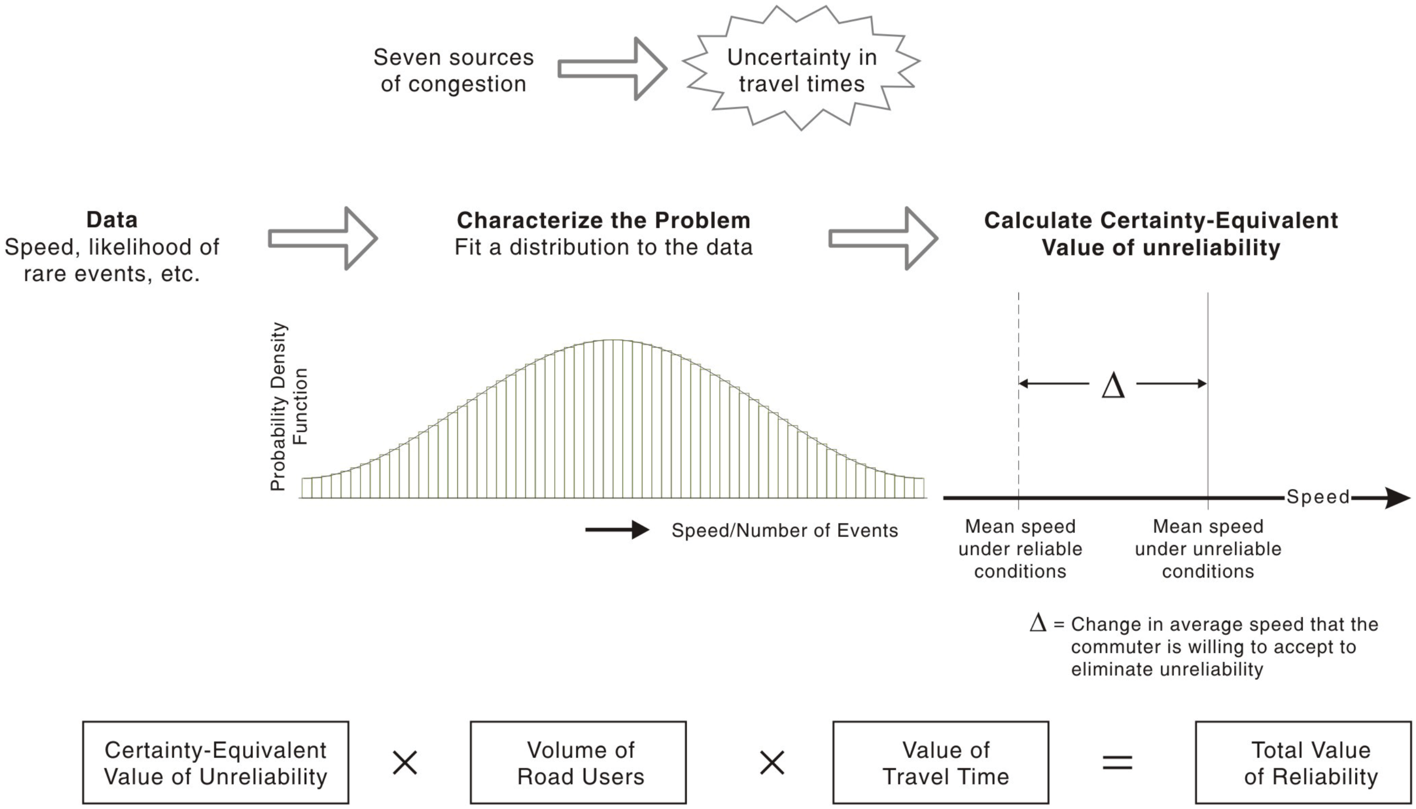


Figure 7.1. Calculating the value of travel time reliability.

1. U.S. DOT
    - Reliability policies have been established to promote the importance of reliability as a key performance measure and to promote its implementation by agencies.
    - Limited performance measures data are being collected.
    - Funding for reliability research and improvements has been provided.
2. State DOTs
    - Very limited congestion-based facility tolling has been implemented.
    - Ramp metering is much more common than tolling and congestion pricing; bottleneck elimination also contributes to boosting reliability.
    - Some performance measures data are available for some of the state roadways, but there is limited reporting of these data.
    - Some truck lanes at ports of entry and weigh-station bypass lanes are provided.
    - Traveler information is provided with various delivery methods.
    - Limited ramp metering, variable speed limits, hard-shoulder running, and truck lanes have been deployed.
    - Variable message signs (VMSs), highway advisory radio (HAR), 511, and traffic enforcement applications are increasing.
3. Local transportation agencies
    - Traffic-signal timing and signal optimization strategies are deployed.
    - Traveler information systems are being deployed.
4. Private data information providers
    - Traffic and weather conditions are available from websites, radio traffic reports, and Twitter.
    - Travel time data are available from private firms.
5. Emergency responders
    - Some major highway corridors have incident-response coverage that is coordinated among jurisdictions.
    - Some ITS applications are in place.
    - Service patrol programs, such as Road Rangers, are implemented.
6. Freight shippers
    - Freight real-time tracking and advanced scheduling of products delivery are widely used to improve freight travel time reliability.
    - Just-in-time (JIT) manufacturing has motivated comprehensive logistics management to respond to network reliability.
7. Vehicle manufacturers
    - Luxury car models have in-vehicle safety systems such as automated cruise control and lane-departure warning systems.

  - All new vehicles have stability control and air bag systems.
  - Vehicle manufacturers have teamed up with the U.S. DOT and state DOTs to develop vehicle–infrastructure integration (VII), an initiative to provide vehicle-to-vehicle communications and to improve safety and mobility. VII is currently being tested in California and Michigan.

8. Travelers
   - Increased use is being made of traveler information through cell phone and Internet services.
   - Onboard distractions from phones, TV, and games contribute to reduced reliability.
   - Travelers are purchasing vehicles with higher safety ratings and in-vehicle information systems.
   - Telecommuting is increasingly common but still accounts for only a tiny fraction of the urban travel market.

Future Scenarios—ConOps Perspective

Key characteristics that describe future conditions are described below. Technologies, organizational activities, and key responsibilities are described for the future baseline, optimistic, mediocre, and pessimistic conditions.

Overview of Future Baseline Conditions

A realistic yet beneficial situation can be achieved with today's technology if agencies are committed to implementing performance-driven strategies. The technologies for the future baseline condition involve widespread deployment of all current traffic management strategies, such as ramp metering, variable speed limits, hard shoulder running, congestion pricing, truck lanes, and adaptive signal control across all major urban areas, as compared with the patchy deployment of today. The key factor to achieve this is an increased level of technical integration and interagency coordination. All these technologies can be operated as an active traffic management system.

The deployment of currently available traveler information systems such as dynamic message signs (DMSs), HAR, 511, traffic websites, radio traffic reports, and Twitter will be common among transportation system operators. Both real-time and historical information will be disseminated. Congestion information will be available for both freeways and major arterial roadways and will be coordinated across jurisdictions so that customers can use one portal to access all the information.

Weather and road condition information will be factored into traffic management decisions in addition to being used for winter road maintenance. Comprehensive real-time and predictive weather and road condition information will be provided to the public. All roadways will have incident-response coverage that is coordinated among jurisdictions. All safe and legal commercial vehicles will bypass inspection and weigh stations at freeway speeds. Agencies will have some type of performance data for all of their roadways and will provide limited reporting of performance. These data will be provided in an archive that can be easily accessed in a usable format. Work zone management will be widespread, and information of traffic delays related to work zones will be available to the public.

Automobile manufacturers will play a role by providing a broader range of car models (more than just luxury models). These models will have in-vehicle safety systems such as automated cruise control and lane-departure warning systems. All vehicles will have stability control and air bag systems. Telecommuting will be more widespread than in today's condition. Most terminals at ports will have gate appointment systems to manage queues and congestion on surrounding streets.

Overview of Alternative Futures and Their Impact on Transportation

The alternative futures discussed previously in this report define a range of conditions within which travel time reliability can be managed. These bound and characterize the likely future situations that transportation managers will face in terms of the key variables that can influence reliability. These futures were grouped according to current and potential trends to identify a range of factors affecting the operation of the transportation system and demands for it, the frequency of nonrecurring congestion, the priorities likely to be placed on mitigating such congestion, the technologies that may exacerbate the problem or facilitate effective responses to it, and the broader social and environmental contexts within which the future transportation system will be managed. As noted before, these trends were combined to produce a set of three future scenarios.

Optimistic Scenario

The Optimistic Scenario assumes positive future outcomes for climate change, economy, and energy. A key assumption of this scenario is that technological advances will provide alternative sources of energy at costs similar to today's levels. New technology will also dramatically reduce transportation's contribution to greenhouse gas (GHG) emissions, achieving a 75% reduction in GHG emissions relative to year 2000 levels by 2030. The impacts on transportation from climate change will be less severe than expected. This will occur, in part, because new technology will provide a solution to anticipated escalating energy prices and climate change, and economic growth will be stimulated with a steady increase in employment and population within the United States. The demand for reliable transportation will increase because of increased travel demand as a result of strong economic, population, and employment growth, and as new technology makes more-reliable transportation systems feasible.

In terms of technological advancements, improvements in computing and communications will make levels of data analysis and technical and institutional integration possible. Open road tolling will be used to generate transportation funds. Congestion pricing and variable speed limits will be implemented on major commuter routes to maintain maximal flow and reliability. This management strategy will make roadways reliable enough so that travelers will use the Internet to reserve a space in a lane or on a freeway (for a price) that will ensure arrival at a selected time. Advanced traffic-signal algorithms will work with pricing algorithms to optimize traffic flow on arterials. Arterial corridors will have multijurisdictional adaptive signal control. Weather and road surface information will be integrated into the decision-making process so that traffic flow can be optimized for weather and road conditions and to optimize winter maintenance operations.

Agencies will have policies and procedures in place and available to manage transportation systems for reliability. The toll systems will provide a wealth of probe vehicle data. Historical, real-time, and predictive traveler information will be available so that customers can compare travel time and costs and choose the travel option that provides the best value for their situation. Information will be available in homes on mobile devices and in vehicles through seamless interfaces. Road and congestion information will be good enough, connections to the Internet will be fast enough, and remote office technologies will be effective enough so that people can decide to telecommute when the system is not working well or when costs are too high. With the advance of vehicle–infrastructure integration (VII) technologies, some automated highway systems will be deployed for trucks, transit, and automobiles.

Because there will be adequate transportation funding, intercity transport alternatives such as high-speed rail and automated lanes will be available for trips of less than 300 miles, thereby reducing vehicle miles traveled (VMT). Parking information systems will eliminate wasted urban mileage spent searching for parking spaces. Active and passive driver assistance systems will dramatically reduce accidents and, concomitantly, nonrecurring congestion. Driver assistance systems will be good enough so that only minimal automated enforcement is needed.

When an incident does occur, response will be very quick. The appropriate emergency services and vehicle removal equipment will be routed optimally to the incident and then to the trauma center. First responders will be in communication with the trauma center, incident response, and transportation management center (TMC) during the process. Because driver assistance systems will reduce the number of incidents, incident response will be more focused on disaster response, including evacuation planning. Intermodal transfer of goods will be seamless because of appropriate information systems and technology. Freight information and a cargo-matching system will reduce the number of empty trips by trucks. Systems will be available to indicate availability of loading dock space to reduce truck search-and-wait times in urban areas.

Mediocre Scenario

In the Mediocre Scenario, the key drivers (climate change, the economy, and energy) will be in a range that supports moderate economic growth as well as the deployment of advanced technologies for transportation systems and operations. Energy prices will continue to increase, but supply, in the form of traditional and alternative fuel sources, will be fairly reliable. The demand for reliable transportation will increase because of a stronger economy and increased employment, the pressure for efficiency coming from climate change and energy constraints and regulations, and emerging technologies making more-reliable transportation systems feasible. This demand will draw new technologies into the marketplace and promote their deployment. The economy in this scenario will be less robust, so both the level of tolling and the amount of funding for transportation improvements will be less. Increasing energy prices and moderate population growth will mean less pressure to accommodate car use than in the Optimistic Scenario. However, congestion will still need to be managed.

In terms of transportation funding, a gas tax will still be used to raise some revenue, and tolling will be implemented on major freeways and on facilities in need of replacement. Congestion pricing will be implemented only in the most heavily congested large cities. A few lane or facility reservation systems will be in operation. Advanced traffic-signal algorithms will improve arterial traffic flow, but congested conditions will still occur during peak periods. Agencies will manage major facilities for reliability but will lack data to manage the overall system. Weather and road condition information will be closely monitored because of the increase in rare events. This information will be incorporated into traffic management, pricing, and maintenance decisions. In general, it will not be possible to keep traffic flowing at an optimal level, because data will not be available for all parts of the system and prices on many parts of the system will not be set high enough to optimize traffic flow.

In terms of technology, some automated transit and freight lanes will be deployed in markets for which fares or fees can be raised to cover costs. The only automated auto lanes will be located where private companies are granted franchises to build lanes. A great deal of traveler information will be provided, but it will not be as good as the information provided in the Optimistic Scenario because of fewer probe vehicles. Automated enforcement will be needed for speed, red-light running, and toll evasion. Luxury and mid-priced vehicles will have active and passive driver assistance systems, but lower-priced vehicles will lack the latest systems. The slower economy means that more people will still use older vehicles without the latest safety systems. As a result, more incidents will occur than in the Optimistic Scenario. Nonrecurring congestion will be worse. Incident management will be used to improve communication technology to efficiently coordinate between first responders, towing companies, trauma centers, and TMCs. The deployment of incident-response systems will be the same as described in the Optimistic Scenario, but there will be more emphasis on incident management and less emphasis on disaster response. Telecommuting will be popular when congestion is bad, but commuters will not have the comprehensive information needed to make optimal choices. As a result, the effectiveness of the information will not be as high as it could be.

Some weigh stations, ports of entry, and borders will use inspection technology that allows for trucks to bypass at freeway speeds or to have a facilitated inspection. Logistics efficiency and JIT strategies will be relevant but will not be primary drivers of freight mobility. Security and infrastructure health monitoring will be limited to major facilities. Some vehicles carrying hazardous materials (hazmat) will be tracked. The location for some global trading patterns will shift as more manufacturing moves back to North America because of rising energy prices. Also, more containers from Asian ports will go directly to East Coast and Gulf ports through an expanded Panama Canal or the Northwest or Northeast Passages—thereby reducing cross-country rail and truck trips but increasing short-haul trips in those port cities.

Pessimistic Scenario

For the Pessimistic Scenario, the key drivers (climate change, the economy, and energy) will be in a range that does not support economic growth because of, among other influences, more-frequent severe-weather events and increasing energy prices. It is assumed that the drivers of change will result in negative outcomes, such as an increasing rate of climate change, a greater decline of economic conditions, and increasing energy prices. In this scenario, the demand for reliable transportation will increase because of policies and goals focused on reducing fuel consumption, decreasing greenhouse gas emissions, and supporting economic growth. With the high value of travel cost, delays will become a much-stronger economic constraint. Thus, strategies aimed at reducing delay and travel variability will become an important component of state and regional transportation strategies to improve system performance. Large-scale applications of technology, financial tools, and institutional arrangements will be needed to support this focus on system reliability. The economy in this scenario will not be very robust, and as a result, the amount of funding for transportation improvements relative to needs will be greatly restricted. Steep increases in energy prices, the increasing effects of climate change, and low population growth will mean that car use will be limited and agencies will experience less pressure to improve traffic performance. An increased number of disruptive weather events will occur.

In terms of transportation system funding, very limited tolling will be implemented on facilities with existing tolls and funds will be available to pay for only new facilities. Tolls will be removed when a facility is paid for. A relatively large gas tax increase will occur, but this increase will not generate enough revenue to cover major improvements to the system. The number of existing congestion pricing systems will remain at current levels. Agencies will report performance on some facilities but will lack sufficient data to manage the overall system. High energy prices will keep congestion somewhat manageable. Congestion in this scenario will still be the worst of the three scenarios. In terms of technology, ramp metering will still be in use. Advanced traffic-signal algorithms will improve arterial traffic flow, but congestion will still occur during peak periods. There will be a need for widespread automated enforcement related to speed, red-light running, ramp meters, and toll evasion. Automated highway systems will not be fully implemented, and some motorist awareness will be required while driving. A great deal of traveler information will be provided, but the overall level of information will not be as good as that provided in the Optimistic Scenario because of fewer probe vehicles. Luxury and mid-priced vehicles will have active and passive driver assistance systems, but lower-priced vehicles will still lack the latest systems.

The slower economy will mean that more people will still use older vehicles without the latest safety systems. For these reasons, this scenario will have the highest crash rates and the highest levels of nonrecurring congestion. It will therefore be the most-unreliable scenario. Because of the high cost of fuel, telecommuting will be popular, but it will not be done on a scheduled basis (much as it is done today). Telecommuting will not be practiced in response to traffic fluctuations as predicted in the Optimistic Scenario. Incident-response advances will not be noticeable in the same way as in the Mediocre Scenario. It will be difficult for agencies to devote enough resources to both incident response and disaster management because crash rates will be high and disasters will be frequent. Some weigh stations and ports of entry will have inspection technology that allows for bypass at freeway speeds. Logistics efficiency and JIT strategies will not be emphasized because many companies will be in a survival mode and the network will be congested—thereby reducing freight reliability. Security monitoring of major facilities will be implemented, and limited hazmat tracking will occur.

Baseline and Alternative Futures Strategy Assessment

To establish a reference point for the implementation of the key strategies, the impact of each alternative future scenario on the sources of congestion was ranked as low, medium, or high. The information provided in Table 5.1, Table 5.2, and Table 5.4 (see Chapter 5) served as a basis for the ranking process. The results of this process are shown in Table 7.1.

As shown in Table 7.1, traffic incidents and physical bottlenecks are expected to be significant sources of travel time unreliability in the Optimistic Scenario. The decline in reliability from these sources will be mitigated through safety gains achieved from the extensive use of ITS technologies aimed at improving traffic operations. For the Mediocre Scenario, traffic-control devices and fluctuations in normal traffic and special events are expected to be increasingly frequent sources of congestion because of the increase in the variation of day-to-day travel demand, resulting from population growth and relaxation of economic constraints on travel. The economic and environmental conditions in the Pessimistic Scenario along with reduced travel demand will most likely increase delay due to weather and work zones. Increases in the frequency of rare events such as tornadoes, snowstorms, and flooding will be responsible for infrastructure failure and interruptions.

Improving agency management, organization, and resource allocation will become increasingly more important in any of the future scenarios, given that each scenario is expected to have high impacts from more than one source of congestion. Therefore, the systems operation and management (SO&M) structures within agency organizations will need to be better balanced in the future to provide both travel time reliability and infrastructure improvements.

Given the impact of the future scenarios on the sources of congestion, specific treatments from Chapter 6 are listed for each future scenario in Table 7.2. The list should be viewed as an example of a combination of treatments to improve travel time reliability under each of the three alternative futures. This assignment should not be understood as an exclusive set of treatments, but as a directory of the treatments that will be most effective, given the characteristics of each scenario. The treatments not listed should not be discarded by agencies, because all treatments listed in this report can continue to improve travel time reliability. To better understand the logic behind Table 7.2, the examples below illustrate the applied methodology:

- In Table 7.2, under the traffic incidents source of congestion, TMC was assigned to the Baseline Scenario, because it is currently implemented, as well as to the Optimistic and Mediocre Scenarios (ranked as high and medium in Table 7.1). Even though the TMC treatment was not assigned to the Pessimistic Scenario, that does not mean it will not be used under this scenario. The correct interpretation is that under the Optimistic and Mediocre Scenarios, there is a greater need to expand the TMC strategy (given the characteristics of each scenario), while under the Pessimistic Scenario, this strategy use will remain about the same when compared to the baseline conditions.
- Under the weather source of congestion, National Traffic and Road Closure Information was identified in the Baseline and Pessimistic Scenarios. For this specific treatment, the proper interpretation is that it is being actively used today, but because of the higher number of disruptions related to recurrent weather events in the Pessimistic Scenario, the expansion of this treatment will be critical to

Table 7.1. Impact of Alternative Future Scenarios on Sources of Congestion

Source of Congestion	Impact Based on Future Scenario		
	Optimistic	**Mediocre**	**Pessimistic**
Traffic incidents	High	Medium	Low
Weather	Low	Medium	High
Work zones	Low	Medium	High
Fluctuations in normal traffic and special events	Medium	High	Low
Traffic-control devices	Medium	High	Low
Physical bottlenecks	High	Medium	Low

Table 7.2. Key Treatments to Respond to Baseline and Future Scenarios

Source of Congestion	Baseline System and ConOps	Optimistic Scenario System and ConOps	Mediocre Scenario System and ConOps	Pessimistic Scenario System and ConOps
Traffic incidents	Remote verification Service patrols TMC	Remote verification Driver qualification Automated enforcement Pretrip information TTMS VII, driver assistance Service patrols On-scene incident management TMC Traffic-signal preemption	TTMS Service patrols On-scene incident management TMC	TTMS Service patrols On-scene incident management
Weather	Remote verification National Traffic and Road Closure Information RWIS	TTMS Better weather forecasts and winter maintenance decisions	TTMS	Remote verification National Traffic and Road Closure Information Pretrip information RWIS TTMS VII TMC
Work zones	National Traffic and Road Closure Information WZM	VII WZM	TTMS WZM	National Traffic and Road Closure Information Pretrip information TTMS WZM TMC
Fluctuations in normal traffic and special events	Remote verification PSEM Pretrip information	PSEM Pretrip information TTMS VII TMC ATA VSL Managed lanes	Remote verification PSEM Pretrip information TTMS TMC ATA VSL Managed lanes	Variable speed limits Managed lanes
Traffic-control devices	Remote verification TMC SRO	VII TMC SRO Traffic-signal preemption ATA	Remote verification TMC SRO ATA	TMC SRO
Physical bottlenecks	CVO Bottleneck removal Geometric improvements Managed lanes Freight-specific corridors	Automated enforcement CVO TTMS VII Bottleneck removal Geometric improvements Ramp metering, ramp closure Variable speed limits Electronic toll collection Managed lanes	Bottleneck removal Geometric improvements Ramp metering, ramp closure Variable speed limits Electronic toll collection Managed lanes	Ramp metering, ramp closure Variable speed limits Electronic toll collection Managed lanes

Note: ATA = advanced transportation automation; CVO = commercial vehicle operations; PSEM = planned special events management; RWIS = road weather information systems; SRO = signal retiming and optimization; TMC = transportation management center; TTMS = travel time message signs (including variability); VII = vehicle–infrastructure integration; WZM = work zone management.

keep roadway users informed about traffic, roadway conditions, and safety.

- The third example explains the logic behind the signal retiming and optimization (SRO) treatment under the traffic-control devices source of congestion. SRO was assigned to the Baseline Scenario and to all future scenarios because of its effectiveness in mitigating delays at signalized intersections. The relatively low cost associated with this treatment makes it essential to improve travel time reliability in all three future scenarios.
- The last example applies to VII. Under the fluctuations in normal traffic and the special events source of congestion,

VII is identified for only the Optimistic Scenario. VII is a set of technologies that is still being tested, so its application was not assigned to the Baseline Scenario. Because of the increased level of technological development in the Optimistic Scenario, this treatment was identified as a key application to reduce travel time variability in the future. The high cost of VII along with a reduction in VMT for the Pessimistic Scenario and moderate technological investments in the Mediocre Scenario led to dropping VII as a priority treatment.

The same rationale was applied to the other treatments shown in Table 7.2. Note that this list provides the foundation of ITS strategies to the implementation road map from the present to the future scenarios described next in this chapter. Innovative technologies are likely to cause significant changes in travel time reliability in the future. The potential impacts of innovative technologies are discussed at the end of this chapter as well.

Implementation Road Map

The implementation road map covers the range of challenges and opportunities that may result from the future scenarios and discusses the needed approach to address travel time reliability needs over the next 20 years. Rather than focusing on one alternative future, this section will provide an overview of what is needed to improve travel time reliability by 2030. Afterwards, a discussion is presented on institutional challenges, funding constraints, and technological opportunities that will need to be addressed to overcome congestion and travel time reliability threats generated in all three alternative future scenarios.

Improved Travel Time Reliability: What Is Needed

The most-significant benefits in improving travel time reliability will be attained when technological changes, operational solutions, and organizational actions are integrated to improve the balance between travel demand and capacity. A variety of technological changes, operational solutions, and organizational actions currently exist or will become available in the next 20 years. These changes, solutions, and actions will allow more-effective management of transportation demand, increases in person- and freight-moving capacity, and faster recovery of the capacity lost to various types of disruptions. A wide range of activities will be employed by groups ranging from individual travelers, carriers, and shippers, to highway agencies, local governments, and private companies that supply services that support roadway operations.

To do this would require major institutional and functional changes in how our roadways (and the transportation system as a whole) are currently funded and operated. That is, technical improvements, while highly beneficial in specific instances, would have only a modest benefit for travel time reliability unless more-significant structural changes occur in balancing travel demand and transportation supply (capacity) as shown in Figure 7.2.

Balancing travel demand and transportation supply will require changes in the following areas:

- All agencies that provide transportation supply would work cooperatively to integrate the multimodal transportation services they support to maximize total available (useful) capacity.
- Accurate information would be easily available describing available travel options, the expected travel times for those options, and the price to be paid for each option, so that travelers and shippers can make informed choices when they plan trips, just before the execution of those trips, and during the trips.
- Travelers would be required to pay more directly for the transportation services they receive, and prices would be set to reflect both the cost of providing transportation services—to providers as well as to other users—and the value received by the traveler.
- Agencies that deliver those services would be held more directly accountable for the quality of those services.
- Funds generated from user fees would be returned to the agencies that supply the multimodal, integrated transportation services being used to give them significant incentive to identify, select, and deploy effective services and technologies.

Operating a more-reliable transportation system will require a more holistic view of funding, managing, and operating that

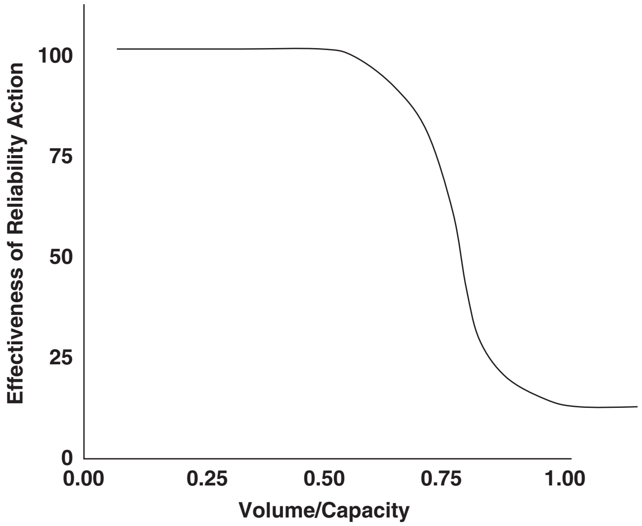


Figure 7.2. Implemented reliability performance.

transportation system than now exists in the United States. It will require that consumers (individual travelers, shippers, and carriers) be given travel options, as well as information about those travel options, and be charged separately and explicitly for each option, and that the cost associated with each option reflects the costs of providing those services. Consumers will then be able to select intelligently among the different transportation options, trading off cost versus level of service, including reliability. By observing the behavior of consumers, transportation agencies will learn which travel options are valued and (through effective pricing) will gain the funds required to supply them.

In this system, some consumers, for some trips, will choose high-cost, faster, more-reliable travel options (e.g., overnight air express shipping, or single-occupancy vehicle commuting on high-occupancy toll lanes). Other consumers will choose slower options with less-reliable travel times that cost them considerably less (e.g., conventional ground shipping, or local bus service operating in mixed traffic). The results will be the following:

- Travel consumers have choices and know what those choices are.
- Travel consumers have monetary incentives to select among those travel options based on the agency and social costs to provide the services.
- The revenue generated will go toward providing and improving that combination of transportation services.

Improved transportation system reliability does not mean that all travel will take place at the speed limit. It means that consumers will be able to obtain estimates of how long a trip will take, know that the estimate is reasonably accurate, and make travel decisions accordingly.

Institutional Challenges

To effectively manage the transportation system with a focus on reliability and to achieve the future ConOps, transportation agencies will need to adopt an institutional structure that is more multidisciplinary, exercise horizontal integration across all focus areas, and facilitate effective interagency collaboration. The critical change will be to focus on systems operations rather than on the historical focus of roadway expansion. A true focus on maintenance and preservation of the existing system is also essential to maintain mobility because a deteriorating system could make it exceedingly difficult to manage reliability. Because it is unlikely that enough transportation revenue will be available in the next 20 years to replace and restore all aging infrastructure, infrastructure monitoring will be crucial. Delays due to toppled luminaire poles, outages of traffic-signal lights, bridge expansion, joint deterioration, potholes, and more-serious structural failures could be major contributors to reduced system reliability in the future. Systems for monitoring infrastructure are likely to be a critical part of any attempt to ensure transportation system reliability. These monitoring systems can also be used for security-oriented transportation infrastructure protection.

Systems Management

There are good reasons for systems management to be a business practice with supporting performance measures and outreach materials that report on the benefits of the program. Many highway systems of the future are likely to be greatly dependent on pricing systems for revenue, congestion management, and data collection, so it is crucial that the system is managed with these aspects in mind to provide value to the traveler. A motorist who pays a premium to arrive at a destination at a specified time (i.e., who pays for a trip of a certain travel time and reliability) will be a very disgruntled customer if the system fails to deliver and the trip takes longer than expected. Depending on the operating policy, the toll or fee for service may need to be refunded. Operators of systems that consistently meet motorists' expectations and deliver the expected value can be rewarded. Agencies may wish to consider ways to measure customer satisfaction and reward efficient system management (possibly with more resources to further improve operations) and penalize inefficient system management (by sending nonperformers to lower status jobs as is done in the case of nonperforming sports team managers.)

Reliability will become even more crucial to freight movers. As a result, freight mobility deserves at least as much consideration as personal mobility. Agency planning procedures will need to consider a wider range of options, such as truck-only lanes, microcars, or other vehicles powered by alternative propulsion systems.

The Mobility Agency

This focus on system operations means that many agencies in the future will not only be concerned with managing the infrastructure that moves vehicles or people from A to B but will also focus on the movement of information from A to B. Providing the information needed by commuters to make informed decisions on telecommuting that is based on real-time traffic and infrastructure conditions is an example of this change in emphasis. The "mobility agency" is envisioned to support mobility of people, things, and ideas. For some modes, the agency would be an infrastructure owner-operator; for others, it would be a service provider or a provider of information only. In the new world of customer orientation, this agency is expected to be evenhanded in providing service and advice. Thus, it would never be an information carrier, such as a cell phone company, but it might tell people that telecommunications is an option. It would not be a central controller of land use, but it might inform people of the costs and travel characteristics associated with living in certain areas. The purpose of integration would be to evaluate all the forces behind travel to accomplish reliable connectivity through timely, objective, and accessible information. Essentially, travelers would be informed about the service characteristics, including the reliability, of all reasonable options.

In corridors where congestion and reliability are problems for the road network, a complementary and competitive transit option can sometimes be designed that will lure choice riders out of their cars, producing benefits for both transit and highway users. A competitive transit option requires a time-competitive and seamless service in which the separate links are effectively integrated; transfers and waits are easy and short; the en route experience is quick, safe, and comfortable; and reliability is high. For bus-on-highway transit operations, the challenge of delivering reliable service is the same as for the automobile. Thus, improvements to one mode can bring benefits to the other. When road pricing is used, allocating some revenues to support such high-quality transit services can be both cost-effective and equitable.

Data Management

With the future emphasis on data collection, the agency of the future will need to be prepared to manage a wealth of data. Data will need to flow efficiently to and from the following:

- Other traffic management systems, both within an agency and from other agencies;
- Other agencies (law enforcement, transit, emergency management);
- Vehicles—either directly or passed through private monitoring systems; and
- Pricing systems.

Good practice suggests that data must be used and handled consistently across different agencies and jurisdictions. Consistency can be achieved by adopting certain standards and definitions such as common geographic references, data stamping, and data collection practices. Although it is important to have consistent data collection and archiving across different regions, it is undesirable for agencies to aggregate data from multiple locations with different traffic characteristics. Each location has specific traffic patterns, and the data archiving and management of each area is fundamental to developing appropriate strategies.

By 2030, this data stream will be of a size that is difficult to imagine today. The traffic management system operators of the future will need decision support systems to sort, compile, and display these data in a form that will be useful. Effective data management and data archiving will become critical measures of how well agencies use the current and historical data for decision making.

Once an agency starts to focus on operating and managing the system for reliability, the information can be shared with the public to make the system truly effective. Motorists will have a much different attitude toward the system, because they will be able to relate what they pay to make a trip with the value they receive in return. Agencies will need to be much more transparent about where revenue goes and how effectively it is used. In effect, today's relatively minor emphasis on performance measures will need to be greatly increased. Instead of waiting for quarterly or yearly reports on performance, motorists will expect to see some information in real time (the relation between travel time and toll prices, for example). Historical and predictive information on travel time reliability and traffic conditions will be necessary so that users can make informed decisions. Similarly, performance measures with a consideration of cost, including the value of user time, would allow comparative evaluations of the effectiveness of different strategies and their monetary benefits to the end user.

Freight will continue to require the movement of physical goods on the transportation infrastructure, but improved information from the agency of the future will support tools such as freight tracking and load matching to operate the transportation system efficiently and reliably and increase the efficiency of freight movement.

The Private Sector

The future is likely to see the private sector provide mobility services such as technology, information, service management, and franchises to build and own infrastructure. The private sector is motivated by profits to innovate and implement new ways of making transportation—both freight and passenger—more efficient and more reliable. Ensuring an open, collaborative environment in which this innovation can occur will be important for improving transportation system performance, achieving the most-beneficial division of responsibilities, and arriving at the most cost-effective, market-driven solutions.

Among the most-important actions that an agency can take to prepare for the future are to follow developments in new technology, seize opportunities quickly, develop partnerships with both public- and private-sector partners, and operate in a flexible, resilient, and entrepreneurial manner. This involves organizational and attitudinal changes. It will not be easy to find the right balance of risk taking and good public stewardship of resources, but several agencies operate today in a manner that show it can be done. Some examples from DOTs include Maryland DOT's Coordinated Highways Action Response Team (CHART) program, Florida DOT's Rapid Incident Scene Clearance (RISC), Georgia DOT's Towing and Recovery Incentive Program (TRIP), Washington State DOT's quarterly performance measurement report (*Gray Notebook*), and the I-95 Coalition among 16 states. Each of these initiatives has resulted in positive impacts on travel time reliability, such as quicker clearance of stopped vehicles on the roadway, effective information dissemination, effective work zone traffic control, and restructuring of ITS and transportation systems management and operations programs with detailed budget and periodic performance measures evaluation.

Funding

Funding is essential to any discussion of the transportation system of the future. Despite the current funding crisis, the central assumption implicit in this road map is that transportation funding during the next 20 years will be adequate to deploy the infrastructure to implement the ConOps developed here. Agency approaches to generating these transportation funds are discussed below.

Revenue contributed to the U.S. National Highway Trust Fund is not growing as fast as the needs for it. Supplemental funds from general revenues have been appropriated on an ad hoc basis to meet current needs. The next federal surface transportation legislation will presumably address this funding shortage. It is unknown whether the remedy will be an increase in the federal gas tax, legislation enabling pricing or tolling, or some other option. It appears likely that the current gas tax will remain, agencies will expand facility tolling using tags and readers, and demonstrations of road pricing using GPS will continue and expand, eventually providing the experience and knowledge base to support more-general use of this funding method.

Current projections indicate that hybrid, electric, and high-mileage gasoline and diesel vehicles will become an increasing share of the nation's vehicle fleet, thereby reducing the amount of gas tax revenue that is generated. Over the next 20 years, it is likely that the nation will become increasingly dependent on road pricing for generating transportation revenue. The advantage of road pricing is that it is a fee directly related to the use of the facility. Different rates can be charged according to the vehicle damage (weight), the number of occupants, the type of facility used, and the number of VMT. Access to transportation facilities can be priced so that the system operates like a utility with demand spread to times or roads that are less congested. VMT metering and charging systems could, from a technical perspective, be implemented quite rapidly. In contrast to a general system of VMT fees for all vehicles, weight-distance truck tolls could be planned and implemented now.

The issue of mobility equity associated with congestion pricing can also be addressed through properly aligned incentives. This revenue stream can be directed to provide toll discounts to selected travel groups or reduced cost transit options in the corridor. Reserving some amount of the revenue stream to support enhanced transit services or to reward agencies or private companies providing reliable and speedy service could also be considered. At the same time, care is necessary to ensure that those priced off congested highways indeed have viable transit options.

Public support comes from a conviction that there is some benefit for everyone. Accordingly, some portion of revenue from road pricing may be used to enhance other modes of travel, such as transit, and transit service may be integrated into the project design so that transit passengers benefit directly.

Travelers and shippers behave to maximize the value of their travel experience. Their behaviors can be influenced by prices and service quality. Pricing alone will give people incentives to modify travel behaviors and reduce their use of congested facilities if the prices exceed the value of the trip at a particular time and place. For some, of course, even high prices will not discourage travel. Such behaviors will be dependent on traveler and shipper characteristics, such as income, commodity type, and situational factors (such as the importance of a particular trip at a particular time). The implications of pricing, including the effects on behaviors and the equity consequences, are complex and difficult to anticipate. However, the developing body of evidence suggests the following:

- Pricing is an effective strategy for managing demand.
- The equity consequences can in some cases be remediated by the targeted deployment of funds collected (including discounts or subsidies) for providing better transit services or other benefits that may or may not relate to transportation.
- Data collected by location-based pricing schemes are of high value for providing traffic performance information to users and managers.

Pricing systems can produce the benefit of allowing improved traffic management (including better travel time reliability) through demand management in time and space, as well as improved performance data and traveler information using location data from tracked (probe) vehicles. The value and effect of traveler information and pricing are shown in Figure 7.3.

One should bear in mind that pricing is not the only means of allocating scarce roadway capacity to users. It has long been recognized that travel time is an implicit or "shadow" price road users pay to drive on congested roads not subject to tolling or pricing. Thus, historically, travel time has been the primary means of allocating scarce road capacity to vehicles, both spatially and over time. One of the consequences

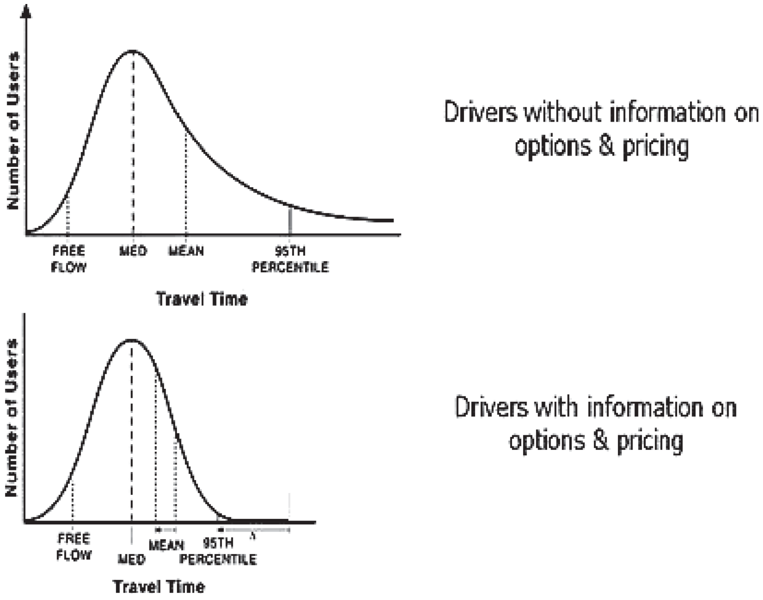


Figure 7.3. Value and effect of pricing information.

of making travel time reliability more visible as a cost and an operational consideration is that, in the absence of pricing, it becomes apparent that the implicit or "shadow" price road users really pay includes both the cost of travel time and the unreliability they experience in using a particular route. So in reality, both of these factors are influencing the allocation of road users on a network of free roads. In the future, the free portion of the highway network will continue to have its use governed by the costs of travel time and unreliability that drivers expect and experience on each link. These costs, as in the past, will not be reflected in the market place through a toll or other pricing transaction. A major attraction of just using travel time and travel time reliability to allocate scarce highway capacity to road users is that every person has an endowment of 24 hours per day, and the approach is equitable because the time resources each person has are the same.

Another option for bringing supply and demand into balance on highly congested roads is reservation systems. Road users can reserve slots in a stream of traffic on the network, and in this way, the scarce capacity can be assigned. Reservation systems can be designed in many ways. They can be based on a first-come–first-served basis, a lottery, an auction, various pricing strategies, or a combination of these. Depending upon the approach, various degrees of economic efficiency and equity can be achieved.

Technology

As noted before, the key for managing the transportation system for reliability and, therefore, making the ConOPs of the future possible, is by implementing technology through integrated transportation operations. In turn, the key for making integrated transportation operations possible requires two systems: a data collection system and a communication system. Data are essential to know the performance of the transportation system and to support informed decisions about system management and investments. Communication is necessary to exchange that data and to provide guidance to users. To properly manage for reliability, transportation agencies will need to find cost-effective ways to perform these data collection and communications tasks. Potential ways for dealing with these challenges are discussed below.

Data Collection

Transportation agencies and the private sector will install data collection systems for operational, traveler information, and logistics purposes. Agencies will use a variety of data collection technologies including loops, radar, automated vehicle identification, automatic vehicle location (GPS), road weather information systems, pattern recognition technology, and data entered into fixed and mobile computers. Collectively, data regarding travel time and its variability, incidents, weather, work zones, special events, changes in traffic-control systems, and variations in demand and supply will be available to systems operators and managers, private suppliers of traffic data, and road users. Toll collection systems are a good source of traffic management data in that they can supply a wealth of real-time probe vehicle data for pricing and congestion management, traveler information, and telecommuting decisions based on traffic and weather information.

In addition to travel times, the following data relating to the operation of the probe vehicles—in many cases accessible from the vehicle engine data bus—could also be available for transmission to a central database for traffic management purposes:

- Outside air temperature;
- Road surface conditions;
- Traction status;
- Average travel speed;
- Location;
- Windshield wiper activation;
- Number of occupants;
- Hard brake applications;
- Headlight and fog light status;
- Air bag deployment; and
- Transmission status (in a specific gear or in park).

Communications

Although fiber-optic backbone communications systems are essential to today's freeway-based data collection systems, the communications systems of the future will probably depend on wireless networks such as cellular, satellite, and transponders (dedicated short-range communications) that support connected vehicle and vehicle-to-infrastructure applications; 3G wireless is widely available, 4G deployment is starting, and WiFi Max is available. An increasing number of wireless data applications are appearing. Current and next-generation wireless data systems will make it possible to improve communication capabilities and optimize exchange data between the following:

- Traffic management centers, traffic-signal systems, and freeway management systems;
- Vehicles and roadsides;
- Vehicles and other vehicles;
- First responders and trauma centers;
- Traffic management and law enforcement personnel;
- Telecommuters and workplaces; and
- Freight conveyors and dispatchers as probe vehicle brokers.

The data on vehicle operations from probe vehicles discussed previously will be transferred from the vehicle to a monitoring center similar to OnStar, possibly run by automakers. From there, the data will be transferred to traffic management agencies for use in operating the roadways. In return for subscribing to a wireless data plan that allows this connectivity, the motorist could receive a discount on tolls and a tailored car insurance rate based on actual mileage traveled, by road category and weather conditions. The relationship between the agencies and the private-sector monitoring center could involve a fee for service or a partnership. Much of these data could also move between vehicles so drivers could react to data from the vehicle "cloud." For example, vehicles could receive data indicating that vehicles ahead of them were losing traction, were rapidly decelerating, or starting to use windshield wipers. This could trigger a warning message in the receiving vehicle that indicates ice on the roadway, congestion ahead, or rain ahead, respectively.

How the Future Transportation System Could Work

Imagine four different travelers:

- Anne is a business person who works in the northern suburbs of a major city. She needs to travel to an afternoon meeting in the southwest portion of the city.
- Fred is a janitor who works the late shift and also lives north of the city. He needs to be at work by 5:00 p.m. and comes home at 1:00 a.m. He drives to work despite his limited income because the bus service is infrequent at 1:00 a.m.
- Armand also lives north of town. He is on his usual day off from work and is planning to make a shopping trip to the large mall west of town to visit a new department store.
- Giovanni is a shipping services manager for a distribution company whose warehouse is located north of the city. He needs to deliver a shipment of high-priority, just-in-time goods to a customer by 3:30 p.m. or face a late fee of $300 for every 10 minutes the delivery is late.

With normal traffic, all four travelers had planned to use the general-purpose lanes on the Western Loop Expressway to reach their destinations. However, today a major crash occurred at 2:45 p.m. on the Western Loop. An older-model car (one without automated tire pressure warning gauges) blew a tire and swerved into the car next to it. Because traffic volumes are at 85% of capacity in the middle of the day on the general-purpose lanes of the Western Loop, the high density of vehicles caused several other cars to be involved in the crash. The automated braking systems of those cars limited the size and scope of damage to them, but two of three lanes are closed, and emergency medical services (EMS) are needed for the occupants of the older-model vehicle.

Because of the size of the crash and the high volume-to-capacity ratio on the roadway, heavy congestion quickly forms on the Western Loop. Travel times for all vehicles using the Western Loop increase. However, as a result of the private- and public-sector roadway performance data collection systems (as well as the Mayday system in the newer model car that was hit), the traffic management center knows immediately that a crash has occurred.

Agency Responses to Western Loop Expressway Crash

The TMC dispatches traffic management personnel, crash investigation personnel, and emergency services personnel (on the basis of a combination of the Mayday information and video surveillance of the scene). TMC staff also enter the basic parameters of the crash—describing the event in their traffic management software (two lanes blocked, five cars involved, EMS involved). The freeway management software automatically adjusts the active traffic management system for the Western Loop, which includes the following:

- Broadcasting lane closure information on the crash notification website while also "pushing" that information to all public and private participants in the crash notification program;
- Forecasting the expected delays on the basis of an expert system that integrates information on current traffic volumes, expected future demand, and size and scope of the crash;
- Adjusting lane control and DMSs upstream of the crash site, as well as adjusting traffic controls and DMSs on connected freeways;
- Notifying the connected arterial management systems of the forecast changes in traffic volumes resulting from the blockage, the revised freeway management controls, and the travel advisories; and
- Changing pricing values on the high-occupancy toll (HOT) lane that is part of the Western Loop (the base roadway pricing for the general-purpose lanes remains the same).

Regional and private-sector traveler information systems receive the crash notification, including details about the crash (location, number of lanes closed, number of vehicles involved, and call for EMS). These systems combine that information with their own roadway performance data feeds and make their own predictions of expected roadway and network performance. They then broadcast those forecasts via their own distribution channels. These channels include the following:

- Conventional web-based map systems (including a central system run by the regional planning operations clearinghouse, a joint-operation organization designed to ensure that roadways and transit services operate in a seamless manner);
- In-vehicle, VII-based, onboard systems that provide voice notification of changes in roadway conditions to all VII vehicles approaching the scene and to all vehicles that have planned itineraries that will use either the Western Loop Expressway or one of the roads forecast to carry rerouted traffic;
- Mobile-device text and audio messages (including links to more detailed information accessible via smartphone or in-vehicle navigation systems); and
- Mobile and web-based real-time navigation tools.

Other public transportation agencies (e.g., transit providers and local cities) and incident-response agencies (e.g., police, fire, and EMS) receive the crash notification details as well as the forecasted traffic conditions from the active traffic management system. These data are entered automatically into the agencies' various traffic control, operations, and personnel and equipment dispatch systems. These systems (in concert with the respective operations staff) make adjustments to planned operations, including the following:

- Adjusting plans to control traffic signals to account for expected levels of traffic diversion;
- Alerting and potentially dispatching response personnel and equipment;
- Adjusting bus routing to allow the best possible adherence to schedules upstream and downstream of the crash site;
- Calling out additional buses and drivers to complete scheduled trips that have been delayed and to start later trips that are dependent on delayed buses;
- Sending out "late-bus" and "off-route" bus notifications via multiple communications protocols concerning all bus routes and trips affected by the crash (this includes "be aware of possible delays" notifications on routes that might be affected later in the day); and
- Updating real-time arrival information for affected routes based on real-time position information and forecasted roadway performance information.

Traveler Responses to Western Loop Expressway Crash

How do our four travelers respond?

A software app running on Anne's phone and connected to her calendar has the location of her meeting and knows her current location through its GPS chip set. It assumes she will be driving (her selected default mode). In its background processing, the app was monitoring traffic alerts—a service provided by her wireless carrier. When the traffic alert occurs, her app receives the carrier's privately developed forecast of travel conditions and notifies Anne that her trip is no longer possible as planned. Anne responds by using her smartphone's full-feature navigation function (connected to the metropolitan planning organization's regional travel options database). The base map feature of that software shows her three possible travel options for a single-occupancy vehicle (a "fastest available" general-purpose freeway lane, a HOT lane, and a city street), each of which is accompanied by periodically updated expected travel times and out-of-pocket costs. In the bottom right corner of the screen, Anne selects the "transit options" button and is shown two more options, one involving a walk to her closest bus stop and the other a drive to a park-and-ride that offers a faster total trip option. Given the importance of the meeting and her interest in making three other stops on her way home from the meeting, Anne chooses the HOT-lane option and decides on a new departure time to ensure that she arrives on time for her meeting.

Fred is thinking about getting ready for work. He checks the regional operations website at his neighborhood library and sees the alert about the Western Loop (his route to work). He does not have enough money to take the HOT lane. But, by entering his trip start and end points on the map and clicking on the bus icon, the regional operations website displays a second web page that highlights the bus routes and arrival and departure information he needs. A link on the transit page takes him to a late-night dial-a-ride service reservation page. He schedules a pick-up at 1:15 a.m. that will take him to a transit center 2 miles from his workplace, just in time to catch a bus to get home safely and fairly quickly. He had never explored that late-night option before, but it works well enough that he may use it regularly to save money now that he knows about it.

Armand is not online, and his cell phone is turned off. It is his day off, and he has been working in the garden. However, as he prepares to leave, he listens to the radio in his kitchen. A short news broadcast gets his attention. A crash on the Western Loop. He uses the computer built into the kitchen cabinets to pull up the state DOT's website that describes freeway congestion, travel times, and options. With two clicks and a couple of keystrokes, he enters his proposed trip and learns the time and cost that reaching the store will require. He decides that this trip is not worth the trouble and expense. The store will still be there on the weekend. Armand goes back to the garden and his tomato plants. In the meantime, the roadway delay just got one car shorter, and the recovery time just got one car faster.

Giovanni's dispatch system receives the automated crash notification and automatically updates its expected delivery times for shipments scheduled for the rest of the day by using the traffic forecasting algorithm that the vendor of the dispatch system sells with the software. It notifies him that one of his high-priority shipments is likely to miss its guaranteed delivery time. That would be an expensive failure for Giovanni's company. He checks his options and sees that his parcel delivery van is eligible to use the HOT lane, which is not directly affected by the crash. Although the HOT-lane price is more expensive than usual for that time of day (and not an option Giovanni would normally instruct his drivers to use in the middle of the day), it will save the delivery van enough time to avoid a late charge. The driver gets this same information through his heads-up display. He calls Giovanni with the voice-activated phone in his van and gets the OK to take the HOT lane. Giovanni has avoided the late delivery fine and will not have to pay the driver for overtime.

Funding Agency Response

While our four travelers are revising their travel decisions (all different choices but all choices designed to maximize their own values), the agencies that supply transportation and incident management services are actively responding to the crash. In this story, funds from general roadway tolls and the HOT lanes are used to fund or subsidize many of the incident-response services. These funds provide equipment and communications for the EMS crews, as well as training to allow more fire department personnel to become qualified EMS respondents, thus dramatically reducing response times. These funds also help to acquire the sophisticated communications equipment the EMS crews carry, which allows them to move injured patients off the scene more quickly—both saving lives and decreasing the durations of incidents. The actual response actions have also been improved, with funding provided for specialized systems for quickly containing and cleaning up the hazardous materials spilled at the site as a result of the crash. Of course, fewer incidents occur nowadays, thanks to the vehicle improvements provided by VII. But, no mechanical system is failure proof. In addition, there are still some older, non-VII vehicles on the road.

Corridor revenues have funded the active traffic management system. When combined with the in-vehicle VII functions of most vehicles, the current roadway carries more vehicles at more-consistent speeds than was possible in 2010. However, those higher volumes mean larger queues when disruptions occur, despite the fast incident response. In addition, these capacity improvements do not meet peak-period travel demands. Public resistance to the loss of housing, parks, and businesses that must be moved to expand right-of-way may mean that other kinds of capacity must be found.

Consequently, corridor revenues also have helped to fund specific transit improvements. Those improvements have helped to reduce peak-period vehicle demand, decreasing total congestion and providing travel options on the occasions when incidents cause higher than normal congestion. In the off-peak period, better transit traveler information and cooperative agreements with taxi companies have allowed quantum improvements in on-demand carpool formation and short-distance, flexible-route transit services to solve the "last mile" problem that off-peak transit has traditionally faced. This allows transit agencies to concentrate significant portions of their revenue service hours on fast, frequent, direct regional transit service that is available throughout the day. The result is that quality transit service is provided to diverse origins and destinations throughout the day. All transit fares are paid with a unified smart card, eliminating fare payment barriers and fare collection delays on all transit vehicles.

People may still like (and prefer) to drive their cars. The difference will be that it is easy to find fast, convenient, and safe alternatives when driving is not a good option. And travelers will know when driving is not a good option.

Next Steps for Migrating Toward a More Reliable Future

The most-important changes necessary to produce significant improvements in travel time reliability are (*a*) to bring market forces to bear on travel decisions (which results from better and more-ubiquitous information available to all travelers) and (*b*) to provide additional supply in a way that is balanced against demand.

As noted earlier in this chapter, a more-reliable roadway system will occur on a sustainable long-term basis only when travel demand and roadway capacity are in balance. Achieving that balance requires a combination of technical improvements. But, those technical improvements are themselves dependent upon institutional and attitudinal changes that drive both how we operate our transportation system and how customers (travelers, shippers, carriers) make their travel decisions.

Travel is an economic good. It behaves like all economic goods: when price is low, demand is high; when price is higher, demand is lower. Because price is not an integral part of most current roadway travel decisions, the following occurs: (*a*) roadway agencies are constantly faced with situations in which demand exceeds capacity, (*b*) the resources to remedy that situation are not being generated and deployed to meet those demands, and (*c*) travelers have insufficient information and incentive to change their behavior to travel at less-congested times or by other modes.

Allocating scarce highway capacity according to driver expectations of travel time and reliability on alternative routes, while equitable as explained above, is not economically efficient. When pursuing economic efficiency, market forces and other approaches that can achieve equivalent results need to apply to both demand and supply. Ideally, revenues would be better targeted if the full social costs of travel were a part of the travel decision. In addition, it is desirable if the funding generated by that travel were spent in the corridors where it is generated to support needed increases in supply (travel capacity).

The demand to be accountable for how funds are spent will increase if a shift to a more information-driven approach to travel were to occur. This would create the incentive systems that are needed to encourage the technical and institutional changes that would result in the appropriate level of travel time reliability (as valued by travelers). These technical and institutional changes could include the following:

- An increase in the quality and completeness of traveler information systems, as consumers of travel services demand better information about their choices, the cost of their choices (whether priced in the market place or not), and the performance of those choices;
- A continued rise in the importance of improvements to the real-time control and operational performance of transportation systems;
- The capability to fully integrate highway operations with arterial and transit system operations;
- Better, faster, and more-capable systems for responding to capacity disruptions (e.g., incidents, weather) and for restoring capacity lost to those disruptions;
- More engagement of the private sector, especially for the collection and dissemination of information about travel options and the performance of the transportation network; and
- An increase in revenue targeted at capacity enhancements where demand is high.

To implement these improvements, the following steps are offered for consideration:

- Steps toward balancing demand and capacity;
- Steps to strengthen interagency and intermodal relationships; and
- Technical and technological steps to improve reliability.

Steps Toward Balancing Demand and Capacity

If achieving more-effective, market-based strategies for both funding transportation and guiding the expenditure of those funds is desired, it will require considerable effort. A number of actions can be taken now to facilitate this shift:

- Educate the public and decision makers to generate the support necessary for the economic management of roadway capacity. The case is often most readily made if there is a strong connection between where revenue is generated and where improvements are made, although expenditures could be targeted in other ways in the face of market inefficiencies or for equity reasons.
- Select performance measures and the ways that those performance measures are applied to ensure that agencies and jurisdictions are accountable for their actions.

- Participate in more-comprehensive demand management programs (see Steps to Strengthen Interagency and Intermodal Relationships).

Of particular significance is determining the base price–performance level that is acceptable. A congestion-free HOT-lane price is acceptable because low-cost or no-cost general-purpose lanes also exist. However, pricing all roads to the point at which congestion does not exist and roads are perfectly reliable in a currently congested urban area would require setting the price higher than is acceptable for a large segment of the population.

As long as congestion exists, some nontrivial level of travel time unreliability will remain. A part of gaining buy-in to the shift to a more market-based system involves finding the base price point at which the balance between price and congestion is acceptable. That is, how much congestion (and consequently how much variability in travel times) are we willing to live with, compared with how much money are we willing to pay to help manage the limited roadway capacity that we have?

The answers to these basic questions will undoubtedly be different in congested urban areas than in uncongested rural areas. These answers will also be different in areas where many travel options exist as opposed to areas where no acceptable travel options exist. Of significant interest will be the response to pricing on roads in rural areas subject to seasonal (e.g., recreational) traffic congestion. For areas where only limited pricing is possible, use of at least some of the funds to dramatically improve traveler information (so that travelers know the nature of delays they are likely to experience before they make their travel decisions) and improve operations (to minimize delays and maximize reliability to the extent possible) may be the best mechanism for reducing travel time uncertainty and improving travel time reliability. Better information will tell consumers when travel times are not reliable.

Another important step is to reach agreement that funds generated by pricing would be made available to improve all forms of capacity within the corridor in which they are collected. That includes, in some cases, expansion of roadways. It also includes funding for operations and funding for alternative sources of capacity, including improvements to transit service and parallel arterials. Gaining the buy-in for these types of improvements and balancing these improvements with expenditures will require time and effort. Equity concerns will likely be among the major obstacles to road pricing, particularly income equity—the impacts of network-wide pricing on low-income travelers. Once the public and its leaders begin to understand the merits of road pricing, equity will become addressable through a variety of paths that include providing better information on travel and location options, offering alternative services, enhancing transit services, and providing discounts and subsidies.

Steps to Strengthen Interagency and Intermodal Relationships

A more reliable roadway network requires the integration of arterial network operations with adjoining freeway operation. This integration includes adjusting arterial traffic controls to account for freeway performance. (This does not mean that arterials must sacrifice local performance in favor of regional travel time reliability. It does mean that local arterials need to operate differently during times when adjacent freeways are unreliable.) Similarly, transit system operations need to be an integral part of corridor demand and capacity management actions. The fact is that the roadway network operates as a system that is independent of jurisdictional boundaries. Network operators need to consider this to foster interagency cooperation.

Public agencies could consider the following five actions in the near term to foster interagency and intermodal relationships:

- Change the agency culture so that agencies work together (and perhaps even coalesce) to achieve better system performance rather than work toward agency-specific goals.
- Strengthen relationships with neighboring jurisdictions, especially when improved integration of facilities benefits both agencies (e.g., shared traffic operations centers, multiagency incident-response teams, and corridor management teams).
- Create and provide easily accessed, standardized transportation system performance data to those who need it.
- Work with the private sector to support community goals. (For example, encourage the private sector to limit the amount of “cut through” traffic that occurs on residential streets by avoiding the use of portable navigation devices to reroute traffic through local streets.)
- Work with private-sector trip generators (i.e., all events that will generate trips) and private-sector information providers to obtain and disseminate better information on travel demand fluctuations. Provide better coordination of demand management activities serving those who wish to attend those events.

A key element that could help to strengthen interagency and intermodal relationships is the consideration of corridor-based revenue sharing associated with a use-based and a value-based revenue generation structure.

Technical and Technological Steps to Improve Reliability

It is difficult to identify which technical improvements are likely to have the greatest impact on travel time reliability by 2030. This is because it is difficult to forecast technical improvements 20 years into the future, especially those that will result in quantum improvements in traffic operations. As noted in the U.S. DOT's congestion management process, technical improvements will occur in four basic areas:

- Improved capacity from both targeted infrastructure improvements and better operational controls (see, for example, the new operational strategies evaluation tools developed under the SHRP 2 C05 project [Kittelson & Associates et al. 2013]);
- Reduced occurrence of incidents through improved vehicle technology, supported by targeted infrastructure improvements;
- Improvements in the speed of roadway recovery from incident-induced capacity losses; and
- Better balance between travel demand and available capacity through better demand management.

The U.S. DOT VII program has considerable potential to contribute to many of these areas. But, the simplest technical aspects of the VII program highlight the major technical improvements that are likely to contribute in all of these areas: better sensors, better communications and sharing of data collected from those sensors, and better control and response systems that take advantage of those shared data.

Consequently, the following six technological steps could be taken now to enhance travel time reliability:

- Make data that are already collected widely available to partners (see the previous section on strengthening interagency and intermodal relationships).
- Ensure that data collected from new systems can be and are widely shared by establishing common architectures and open data-sharing agreements.
- Actively look for partners, particularly in the private sector, who can provide data that are already collected and that can be useful for improving the demand-capacity balance.
- Actively seek partners, particularly in the public sector, who can leverage data already being collected to improve the demand–capacity balance.
- Establish and use performance measures computed from those data to identify (*a*) the actual causes of unreliable travel time in areas specific to the agency and its partners and (*b*) the effectiveness of technologies, responses, and actions that are implemented to improve travel time reliability. That is, use the transportation network strategically as a laboratory to continue to learn what works and what does not work in a particular setting.
- Develop and apply more robust traffic management and traffic-control strategies to improve facility operations, better coordinate those facilities, and improve the use of those facilities through cultivation of "smarter" users.

Impact of Innovative Technologies

Chapter 6 discussed the potential impact and application of several innovative technologies on improving travel time reliability. This section provides a summary of different areas related to reliability in which new technologies are emerging. Table 7.3 shows how different the future (2030) can be when compared to today if the implementation road map and steps presented in this chapter were followed by agencies and involved stakeholders.

Conclusions—Building a Reliable Future

Enduring and systemic improvements to the reliability of a transportation network can occur by planning and design. However, this process will take time if the improvements are to be truly enduring and systemic. Further, the plan of action from which these improvements emanate offers significant benefits if it is multidimensional in scope. More specifically, the plan needs to address three important elements defining the overall concept of operations: organizational, business practice, and funding. Plans that affect all three of these fundamental elements simultaneously are ideal and will probably achieve the greatest amount of change; however, it is also possible to achieve sustained and significant improvement by focusing on only one or two of these elements at a time.

The remainder of this section provides an overview of the organizational, business practice, and funding strategies that are needed to improve Year 2030 travel time reliability.

Organizational Changes

Breaking down the communication silos that dominate current public-agency organizational structures has been a desirable goal for many years. Attempts to fine-tune these structures to improve communication efficiency are frequent events. The problem with these fine-tuning efforts is that they do not address either the breadth or depth of fundamental changes that will ultimately be necessary if the 2030 vision is to be achieved. Broad-based integration across modes, functions, jurisdictions, and data are the requisite foundation for building and maintaining a reliable transportation network.

Significant new work has been completed in SHRP 2 Reliability Project L06 (Parsons Brinckerhoff et al. 2012) that can be a blueprint for effecting the organizational changes necessary for broad-based and comprehensive implementation of operational strategies to improve system reliability. Parsons Brinckerhoff has noted:

> The research across state DOTs has resulted in the development of an operations capability maturity model (CMM).

(*continued on page 92*)

Table 7.3. Comparison of Current and Future Status

Focus Area	Existing or Near-Term Status	Future (Year 2030)
Communication	Communication mostly via pretrip information such as: • Traffic reports (511) • Weather and road condition detection information mostly used for maintenance • Demand for information growing	Communication expansion through widespread real-time traveler information Large-scale information collection and dissemination delivered in advance to users in more-accessible and usable forms including real-time, predictive traffic information Sensor technologies and next-generation road weather information systems used in traffic management strategies
Traffic management	Isolated traffic management actions (lacks technical and institutional integration) • Roadside messages (DMSs, VMSs) • Signal retiming • Variable speed limits • Lane treatments (managed lanes, HOT, hard-shoulder running) • Ramp metering • Service patrols • Electronic toll collection • Transportation demand management Active traffic management deployed locally	Integrated transportation operations Integrated multimodal corridors • Adaptive signal control • Freeway systems • Integrated ramp meters (networkwide) • Automated incident response (automated detection; rapid clearance using advanced technologies—data collection systems, fire suppression, medical treatment and vertical evacuation, on-scene traffic control) Innovative construction techniques to reduce impacts of construction (prefabrication, quick repair materials, self-repair materials, embedded sensors that give early warning of infrastructure failures) Work zone management (real-time traffic control, performance incentives) Pricing and congestion management Route and mode choice based on system optimization rather than solely on user convenience, which can be done with pricing and will yield better overall solutions Active traffic management with multiagency and regional cooperation Advanced transportation automation systems (automated limited-access highways, automated truck-only highways, merger of truck and rail technologies, etc.)
Geometric treatments	• Access management • Bottleneck removal • Alignment • Weaving	Optimized use of infrastructure and integration with land-use development to minimize the need for spot geometric treatments
Commercial vehicle operations	Limited	• Load matching • Route optimization • Traffic forecast by hour • Vehicle and driver inspections • Automated vehicle inspection • Weigh-in-motion • Land-use information
Performance measures	Very limited	Performance-driven decision making at the corridor and system levels
Fuel technologies	Mostly gasoline	Mostly clean-fuel technologies that reduce environmental impact
Vehicle features	Stability control and air bags Automated cruise control and side-collision and blind-spot warnings in luxury vehicles only	VII, including: • Vehicle-to-vehicle communication • Vehicle-to-system communication • System-to-vehicle communication Driver assistance products, including: • Collision avoidance • Adaptive cruise control • In-vehicle signing • Self-guiding vehicles Growth in market share of small cars and microcars that may possibly allow greater throughput and sustainable-flow Integrated weather information
Travel choices	Travel focused on convenience and economic feasibility	Travel focused on convenience and economic feasibility, but increasingly sensitive to energy consumption and green living
User decision making	User reaction to congestion	More choices than today: modes, departure times, fee-based quality of service options User understanding of travel options and associated costs

(continued on next page)

Table 7.3. Comparison of Current and Future Status (continued)

Focus Area	Existing or Near-Term Status	Future (Year 2030)
Information	Growing need for information Use of information through cell phones and Internet limited Navigation limited to route guidance	More, and more-reliable, pretrip information based on real-time measurements as well as forecasts of system performance In-vehicle navigation and congestion information
Telecommuting and ride share	Some telecommuting Increased ride-share programs	Technology innovations fully in support of telecommuting Well-established ride-share programs
Travel pricing	User acceptance of service that is already paid for	With roadway pricing, users trade fees for service quality
Demographics and land use	Spatial growth, mode choice mostly auto Focus on reducing travel	Urban locales with multimodal choices Focus on supplementing travel

The CMM is designed to support agency and unit-level self-evaluation and identification of critical priority next steps to putting TSM&O activities on a path to continuous improvement and formal program status. It is not oriented just toward "start-up" programs—but to organize improved effectiveness for TSM&O activities at any level of development.

There is no black-box magic about the CMM. The CMM concept was originally developed in the private-sector information technology industry and is widely applied in the U.S. and internationally as a means of improving the products and services related to effectiveness, quality, costs, schedule, and other key performance measures. Basically, it takes a lot of generally recognized issues and organizes them into a framework that focuses on the factors most essential to effective TSM&O—and on logical improvement steps. The CMM offers a transparent process for key players to mutually recognize key issues and reach consensus on strategies to move forward. The CMM structure is now used as the organizing principle of the AASHTO Guide to Systems Operations and Management. The CMM has already been used by many state DOTs to support the development of strategic plans and programs to upgrade TSM&O activities.

Business Practices Changes

Modifying the traditional business practices of transportation agencies will also help mainstream the implementation of operational strategies to improve system reliability. To a large degree, the organizational changes embodied in the CMM concept described above will also affect day-to-day business practices in a positive way. Close collaboration with private entities is another business practice that will yield significant benefits. The private sector is far more adept at taking risks and implementing technological innovations, and this is a strength to leverage. Making agency resources available to the private sector (for example, historical databases), eliminating, or at least minimizing, institutional barriers to private participation, and engendering a culture of collaboration and good will among staff will greatly facilitate the development and deployment of technological innovations.

Funding Changes

The transportation system will be most reliable when a balance is achieved between travel demand and supply. Such a balance can be achieved when three conditions are present:

- More than one (and preferably many) travel option is available to each traveler, which is most practical to achieve in urban areas.
- The cost of each travel option is known.
- The traveler is responsible for the cost associated with whatever option is ultimately chosen, including externalities.

There is a broad spectrum of willingness on the part of the public, government agencies, and private firms to pay, to act, to address equity issues, and to confront externalities such as carbon emissions. The purpose of setting out the alternative futures and associated ConOps is to provide readers, including decision makers, an opportunity to think about what type of transportation system would be desirable to have in the year 2030 and develop a plan for achieving it. Of particular concern in this study is how to deal with both recurring and nonrecurring congestion—the delay and unreliability that occur at times and locations where congestion is severe or where unexpected events occur, such as an accident, a hazardous spill, or a tornado that severely disrupts travel. Addressing these unexpected delays is a challenge in both urban and rural areas, for person and freight movement, for different classes of road users, and for system operators and managers.

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APPENDIX A

Reliability Performance Measures Available to Agencies

Agency Measures

This appendix presents measures that demonstrate management and reporting of reliability and travel time information from some departments of transportation (DOTs) and metropolitan planning organizations (MPOs). Table A.1 summarizes some of the best practices.

The information that follows is a summary of current activities by public-agency programs and private-entity sources related to travel time reliability.

Washington State DOT

The Gray Notebook is Washington State DOT's main performance assessment, reporting, and communication tool (2012). 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 the 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.

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 in the Transportation MAP Report are the following mobility 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 this 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 with Georgia DOT's NaviGator video detection cameras.
  - PTI is the ratio of the 95th percentile travel time, also known as planning time, over the free-flow travel time obtained for a certain portion or segment of the freeway system. In other words, PTI tells a traveler how much longer a trip will take under congested conditions compared to free-flow conditions—so that the traveler arrives on time 95% of the time.
  - BTI is defined as the difference between the 95th percentile travel time and the average travel time. BTI is the size of the buffer time expressed as a percentage of the average travel time and is obtained for a segment of the freeway system. In other words, BTI tells a traveler the extra time as a percentage of the average travel time necessary for a trip so that this traveler reaches destination on time 95% of the time.
- *Daily vehicle miles traveled per licensed driver per person.* This measures the average distance each licensed driver in the region drives each day.

Table A.1. Summary of Best Practices

Agency	Performance Reporting Method	Performance Data
Washington State DOT	*The Gray Notebook* 2012	Average clearance time (in min) for major (≥90 min) incidents on key Puget Sound corridors
		Annual weekday hours of delay statewide on highways compared to maximum throughput (51 mph) in thousand hours
Georgia Regional Transportation Authority	*Transportation Metropolitan Atlanta Performance (MAP) Report*	Freeway travel time index: ratio of average travel time to free-flow travel time obtained for a certain portion or segment of the freeway system
		Freeway planning-time index: planning-time index (PTI) and buffer-time index (BTI) • PTI = ratio of 95th percentile travel time—or planning time—to free-flow travel time obtained for a certain portion or segment of the freeway system • BTI = difference between 95th percentile travel and average travel time
		Daily vehicle miles traveled per licensed driver per person
		Roadway clearance time: "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"
Florida DOT	Florida's mobility performance measures outlined in *2020 Florida Transportation Plan*	Person miles traveled
		Truck miles traveled
		Vehicle miles traveled
		Person trips
		Average speed
		Delay
		Average travel time
		Average trip time
		Reliability
		Maneuverability
		Percentage system heavily congested
		Percentage travel heavily congested
		Vehicles per lane mile
		Duration of congestion
San Antonio–Bexar City MPO	Texas congestion index in *Metropolitan Transportation Plan: Mobility 2030*	Texas congestion index, which is a variation of the travel time index developed by the Texas Transportation Institute for the Annual Urban Mobility Report
Puget Sound Regional Council, Seattle, Washington	*Destination 2030 Update: Metropolitan Transportation Plan for the Central Puget Sound Region*	High-occupancy vehicle lanes, intelligent transportation systems, and reliability of transit service
Metropolitan Transportation Commission, San Francisco Bay Region	Reliability listed as one of six goals in *Mobility for the Next Generation: Transportation 2030 Plan for the San Francisco Bay Area*	Capacity added to the metropolitan transportation system
		Levels of service in congested corridors
		Progress with freeway ramp meters and traffic-signal retiming
		On-time transit performance
		Effectiveness of incident management strategies
		New transit connectivity projects
		Progress in improving traveler information
Southern California Association of Governments	*2008 Regional Transportation Plan: Making the Connections*	Statistical concept of standard deviation: indicator is computed by dividing standard deviation of travel time for a given trip by average travel time of that trip, measured over many days and weeks

The roadway clearance time safety measure, which indirectly affects travel time reliability, is also reported. 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.

Florida DOT

Florida's mobility performance measures are tied to the goals and objectives established in the 2020 Florida Transportation Plan. The plan establishes four goals: safety, system preservation and management, economic competitiveness, and quality of life. Table A.2 depicts Florida's mobility performance measures.

As shown in Table A.2, three related dimensions of mobility are measured by the Florida DOT:

- Quantity of travel reflects the magnitude of the use of a facility or service.
- Quality of travel describes travel conditions and the effects of congestion.
- Utilization indicates whether or not a transportation system is properly sized and able to accommodate growth.

Private-Entity Travel Information Sources

The following private agencies that measure and report travel time data were researched and are summarized below: NAVTEQ Traffic.com (real-time traffic information), Noblis, and intelligent transportation systems (ITS) Deployment Statistics.

Traffic.com

NAVTEQ Traffic.com is an independent provider of traffic information serving 51 cities across the United States. Traffic.com delivers traffic content to clients and consumers on terrestrial and satellite radio, on broadcast and cable TV, through wireless applications and services, and through the Internet. The Traffic.com website and the companion site

Table A.2. Florida's Mobility Performance Measures

Dimension of Mobility	Mobility Performance Measures	State Highway System	Florida Intrastate Highway System	Florida Intrastate Highway System Corridors	Metropolitan Highway Systems	Calculation[a]
Quantity of Travel	Person miles traveled	X	X	X	X	AADT × length × vehicle occupancy
	Truck miles traveled	X	X	X	X	AADT × length × % trucks
	Vehicle miles traveled	X	X	X	X	AADT × length
	Person trips				X	Total person trips
Quality of Travel	Average speed	X	X	X		Average speed[b] weighted by PMT
	Delay	X	X	X	X	Vehicle hours of delay
	Average travel time			X		Distance/speed[b]
	Average trip time				X	Door-to-door trip travel time
	Reliability			X	X	% of travel times that are acceptable
	Maneuverability			X		Vehicles per hour per lane
Utilization	% system heavily congested	X	X	X	X	% miles at LOS E or F
	% travel heavily congested	X	X	X	X	% daily VMT at LOS E or F
	Vehicles per lane mile	X	X	X	X	AADT × length/lane miles
	Duration of congestion	X	X	X	X	Lane mile hours at LOS E or F

Note: AADT = annual average daily traffic; PMT = person miles traveled; LOS = level of service; VMT = vehicle miles traveled.

[a] Definitions shown are generally for daily analysis. Calculations for the peak are based on prevailing conditions during the typical weekday, 5:00 p.m. to 6:00 p.m. peak.

[b] Speed is based on models using *Highway Capacity Manual* procedures.

at my.traffic.com are the primary "direct to the consumer" online services. Users can sign up to the website to receive traffic information and travel time data between two addresses in the United States.

Traffic.com obtains information from three types of sources: digital traffic sensors, commercial and government partners, and traffic operations center staff members. Its own network of sensors is already deployed in many major metropolitan areas and is rapidly expanding to additional cities. When local or state government agencies have available data from their sensors or systems, Traffic.com integrates as much of that data as possible. Finally, it maintains traffic operations centers for each of the cities being served, staffed with employees who consistently monitor traffic conditions. The traffic operations staff use a variety of means (such as listening to police and fire scanners, monitoring traffic cameras, driving cars, and flying helicopters or fixed wing aircraft) to collect information.

Noblis

Noblis is a nonprofit science, technology, and strategy organization that helps clients solve complex systems, processes, and infrastructure problems. Over the past two decades, Noblis has been working with government and industry stakeholders on a broad range of activities to improve the transportation system. The following is a summary of activities performed by Noblis:

- Pioneers new technologies to protect travelers from bad weather and road hazards;
- Mines vast amounts of system-use data for major cities in order to understand traffic trends and support informed strategic decisions;
- Partners with government agencies and automakers to develop an integrated telecommunications infrastructure that will connect vehicles and the transportation infrastructure;
- Designs more-efficient mass transit systems to ease congestion; and
- Analyzes the lessons learned, costs, and benefits across a wide variety of ITS applications.

A summary of experience and work activities by Noblis relevant to the SHRP 2 L11 research project follows.

QuickZone Traffic Delay Estimation Tool (Ongoing from 2001)

The purpose of QuickZone is to develop estimates of work zone traffic delays. It also allows for estimates of the cumulative impact of multiple concurrent work zones (including delays and economic impacts on travelers and local businesses) under sequential flagging operations, partial closures, long durations of full closures, and a series of periodic full closures with a signed detour. In addition, QuickZone supports construction cost and delay-cost trade-off analyses.

511 and Travel Information Services Assessment (Ongoing from 2003)

This assessment is a methodology to quantify the mobility benefits of travel information services (including 511) using archived traffic sensor, travel advisory, and weather data. The methodology has been applied to assess benefits of traveler information services in locales across the country. The most recent study provided quantitative support for the Utah DOT to enhance Salt Lake City's 511 from an advisory to a service based on travel time. Similar work has been initiated with the Metropolitan Transportation Commission in San Francisco.

Urban Congestion Reporting (Ongoing from 2002)

The purpose of Urban Congestion Reporting is to monitor and report monthly congestion in more than 20 cities across the nation and to characterize trends as well as report contributing factors (weather, accidents, special events, etc.). Measures were developed that describe the intensity, duration, and day-to-day variation in congestion, and a series of graphical one-page summaries for traffic managers and decision makers are produced.

ITS Deployment Statistics

ITS Deployment Statistics is administered by the Research and Innovative Technology Administration (RITA), which coordinates the U.S. DOT's research programs, and is charged with advancing the deployment of cross-cutting technologies to improve the nation's transportation system. As directed by Congress in its founding legislation, RITA leads U.S. DOT in the following:

- Coordinating, facilitating, and reviewing the U.S. DOT's research and development programs and activities;
- Advancing innovative technologies, including intelligent transportation systems (ITS);
- Performing comprehensive transportation statistics research, analysis, and reporting; and
- Providing education and training in transportation and transportation-related fields.

As part of ITS Deployment Statistics, RITA provides access to data gathered by the U.S. DOT ITS Joint Program Office to measure the level of ITS deployment in 108 metropolitan areas (78 of the nation's largest metropolitan areas plus 30 of the nation's medium-sized metropolitan areas) and in the 50 states. RITA generally includes survey data from 2004 through 2007 on various topics such as

- Arterial management
  - Characteristics of signalized intersections;
  - Roadside technologies to distribute en route traveler information; and
  - Information dissemination to the public.
- Freeway management
  - Freeway surveillance;
  - Ramp control; and
  - Lane management.
- Transit management
- Public safety (law enforcement)
- Public safety (fire and rescue)
- Electronic toll collection
- Metropolitan planning organizations
- Crash prevention
- Operations and maintenance
- Surface transportation weather
- Traffic management
- Traveler information

APPENDIX B

Determining Economic Benefits of Improving Travel Time Reliability

Appendix B presents an approach for determining the economic benefits of improving travel time reliability under recurring-event scenarios. In this approach, uncertainty arising from recurring events is converted to a certainty-equivalent measure so that conventional evaluation methods can be used to place a value on the cost of unreliability. The certainty-equivalent measure is a method that allows the value of reliability to be expressed in terms of the increase in the average travel time a person would accept to eliminate uncertainty. For example, suppose that Mr. A is told to draw a card from a full deck. If he draws a red card he wins $100, and if he draws a black card he wins nothing. Given the likelihood of either winning or losing, if Mr. A could be paid $50 to not play the game, then $50 would be his certainty-equivalence. Thus, Mr. A has placed a dollar value on removing unreliability. He has forgone the chance at $100 but has also avoided the equal possibility of receiving no payment. In this way, a variable that can be characterized by its probability distribution can be converted to a certainty-equivalent measure.

The approach presented for determining the value of reliability associated with recurring events is extended to rare events in Appendix C. Recurring and rare events (and the unreliability produced by them) differ in the probability distributions that characterize them. Unreliability produced by recurring events is assumed to display statistical behavior that is best represented by normal distributions (often, a lognormal distribution). Rare or "extreme" events are better represented by a class of distributions known as extreme value (EV) distributions. It is often possible to observe the effect of recurring events on network performance directly by observing the variability in speeds or other network performance metrics. In the case of unreliability caused by rare events, it may not be possible to observe the statistical nature of the unreliability in real-world data, because the number of such incidents in a given region may be so low that coincident performance measurements are lacking. The rare-event approach is briefly described in this appendix and is presented in full in Appendix C.

Once the certainty-equivalent measure has been computed, valuation can proceed as if the values involved were deterministic. The value of reliability can be derived for multiple user groups or market segments by applying a separate value of time that corresponds to each user group along with the observed average volume for each user group on the roadway segment. The total value of reliability is then computed as the sum of the reliability values for each user group on the highway segment.

To illustrate this concept, let us consider a single link of a roadway network that experiences considerable variation in the average travel time because of recurring congestion. Imagine that a commuter would be willing to spend an additional minute per mile if the uncertainty in travel time were eliminated by a technical or policy action. This additional minute per mile is the certainty-equivalent of the unreliability caused by a recurring source of unreliability. The cost of unreliability to the commuter, converted to the certainty-equivalent measure, can be monetized by the value that he or she places on each minute of additional delay. Most studies report the value of time as being between 40% and 50% of the wage rate for average trips and a much higher rate (around 85% of the wage rate) for commuting and intercity trips. The value of time for freight movement depends on the size of the truck and the value of the commodity hauled, typically with a value ranging between $30 and $60 per hour.

In the following example, the certainty-equivalent value of 1 minute/mile is used. It is assumed that the average value of time of users of the roadway is $20/hour (33.3 cents/minute), the roadway segment is 10 miles long, and it is used by 6,000 users/hour during the time of day when unreliability in travel times is experienced. The cost of unreliability to users on the facility over a 1-hour period would be approximately $20,000 (1 minute/mile × 33.33 cents/minute × 10 miles × 6,000 = 2,000,000 cents or $20,000). This concept for calculating the value of travel time reliability is illustrated in Figure B.1.

The concepts for determining the economic benefits for improving travel time reliability are presented in detail in the

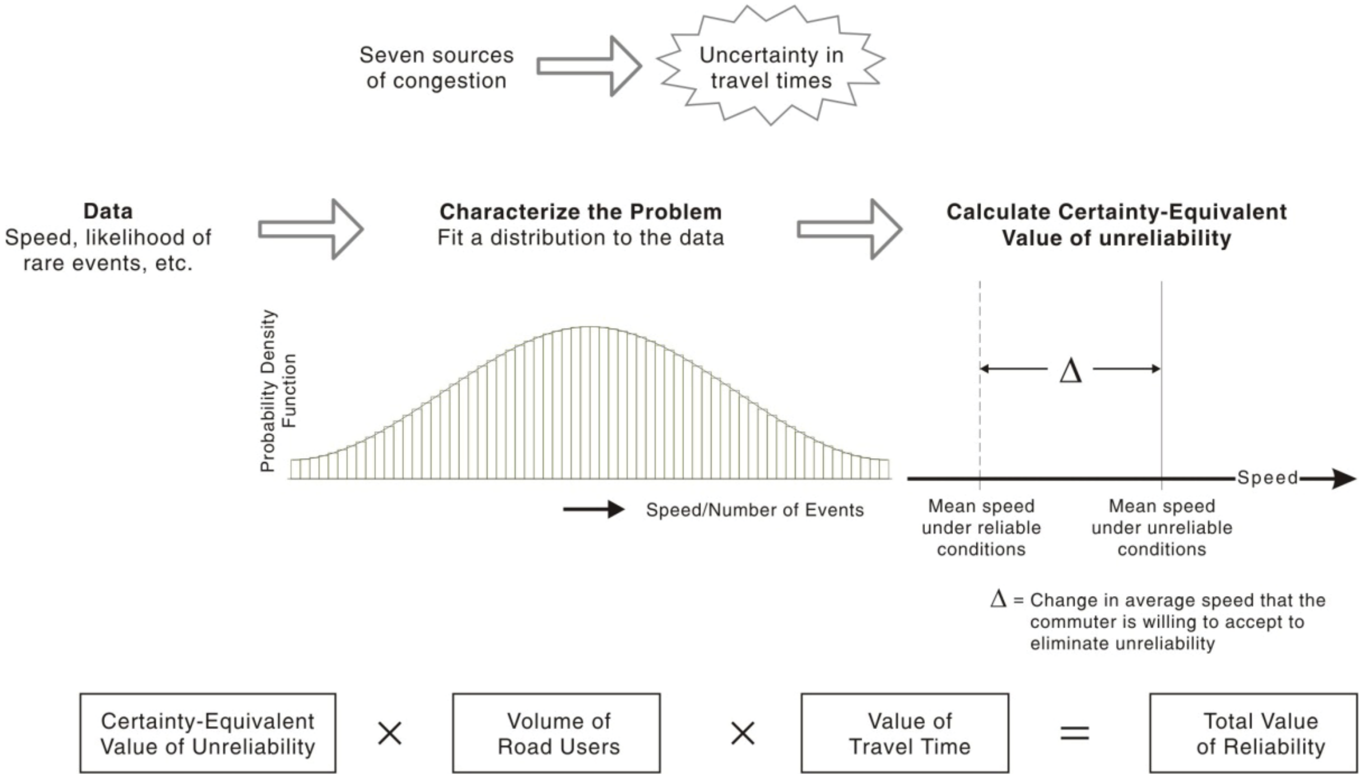


Figure B.1. Concept for valuing travel time reliability.

sections following. These include measuring the value of reliability, valuing reliability for recurring events, measuring networkwide impacts, quantifying the value of time, and applying the methodology. A discussion follows on conclusions for the options theoretic approach and a recurring-event reliability valuation example.

Measuring the Value of Reliability

Evaluating the economic cost of unreliability on the highway system requires a method for valuing reliability. This, in turn, requires measuring unreliability in a consistent manner and a method of placing a value on the costs of unreliability. The methodology outlined in this section provides a consistent means for characterizing reliability and for valuing reliability by using the value of time measures described above. This methodology is adaptable to both recurring reliability issues and the degradation of network performance caused by rare events (such as bridge failures, flooding, and other natural disasters presented in Appendix C).

Although recurring and rare phenomena arise out of processes with very different stochastic properties, the challenge of analyzing these different sources of reliability is similar, and the solutions have a common approach. In both cases, the uncertainty that these two processes impose upon the cost of travel may be converted to a certainty-equivalent measure to enable the use of conventional evaluation methods for determining the value of reliability.

In the case of rare events, the facts are different, but the virtue of the certainty-equivalence notion is the same. For example, if knowledge of the processes that cause a bridge failure can be characterized by an assignment of a probability distribution to the bridge-failure event, then the uncertainty about the occurrence of a bridge failure can be used to derive a certainty-equivalent measure of the number of such events. This quantity can then be associated with the resulting impacts on network performance and valued using conventional techniques for measuring network performance. These techniques involve measuring the incremental delay associated with the bridge failure and the time period over which the delay persists.

The ultimate goal of valuing network unreliability is to guide investments into policies or technical solutions that reduce the economic burden of unreliability. Thus, the methodology for valuing unreliability naturally incorporates considerations of present valuation (the time value of money) and the discount rates associated with considering event timing.

Measuring the value of reliability involves five considerations: (*a*) use of options theory, (*b*) a real option for travel time, (*c*) measuring the economic cost of unreliability, (*d*) evaluating reliability management policies, and (*e*) characterizing reliability for recurring events.

Options Theory

The field of economics that provides a mechanism for converting uncertainty into a certainty-equivalent value is options theory. Options theory provides insights into the value of current and future opportunities whose value is not known with certainty but whose opportunities can be characterized probabilistically. The classic application of options theory in a financial context is to answer such questions as, "How much should I be willing to pay to be able to buy (or sell) a security at a given point in the future at a specific, prearranged price?" An option to buy at a fixed price is a "call option," and an option to sell at a fixed price is a "put option."

Economists have determined that many financial arrangements that involve valuing uncertainty (such as insurance contracts, prepayment penalties on mortgages, or car lease terms) can be analyzed as financial options of one sort or another. In insurance, for example, buyers might ask how large an insurance premium they would be willing to pay to avoid the risk associated with the loss from a fire. The option can provide an opportunity to buy or sell ("exercise the option") at a specific point in time or any time up to a specific time.

The opportunity to buy or sell at a specific point in time is a "European option," and the opportunity to buy or sell at any time up to a specific time is an "American option." Simple examples of the application of a European and an American option are described below:

- An example of an application of a European option is in commodity trading. Here, individuals are buying the right to purchase or sell an asset at a contracted price at *the end* of the contract period. Trading in commodity futures is of the European option type, because people buy the right to purchase or sell wheat, corn, or other products at a specified (strike) price in the future.
- Buying the right to purchase or sell an asset at a contracted price at *any time* during the contract period is an American option. Insurance policies are a type of American option, because the commodity being traded (money value of insured object) can be called or put at any time during the policy coverage.

Economists have expanded the notion of options beyond financial instruments to so-called real options. Real options involve the analysis of quantities such as commodities and time. Formulas have been developed to compute the value of various types of real options under a wide range of conditions. Many real-world insurance policies insure such real outcomes as a policy that ensures that a communications satellite will function at a specified level of performance or for a specified number of years. Application of options theory to travel time reliability constitutes one formulation of a real option.

Practitioners and experts in the real-options branch of financial analysis have a very specific meaning for "real option." Usually, the term refers to real assets in the capital budget context. Because it is not known that anyone else has studied travel time reliability by using the options approach, it is not clear what is the proper terminology to use. However, Professor Lenos Trigeorgis, a well-known expert in the field of real options, has applied the term "real options" in an analogous setting, that is, a decision to increase flexibility of production processes as defense against exchange rate variability. Therefore, the term "real option" is used in a liberal sense for the options theoretic approach for the valuation of travel time reliability because the certainty-equivalent measure is easily converted to minutes (time).

Application of options formulas of the Black–Scholes type to nonfinancial options has to respect certain underlying assumptions of the Black–Scholes model. Analysts should apply Black–Scholes to real options in circumstances in which they make the most logical sense. A full discussion of the underlying assumptions of option-pricing models of the Black–Scholes type and their implications in the development of real options, such as those presented here, can be found in Kodukula and Papudesu (2006).

Because real options are not traded in a formal market, the so-called arbitrage assumption is commonly highlighted as a limitation on the applicability of Black–Scholes to real options. However, as Kodukula and Papudesu (2006, p. 84) point out:

> We believe that a categorical denial of the validity of the models to real option problems is inappropriate and that a "no arbitrage" condition is only a limitation of the model and can be overcome easily by proper adjustment. Practitioners have used three different types of adjustment:
>
> 1. Use an interest rate that is slightly higher than the riskless rate in the option pricing model.
> 2. Use a higher discount rate in calculating the discounted cash flow (DCF) value of the underlying asset.
> 3. Apply an "illiquidity" discount factor to the final option value.
>
> Basically, the objective of these adjustments is to account for any overvaluation caused by not meeting the "no arbitrage" condition. All three methods, therefore, decrease the option value, making it more conservative.

Hence, the development of real options and proper adjustment make development of a real option for travel time possible, despite the fact that the commodity is not traded in a market in which the arbitrage condition is necessarily assured.

Damodaran (2005), in *The Promise and Peril of Real Options,* provides a relatively accessible treatise of the Black–Scholes formula and real options. In addition to providing an introduction to the use of options, the paper includes discussion of the conditions for formulating real options and a comparison of a real options approach to decision making under uncertainty in contrast to the more traditional discounted cash flow models.

A Real Option for Travel Time

To illustrate the applicability of options theory to the issue of travel time, let us examine the phenomenon of unreliability, which occurs on a relatively frequent basis over the course of a year, and how it might be analyzed by using options theory. Imagine that a single link of a network is involved and that we have observed the speeds and resulting travel times on this link for many days. Assume that those observations have led to the conclusion that the travel time has an average value, but there is considerable variation in value around that average. That is, travel times on any specific day are unlikely to be the average, but rather something above or below the mean. (Put differently, the link does not provide reliable service.) Further, over the period of observation, the travel times experienced are distributed lognormally.

Of interest is devising a succinct measure of the unreliability of this link. One way to do that is to ask the question, "How much longer is the travel time I would accept in return for no uncertainty about the travel time?" This question sounds very much like the questions that arise in deciding how much one might be willing to pay to insure property. Given that insurance contracts can be represented by options, the question pertaining to travel time unreliability can be answered with the right formulation and parameterization of an options formula.

This option formulation for travel time reliability is derived from options representations of insurance. In other words, the basic insight of the approach is that one can think of unreliability as analogous to the occurrence of an undesirable outcome in some random-event context (e.g., an accident that impairs the value of a car). In an auto insurance context, one can think of the insurance policy as a mechanism for compensating the driver for any lost value due to an accident during the life of the contract. Carrying this notion over to travel time reliability, one can imagine that an insurance policy could be crafted that compensated the driver for the unexpected occurrence of speeds below the expected (average) speed. Such a policy does not exist for daily vehicle travel, although such policies do exist for long trips (e.g., overseas travel insurance). So, if one accepts that the *concept* of speed insurance makes sense, then the Black–Scholes formulation makes sense, and one can calculate the speed-equivalent "premium" to be ensured compensation for encountering speeds less than the mean (expected) speed.

Thus, the premium of our insurance contract is the excess delay we are willing to pay to be guaranteed a travel time equal to today's average. The specific mathematics of this are presented later, but this example illustrates how travel time uncertainty can be abstracted from to facilitate valuing the unreliability of a road system. Specifically, the real option formulation allows for answering the question posed above with a certainty-equivalent delay, which can be converted to additional travel time per mile.

Measuring the Economic Cost of Unreliability

Once the certainty-equivalent value of a stochastic incidence of a performance metric or the underlying events has been determined, valuation can proceed as if the values involved were deterministic. To continue the example of recurring unreliability phenomena, the certainty-equivalent value of the uncertain travel time performance greatly facilitates monetization of the road's unreliability.

Specifically, assume that the option value of the travel time unreliability is 1 minute/mile. That is, the traveler would be willing to spend an additional minute per mile if the downside uncertain risk of slower speeds or longer travel times was eliminated by some technical or policy action. This implies that the unreliability cost to the traveler is equal to whatever value he or she places on each minute of additional delay.

Using available evidence on the value of time in a given travel setting allows the traveler to place a dollar value on a road's unreliability. To repeat the example that was previously provided in this appendix: if the average value of time of users of the roadway is \$20/hour, then the value of time is 33.3 cents per minute, per mile, per user. If the certainty-equivalent value of delay is 1 minute/mile, the road segment displaying this unreliability is 10 miles long, and there are 6,000 users per hour at the time of day that this unreliability is displayed, the cost of unreliability is approximately \$20,000/hour or \$7 million/year for each hour of the day that this level of unreliability occurs.

If we use the same example as above, the dollar value of the reliability can be easily calculated to account for multiple road-user groups or trip types. Assume that there is a 10-mile road segment with an equivalent option value for the travel time unreliability equal to 1 minute per mile. On the basis of the a.m. peak values of time developed by the Puget Sound Regional Council, the dollar value associated with the unreliability on this road segment is shown in Table B.1.

The dollar value of reliability is calculated as the certainty-equivalent of delay (1 minute), multiplied by the user group volume, multiplied by the value of time per minute per hour (60 minutes) × facility length (10 miles).

Evaluating Reliability Management Policies

Once the cost of unreliability is established, this information can be used to evaluate the cost-effectiveness of strategies to manage unreliability. To do this, it is necessary to determine the effect of the strategy on improving reliability and then

Table B.1. Example Dollar Value of Reliability for Multiple Road User Groups

Road User Group	Share of Volume	Volume	Value of Time/Hour	Value of Reliability/ Hour
Single-occupancy vehicle	70%	4,200	$26	$18,200
High-occupancy vehicle, 2 passengers	15%	900	$30	$4,500
High-occupancy vehicle, ≥3 passengers	8%	480	$38	$3,040
Vanpool	2%	120	$102	$2,040
Heavy trucks	5%	300	$50	$2,500
Total		6,000		$30,280

perform the same options theoretic computation under the improved conditions.

The policy may, of course, affect both the average travel time and its volatility. For simplicity, assume that the policy does not affect average travel times, but rather, reduces the variance (volatility) of travel times. For example, a traveler information system, incident management system, or some other treatment may reduce the travel time variance such that the options value of unreliability is now only 30 seconds/mile on the roadway segment described above. There is now a savings of approximately $3.5 million/year for each hour of the day that is affected by the treatment.

Thus, a treatment that costs less than $3.5 million/year would be worthwhile (cost-effective) to implement because of its impact on improving reliability. In a real-world application, an improvement to traffic information systems might generate improvements in reliability over many years. As traffic grows, values of time evolve, and the computation of the options value of reduced volatility is repeated for each period of time during the life of the improvement. These future savings can be reduced to a present value in the planning year by discounting the stream of annual options values. The advantage of the certainty-equivalent approach is that user benefits from improvements in travel time reliability can be treated deterministically, just as they are in other traditional user benefit categories in standard transportation investment or policy evaluations.

Characterizing Reliability for Recurring Events

Options formulations for travel time reliability have been developed to correspond to the valuation of reliability related to recurring and rare events. The stochastic nature of rare events (such as bridge failures, road closures due to flooding, and other events) is quite different from the uncertainty that characterizes recurring events. Recurring events (such as crashes, weather-related events, and other common sources of travel time variation) can generally be characterized with a lognormal distribution, while the stochastic nature of rare events necessitates adapting the more traditional options formula. For rare events, an application of stochastic variables displaying a generalized extreme value distribution has been adopted and is presented in Appendix C.

Both recurring and rare events cause unreliability, so recurring and rare events are distinguished only by differences in the frequency distributions that characterize them. Unreliability produced by recurring events is assumed to display statistical behavior best represented by normal distributions (often, lognormal distributions).

In the case of unreliability caused by recurring events, it often is possible to observe the effect of these events on network performance by directly observing the variability of speeds or travel time. This is because normal distributions often best describe high-frequency phenomena, so the chances of having useful network performance data improves.

In the case of unreliability caused by rare events, variability in speeds or travel time may not be measured directly. For example, the number of bridge failures may be so low that changes in performance measures may be difficult to study directly. (In cases such as major accidents, for example, there may be a way to directly measure the influence of these rare events on speed variability.) The next section describes the options theoretic approach for valuing reliability for recurring events.

Valuing Reliability for Recurring Events

Unreliability produced by recurring events is defined as the variability in travel time that occurs as a result of events such as accidents, incidents, and poor traffic-signal timing. Over the course of a year, travel times may display high volatility at the same time of day, on individual roadway segments, and on specific paths or routes.

On a somewhat less frequent, but nonetheless recurring basis, weather and other random, natural events can impair network performance. Normal rain events, for example, impair network capacity and performance in a transitory fashion.

The certainty value of unreliability associated with recurring events can be derived by using options valuation techniques that employ a lognormal frequency distribution. This is achieved by recasting the question of reliability in terms of a speed insurance problem, which in turn, can be addressed by options theory.

The options theoretic approach answers the hypothetical question: "How large a reduction in average speed should a traveler be willing to accept in return for a guaranteed minimum travel speed?" The options formula determines the speed reduction premium a traveler would be willing to pay for a minimum-speed-guarantee insurance policy.

A simple speed insurance case is one in which the "coverage" of the insurance is relatively short and the option can be invoked at the end of the life of the insurance period. Recast as a speed-reliability problem, this makes sense because it is of interest to know the burden placed on the traveler, who finds that the speed has been impaired by the volatility created by recurring events.

A short-lived option that pays off at the end of its life is a European put option—that is, an option of finite life that can be exercised at the end of the option's life. Such an option compensates the holder for any losses incurred if actual performance is poorer than the contracted performance guarantee. If performance is greater than the expected performance guarantee, then the option has no value.

A travel time option, which is expressed as a certainty-equivalent of delay measured by speed or additional travel time, can be monetized by using the dollar value of travel time. However, to preserve the underlying distributional assumption of lognormality, it is better to compute the real option in terms of speed, as shown in Equation B.1, which is speed guarantee for recurring events.

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

where

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

$$d_2 = d_1 - \sigma\sqrt{(T-t)} \tag{B.1}$$

and where

$P(V_T, t)$ = value of a European put option in mph, as a function of link speed and option length
$N(x)$ = the cumulative standard normal evaluated at x
V_T = the (unknown) speed experienced traversing the link, in mph ≈ a random variable, distributed lognormally
I = the guaranteed speed, in mph
r = the annualized, risk-free continuously compounded interest rate
σ = variability of V; square root of the log-value variation process of V
$T - t$ = option length in years, where T is the expiration date of the option

Equation B.1 illustrates how the travel time reliability option can be formulated by following standard insurance options formulations, that is, recasting an insurance option as a "speed guarantee insurance" policy. From the mathematics of the underlying options theory, we know that (all other things being equal) the options value of a speed guarantee does the following (and, hence, affects the cost of unreliability of speeds):

- Increases with the variability of speeds,
- Increases with the guaranteed speed,
- Decreases with the length of the contract, and
- Decreases with the average speed.

Absent any quantification of the options value, these insights are helpful in understanding how the characteristics of unreliability, or the benefits of remediation of unreliability, are affected by statistical properties of unreliability.

Two of the elements in the travel time reliability option are the interest rate and the option length. The value of the interest rate used in the formulation should be the real, annual riskless rate of return. This rate varies somewhat with macroeconomic conditions, but it should reflect the real discount rate the market is applying to value funds received in the future versus today. This is also called the "time value of money" in finance parlance. The interest rate in the implementation of the Black–Scholes formula should be a low single-digit annual rate in the vast majority of macroeconomic settings. The option survives for a fixed amount of time, calculated from the lowest 5% speed implicit in the speed distribution. This could be smaller or larger. It is done to avoid the complexity of valuing serial options when multiple road segments, each with a different speed distribution, are involved. In this sense, it is akin to what is called a "capped" option, and it imparts a conservative value (lower) to the option value. This value (and hence the assumed life of the put option [insurance contract]) can be changed by the user. To implement the option, we need to provide the inputs listed in Equation B.1.

In the examples presented below, the following features of the option are used:

- The log mean and log standard deviations of speed are derived from data on segment speeds for a 5-minute time-of-day interval, using a year of daily speed observations.
- The interest rate is set to a riskless, short-term interest rate.

- The guaranteed or "insured" speed is set to the average historical speed.
- The option length is set to the time (in years) that it takes to traverse the segment at the lowest speed observed in the historical data.

Figure B.2 illustrates the lognormal distribution of speed for a 5-minute interval in the a.m. peak period with data from the Puget Sound Region for a 1-year period.

Table B.2 illustrates the value of the implied put option at various average annual speeds and log variability. This exhibit displays the certainty-equivalent value both in mph and in minutes of delay.

The data suggest that speed variability imposes a burden on highway users. A rational and risk-neutral user would be willing to sacrifice speed to avoid traveling considerably below the average speed. This is especially the case when the log standard deviation in speeds is large relative to the average speed.

Although intended only to be illustrative, the data in Table B.2 reveal that the volatility of speeds relative to average speeds is not monotonically related to average speed in the real world. The relative volatility and unreliability (and, hence, the value of speed guarantees in mph) is the largest in the speed range of 45 mph. However, as Table B.2 illustrates, the value of the speed-guarantee option (when expressed in minutes) declines monotonically with speed. Thus, a policy that improves average speeds will decrease total delay, inclusive of the certainty-equivalent volatility burden. Policies that reduce the volatility of speed directly (without necessarily improving average speed) can also be shown to decrease total delay inclusive of unreliability.

As previously stated, the data in Table B.2 are illustrative. They are provided to show the option values associated with varying speeds and log variability on a facility. In this table, the average speed, log average speed, and the standard deviation are calculated from observed speed data. The option value (mph) is calculated from the average log speed and log standard deviation calculated from the data and other inputs to the options formulation previously described by using Equation B.1.

When Equation B.1 is used, the option value will be expressed in the speed reduction that drivers would be willing to accept to obtain their speed guarantee. The option value, expressed in mph per hour can be converted to minutes by subtracting the option value in speed from the speed guarantee and determining the additional average travel time the road user is willing to accept in exchange for travel time reliability.

With the option values shown in Table B.2, the option values (in mph or minutes) can be plotted against the average annual speed for each 5-minute period. From Figures B.3 and B.4, we can conclude that the value of unreliability at an average speed of 20 mph is approximately 0.8 minutes/mile, whereas the value of unreliability at a speed of 60 mph is only about 0.1 minutes/mile. These measures may be idiosyncratic to the facility studied. However, the calculations illustrate that by converting speed volatility to delay equivalents, we can consistently measure the cost of unreliability and the benefits of eliminating unreliability.

When one wishes to value unreliability over an arbitrarily long evaluation horizon, the fixed-life feature of the European put option is inappropriate. First, there is no assumed fixed life, so a perpetual option formulation is required. In addition, the American put option, allowing exercise of the option any time during the (perpetual) life of the option, is the only exercise feature that makes sense in the context of a perpetual valuation horizon.

The value of an American put option with perpetual life can be calculated from Equation B.2, which has been adapted from McDonald (2002). The option in Equation B.2

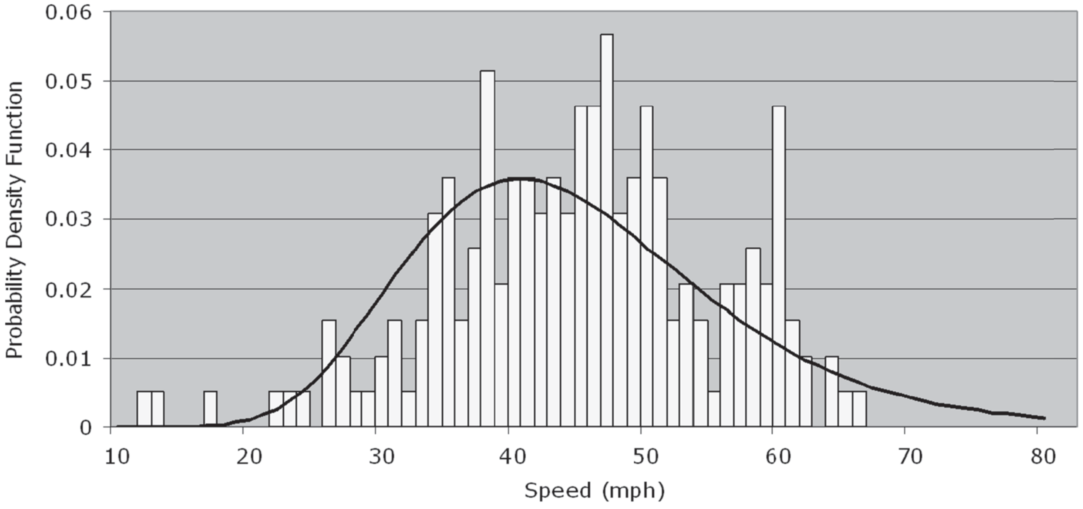


Figure B.2. Illustration of a lognormal distribution of speed.

Table B.2. Illustrative Option Calculation for an Urban Freeway

Time of Day	Average Annual Speed (mph)	Log Average Annual Speed	SD Log Speed	Option Value	
				Miles per Hour	Minutes per Mile
14:00	57.11	4.02	0.25	5.64	0.115
14:05	56.56	4.01	0.29	6.49	0.137
14:10	55.16	3.95	0.42	9.25	0.219
14:15	53.78	3.92	0.43	9.14	0.228
14:20	52.52	3.89	0.45	9.34	0.247
14:25	51.08	3.84	0.50	10.09	0.289
14:30	50.81	3.84	0.48	9.69	0.278
14:35	50.01	3.81	0.51	10.16	0.306
14:40	48.02	3.76	0.53	10.10	0.333
14:45	46.31	3.71	0.57	10.37	0.374
14:50	45.03	3.67	0.59	10.47	0.404
14:55	43.64	3.63	0.60	10.24	0.422
15:00	41.52	3.57	0.61	9.92	0.454
15:05	41.11	3.55	0.63	10.19	0.481
15:10	39.47	3.49	0.66	10.21	0.530
15:15	37.48	3.42	0.68	10.00	0.582
15:20	35.79	3.38	0.67	9.39	0.596
15:25	34.15	3.32	0.67	8.97	0.626
15:30	33.69	3.31	0.67	8.80	0.630
15:35	33.93	3.32	0.66	8.75	0.615
15:40	32.68	3.28	0.67	8.54	0.650
15:45	29.00	3.15	0.67	7.59	0.734
15:50	26.30	3.05	0.64	6.64	0.771
15:55	24.67	3.00	0.63	6.06	0.791
16:00	23.16	2.94	0.61	5.53	0.812
16:05	23.10	2.94	0.60	5.42	0.796

Source: Counter data at I-405/I-90, southbound, 2007.

Note: The calculations apply a guarantee equal to the average speed for each time of day. SD = standard deviation.

can be valued in a case in which the lognormal speed variability can be used to parameterize the option. The valuation would yield the certainty-equivalent value of various speed guarantees, *I*, associated with various average speed measures, *V*.

$$P(I,\infty)=\frac{I}{1-m}\cdot\left(\frac{m-1}{m}\right)\cdot\left(\frac{V}{I}\right)^{m}$$

where

$$m=\frac{1}{2}-\frac{r}{\sigma^2}-\sqrt{\left(\frac{r}{\sigma^2}-\frac{1}{2}\right)^2+\frac{2r}{\sigma^2}} \qquad \text{(B.2)}$$

and where

$P(I,\infty)$ = the value of the perpetual American put option in mph, as a function of the speed guarantee

V = the (unknown) speed experienced traversing the link, in mph

I = the guaranteed speed, in mph

r = the annualized, risk-free continuously compounded interest rate

σ = variability of V; the square root of the log-value variation process of V

The perpetual American put option is useful in valuing a policy intended to control the speed variability of the morning commuting period over a long period of time. The parameters of

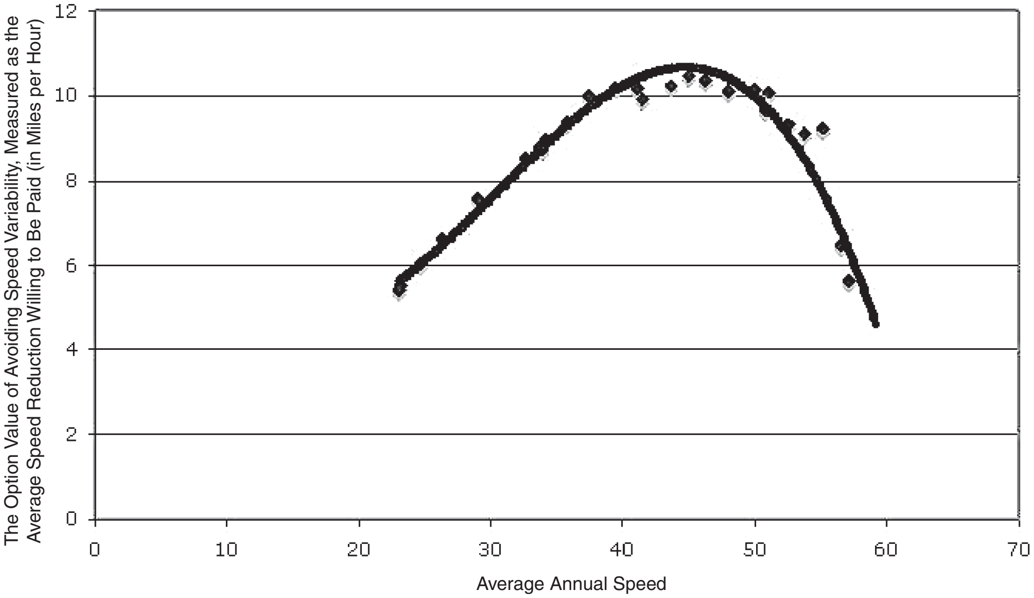


Figure B.3. Illustrative option values (in mph) versus average speed.

the lognormal speed distribution must then be estimated in a manner consistent with this long-lived option (i.e., using long histories of the morning commuting speeds). Because the reliability measure applies to a long time interval, the certainty-equivalent value of unreliability is higher than in the finite European put option.

Parameterizing the Options Model

The examples provided above illustrate how options theory can be used in a setting in which the unreliability problem is caused by recurring events and the speed performance metric is distributed lognormally. The same method can be applied to circumstances other than the volatility of speed measured in 5-minute intervals.

The parameters of the options formulation should be measured to be consistent with the network performance along the facility under study. For example, performance measures can be derived that are specific to a longer period, such as an entire weekday, the a.m. peak hour, weekend travel, and so forth. In all cases, the log mean and log standard deviations need to be estimated from available data or extrapolated from other studies. In the case of an a.m. peak-hour study, travel times or speed data could be assembled for that time of day

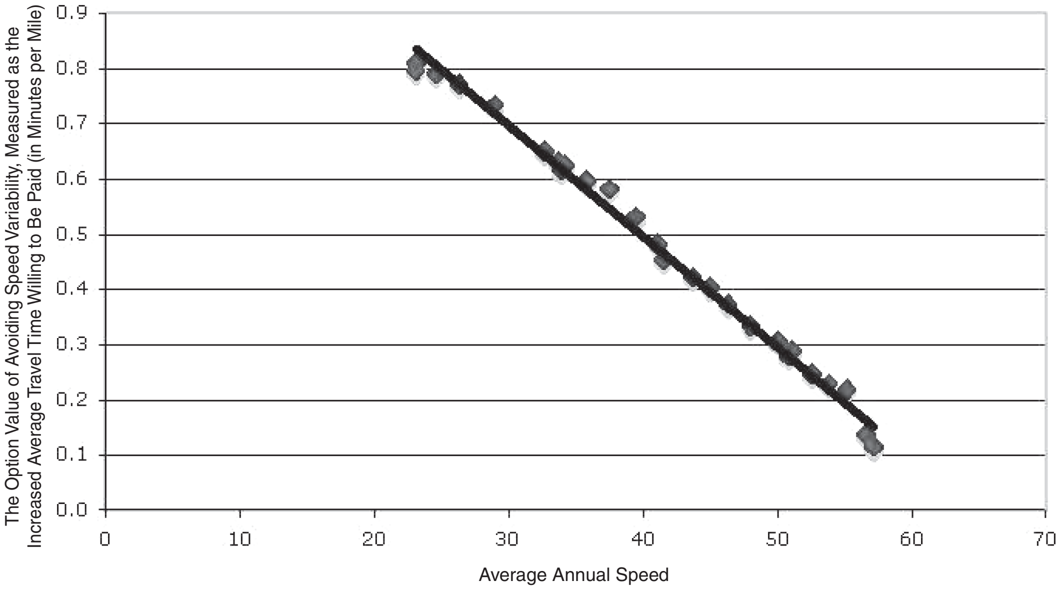


Figure B.4. Illustrative option values (in minutes) versus average speed.

for a year of data. The log mean and log standard deviation would then be computed from this data sample. In the case in which the average travel time for the entire weekday is of interest, daily average travel times could be constructed for each of 250 weekdays in a year.

The life of the option is determined differently in each of these two cases. In the case of the a.m. peak-hour study, the life of the option would be set to 1 hour, and the time period would be examined. In the case of the study of weekday performance, a 24-hour life would be assumed. In all cases, these lives would be expressed in years for consistency with the standard interest rate term.

The interest-rate parameter in the calculation is provided to respect the yield on risk-free alternative uses of the travelers' resources. In short-life options, such as those used to represent recurring unreliability problems, the effect of different interest-rate assumptions is not particularly material. Nevertheless, it is important to place the analysis properly in its surrounding economic conditions. Hence, for short-life options, short-term interest rates (expressed on a per annum basis) should be used to represent these opportunity costs.

The approach developed for recurring events can be generalized, such that the value of unreliability is calculated on the basis of the speeds and travel times experienced on the facility. This approach does not necessarily rely on specific information about the source of the unreliability, as long as the source and the speeds are lognormally distributed. Thus, system performance data determine the underlying stochastic nature of unreliability on a facility. Table B.3 summarizes the disruption data identified in SHRP 2 Reliability Project L03 for use by agencies in reporting reliability performance measures (Cambridge Systematics, Inc. et al. 2013).

Reliance on the normal or lognormal distribution is standard in options theory and a requirement for using the Black–Scholes formulation. The Black–Scholes model is based on the normal (or lognormal) distribution of the underlying asset.

Table B.3. Summary of Disruption Data Characteristics by Type of Disruption

Disruption Type	Data Collected	Source	Availability Location
Traffic incidents	Accident data	DOTs State database Archives Private sector	Major urban or tourist areas
	Statistics on nature (size, severity, duration) of accident Disruption of roadway operations (number of lanes closed) Response after accident Data on traffic incidents (stalled or disabled vehicles, debris)	Traffic.com TMC operators and freeway service patrols Traditional crash data Specific incident-response programs	
Weather	Basic weather data	National Climatic Data Center of the National Oceanic and Atmospheric Administration	Areawide
Work zones and construction	Planned construction activity (number of lanes closed, period of time)	DOTs State database	Urban and rural
Fluctuations in demand and special events	For large events: time and date, nature of changes in traffic demand For other events: no data collected	Public- or private-sector traffic management plans	Urban areas
Signal timing	Traffic control plans (signal cycles, phase length, order, signal offsets, and base ramp metering)	Operating traffic agencies	Usually available
	Specific timing plans implemented	Operating traffic agencies	Rarely available
	Phase length actually operated	Operating traffic agencies	Almost never implemented
Bottlenecks and inadequate base capacity	Change in geometry (lane drops)	All roadway agencies	Good data
	Traffic patterns (weave and merge sections)		
	Visual disruptions (sightseeing, rubbernecking)		No record
	Minor changes in functional capacity		Potentially available

Note: DOTs = departments of transportation; TMC = transportation management center.

In the real option for travel time reliability, the assumed asset is speed, and so the assumption of the lognormality of speed (e.g., to compute the certainty-equivalent measure in minutes of travel time) is an assumption for the options theoretic approach.

The lognormal has been shown to be the most-appropriate distribution for high-frequency speed data collected from roadways. Traffic engineering research has confirmed the validity of the use of the lognormal distribution for travel time and speed. The lower bound of zero and longer right tail of the distribution make the lognormal particularly appropriate for the typically skewed speed data. SHRP 2 L03 cites Rakha et al. (2006), which confirms the use of the lognormal assumption for speeds and travel times in the context of travel time reliability. Other recent papers include El Faouzi and Maurin (2007), Emam and Al-Deek (2006), Leurent et al. (2004), and Kaparias et al. (2008).

Strategies for improving travel time reliability may focus on a specific cause or address multiple sources of unreliability. Determining the various sources of unreliability by using disruption data may then aid in determining the potential strategies to be implemented.

Monetizing the Certainty-Equivalent Values

Because the certainty-equivalent values of an option can be expressed in minutes or hours of delay, unreliability can be monetized by applying the appropriate values of time to these delay measures. Measuring unreliability in future periods permits the analyst to determine the present discounted value of unreliability and to evaluate long-term network improvements or management policies that are directed at addressing unreliability.

Similar to other parameters of the options approach, certainty-equivalent values should be selected to measure what is important to the reliability issue being addressed. For example, if a study is focused on improving the reliability of freight movement, the analyst may only be interested in a strategy's effect on the certainty-equivalent delay experienced by trucks. In this case, only the value of time for truck travel might be used to monetize the value of unreliability. In general, most strategies that are used to reduce unreliability will benefit both freight and passenger travel. In general, the options value of unreliability should be monetized by using a traffic-weighted average value of time by vehicle class and by trip purpose.

To evaluate long-term strategies and treatments to improve system reliability, it is necessary to understand how traffic growth affects both average speeds and the volatility of those speeds. Average speed relationships that are derived from historic data may help determine the future levels of unreliability. In addition, microsimulation models may also help to characterize the stochastic nature of future system performance.

Valuing Reliability for Rare Events

Although a sufficiently long time series of high-resolution traffic performance data (e.g., highway speeds) tends to display lognormal distribution, one can imagine many situations in which a transportation agency is concerned about events or sources of variability that are extremely rare. Some examples include physical phenomena such as earthquakes, avalanches, and particularly severe or rare flooding. Examples could also include bridge failures from various causes and terrorist acts that disrupt transportation links or networks.

Ignoring the prospect of rare events and using pure Gaussian assumptions instead is at the heart of many financial and engineering catastrophes, which include long-term capital and elements of the financial crisis that it precipitated. One of the reasons to distinguish between recurring and rare events in this discussion and the development of the options theoretic approaches is to draw attention to the rare-event issue. Unfortunately, implementation of strategies to protect against rare events in a cost-effective way is very difficult because of the problem of characterizing the event distribution and the complexity of mathematically representing the proper investment strategy. This is especially challenging in the setting of highway infrastructure development and operation.

The options theoretic approach to the valuation of travel time reliability is extended to rare events by using new options formulations aimed at addressing rare events, specifically events that follow extreme value distributions. Research on options theory using extreme value distributions is relatively new, and has not been applied, to our knowledge, to settings other than an example application for research and development in the pharmaceutical industry. Therefore, the rare-event methodology is presented in Appendix C, and future research is recommended to address uncertainty arising from rare events in investment decision making.

Measuring Networkwide Impacts

Policies and strategies that are intended to improve roadway reliability may affect only certain segments or an entire regional network. Similarly, the adverse impacts of phenomena such as flooding, bridge failures, or accidents may occur on just a few segments or over large portion of a regional network. Thus, the final step in mitigating system unreliability is to consider methods for addressing the scale of the impact.

The certainty-equivalent options perspective can be applied to an individual segment or to an entire network as long as the appropriate data exist to provide the necessary parameters. At times, the analysts may be asked to extrapolate the effects of unreliability measured on one link to the entire network. For example, a bridge failure or avalanche may be confined to a single segment or group of segments, but deterioration of reliability in that area may propagate elsewhere in the network.

There are three alternative approaches to addressing the aggregation of reliability considerations on the network level: (*a*) direct measurement at the network level, (*b*) region-specific travel models, and (*c*) mathematical representation. Each of these approaches has advantages and disadvantages.

Direct Measurement of Unreliability at the Network Level

This method involves measuring unreliability separately for each roadway segment in the roadway network. If each segment can be measured, the network-level effects can be aggregated from the individual link effects. Alternatively, unreliability could be measured at the network level. For example, one might measure speed volatility using network-wide vehicle miles traveled (VMT) and vehicle hours traveled (VHT) data. The mean and standard deviation of the log mean and standard deviation of the ratio of regional VHT and VMT could be computed by vehicle class and by trip type from daily observations over some period of time. The certainty-equivalent value of unreliability then can be calculated directly with the European put option approach described earlier in this appendix.

The certainty-equivalent delay associated with each category of travel could then be monetized by applying the appropriate value of time. Strategies or policies that mitigate unreliable travel could then be evaluated with conventional benefit-cost techniques, so long as the strategy or policy can be characterized by a change in the reliability performance measures.

Measurement with Region-Specific Travel Models

Simulation of the effect of strategies or policies that are intended to improve reliability at the network level can be measured with modeling techniques for the regional network that are sensitive to the impact of these strategies (such as dynamic tolling) that affect system reliability. In this approach, a model of the regional network is used to examine the effect of any changes in reliability that occur on the affected segments or on the network as a whole. Certainty-equivalent option models can be used in conjunction with microsimulation, dynamic traffic assignment, or other model platforms that measure how unreliability is affected by a pricing-, or operational-, or capacity-improvement policy.

This approach has the potential to be both comprehensive and respectful of regional network idiosyncrasies. The Puget Sound Regional Council's four-step travel demand model has incorporated link-level augmentations to allow measurement of unreliability effects. Although it is applied only to freeway links (with a representative stochastic rendering for all links), it is a convenient way to automatically consider the benefits of improving reliability when evaluating various strategies and policies (not just policies designed to address unreliability issues).

This regional-model approach also has the potential to help extrapolate events that occur on only a few links in the network to determine the impact on the network as a whole. Xie and Levinson (2008) used this general method to evaluate the effect of the failure of the I-35W bridge in the Minneapolis, Minnesota, region. In this case, total delay was addressed, but reliability was not.

The accuracy of this method is limited only by the capabilities of the model. Obviously, a model that simulates the dynamic behavior of traffic (and the volatility of travel speeds throughout the network) provides a better way to represent unreliability with and without the application of various strategies or policies. The evaluation exercise then proceeds to capture the performance data (link by link or in the aggregate across the network) and apply the valuation methods described above to the reliability metrics.

Mathematical Representation of Network Reliability

A third approach is to employ mathematical models of network reliability to simulate the impact of a strategy or policy on network performance. These models differ from regional models used by metropolitan planning organizations (MPOs) and other agencies to evaluate network improvements because they are pure mathematical constructs rather than simulation models per se. Mathematical models can be considered to be sketch models as opposed to regional-model implementations.

In this regard, these mathematical models may not be fully faithful to real-world networks, but they offer a way to evaluate generic policies in abstract network representations. Examples of these models include those by Clark and Watling (2005), Kaparias et al. (2008), Iida (1999), and Bell and Iida (2003). Unlike many regional models implemented for project evaluation, these mathematical models may capture system reliability issues in a way that can guide policy. Depending upon the context, these models can be used to evaluate either reliability issues associated with recurring events or with rare events. The impacts on reliability can be measured on a few links or across the network.

None of these three methods directly measures impacts beyond those that occur on the network itself. Broader economic impacts must be represented, if appropriate, by other tools that link transportation infrastructure to regional economic viability.

Quantifying the Value of Time

The dollar value of reliability is determined by multiplying the certainty-equivalent penalty (measured in minutes per mile) by the value of time. The value of reliability can be derived for multiple roadway user groups by applying a separate value of time that corresponds to each user group, along with the observed average volume for each user group on the roadway segment. The total value of reliability is then computed as the sum of the reliability values for each user group on the roadway segment.

A literature review on the value of time was conducted to determine the value of time for passenger travelers and for freight movers. Literature related to the value of time has been a productive topic for research. The more-useful measures of time value have been developed from mode-choice or path-choice (route-choice) studies based on household and shipper surveys or from studies of traveler behavior on facilities such as high-occupancy toll (HOT) lanes.

Although the value of travel time may be referred to as an average value, the value of travel time is recognized to take on a range of values that depend on user income and other demographic characteristics (in the case of passenger travel) or on operations and shipment characteristics (in the case of freight travel). The value of time may also depend on factors such as trip purpose, time of day, or travel conditions.

Value of Time Methodology and Data

Value of time modeling and estimation dates back to at least the 1960s. At that time, early empirical research focused on traveler mode choice to determine the value of time by looking at the marginal rate of substitution between travel time and cost across mode alternatives. In addition to mode choice, route choice and, to a lesser extent, housing choice, models have also been developed to help practitioners understand traveler behavior and decisions with respect to travel time, travel cost, and residence and work location (Small 1992).

When revealed-preference (RP) data have been difficult to obtain, the alternative for researchers has been to conduct stated-preference (SP) surveys. SP surveys ask respondents to make travel decisions for hypothetical scenarios in which the alternatives in each scenario have different travel times, travel costs, or other trip attributes. Brownstone and Small (2005) note the difficulty in creating realistic scenarios and accurately presenting the scenarios such that the key variables of interest are properly understood and measured. When comparing results from studies based on RP data and SP surveys for HOT-lane facilities in Southern California, Brownstone and Small (2005) observed that the SP surveys tend to yield much lower results than do the RP data.

RP data from HOT-lane facilities have also been used to improve SP survey instruments and vice versa. As a result, researchers can create scenarios reflecting realistic trip alternatives, thereby reducing measurement errors from respondent perceptions of scenarios that are familiar to them.

Passenger-Travel Value of Time

Since the initial conduct of studies for value of time, the relationship between the value of time and user income has been well established. Waters (1992) conducted a literature review, summarizing the research from the 1960s, 1970s, and 1980s with regard to the value of time as a percentage of the wage rate. Most of the studies reported the value of time to be between 40% and 50% of the wage rate for commuting trips and a much higher percentage (around 85% of the wage rate) for intercity trips. Fewer value-of-time estimates were specific to leisure trips.

These estimates were highly variable—ranging from 35% to more than 200% of the wage rate. Consistent with the findings published by Waters (1992), Small (1992) also observed that the value of time with respect to user income varied from 20% to 100% of the wage rate across various industrialized cities. Small found that a good estimate for the value of time is roughly half of the road user's hourly wage rate.

Miller (1989) also reviewed the value-of-time literature and suggested that the driver's value of time is 60% of the wage rate and the passenger's value of time is 40% of the wage rate. Another finding reported by Miller is that the value of time is approximately 30 percentage points higher in congested conditions as compared with free-flow conditions. From this finding, Miller suggested that the driver value of time in congested conditions is approximately 90% of the wage rate and that the passenger value of time in congested conditions is 60% of the wage rate.

Although it is unpleasant to drive in congested conditions, travelers may be choosing to travel during peak periods because they place a higher value on their travel time or on the schedule delay associated with departing at a less-congested time, or both. If this were not the case, travelers could adjust their departure time so as to travel during the shoulder times adjacent to the peak when congestion levels are not as severe.

In observing travelers on the New Jersey Turnpike, Ozbay and Yanmaz-Tuzel (2008) found that the value of time is higher during the peak period than during the prepeak and postpeak periods for both commuting and for leisure trips. The peak period value of time was found to be $19.72 for commuting trips and $17.16 for leisure trips. This value of time was approximately $2.00 higher (about 10% higher) in the peak than in the prepeak and postpeak periods for both commuting trips and leisure trips, with the exception of prepeak leisure trips, which exhibited nearly the same value of time as peak leisure trips.

The morning peak period has been found to be the time of day with the highest observed value of time, consistent with the findings that travelers with inflexible schedules (such as work schedules) have a higher value for travel time reliability. Ghosh (2001) found higher values of time of $22.00/hour (75% of the wage rate) for the morning commute period along the I-15 HOT-lane facility in San Diego, California. Liu et al. (2007) also used data from the SR-91 HOT lanes in a mixed-logic model to detect time-dependent heterogeneity in the value of time. Estimates of the value of time during the morning commuting period started out relatively high at $16.50 at 5:00 a.m., built throughout the morning, and dropped sharply by 9:30 a.m.

Table B.4 lists some of the value-of-time estimates from recent SP surveys and HOT-lane facility RP studies for passenger travelers.

Table B.4. Passenger Value of Time from SP and RP Studies

Travel Type or Model Type	Value of Time per Hour (% wage rate)	Data or Study Year	Study Type, Location	Reference
Prepeak commute	$16.72	2005	RP, N.J. Turnpike	Ozbay and Yanmaz-Tuzel (2008)
Peak commute	$19.72	2005	RP, N.J. Turnpike	Ozbay and Yanmaz-Tuzel (2008)
Postpeak commute	$17.35	2005	RP, N.J. Turnpike	Ozbay and Yanmaz-Tuzel (2008)
Prepeak leisure	$17.03	2005	RP, N.J. Turnpike	Ozbay and Yanmaz-Tuzel (2008)
Peak leisure	$17.16	2005	RP, N.J. Turnpike	Ozbay and Yanmaz-Tuzel (2008)
Postpeak leisure	$15.33	2005	RP, N.J. Turnpike	Ozbay and Yanmaz-Tuzel (2008)
MnPASS subscribers that were early or on time, p.m. peak	$10.62	2007	SP, I-394 MnPASS	Tilahun and Levinson (2009)
MnPASS subscribers that were late	$25.42	2007	SP, I-394 MnPASS	Tilahun and Levinson (2009)
MnPASS non-subscribers who were early or on time	$13.63	2007	SP, I-394 MnPASS	Tilahun and Levinson (2009)
MnPASS nonsubscribers who were late, a.m. peak	$10.10	2007	SP, I-394 MnPASS	Tilahun and Levinson (2009)
Median value of time per hour	$21.46 (93%)	2000	RP, SR-91 and I-15	Small et al. (2006)
Median value of time per hour	$11.92 (52%)	2000	SP, SR-91 and I-15	Small et al. (2006)
Route-choice model	$19.22	1998	RP and SP, SR-91	Lam and Small (2001)
Route- and time-of-day choice models	$4.74	1998	RP and SP, SR-91	Lam and Small (2001)
Route- and mode-choice models	$24.52	1998	RP and SP, SR-91	Lam and Small (2001)
Transponder, route-choice model	$18.40	1998	RP and SP, SR-91	Lam and Small (2001)
Transponder, mode- and route-choice models	$22.87 (72%)	1998	RP and SP, SR-91	Lam and Small (2001)
Passenger travel—$125,000–$175,000 annual income	$7.11	1998	SP	Calfee and Winston (1998)
Passenger travel—$7,500–$12,500 annual income	$3.06	1998	SP	Calfee and Winston (1998)
Major U.S. metro areas, median	$3.88 (19%)	1998	SP	Calfee and Winston (1998)
Peak period (a.m.)	$30	1998	RP, I-15	Brownstone et al. (2003)
Passenger vehicles	$8–$16	1999–2000	RP, SR-91	Sullivan (2000)
Peak period (commuter)	$13–$16	1999–2000	RP, SR-91	Yan et al. (2002)
Peak period (a.m.)	$22 (75%)	1998	RP, I-15	Ghosh (2001)
Median	$15 (52%)	1998	RP, I-15	Ghosh (2001)
Afternoon commute	$9–$22 (30%–75%)	1998	RP, I-15	Ghosh (2001)

Note: MnPASS = Minnesota PASS express lanes.

In summary, there is a strong consensus in the literature that the value of time for passenger travel depends on the driver wage rate. This is consistent with economic theory that the opportunity cost of not working (driving or enjoying leisure activities) is equal to the workplace value of time. It has also been found that trips during peak periods and during congested travel conditions tend to have a higher value of time. The higher value of time in peak periods also reflects the higher value of time for commute trips, in particular for morning commute trips, which tend to be less flexible. The value of time during the morning commuting period has been observed to be 75% of the wage rate.

Freight-Mover Value of Time

Few studies are devoted to the value of time for freight movers (trucks) beyond the relationship between the value of time and driver pay and inventory costs. Kawamura (2000) noted the shortage of research, particularly with respect to the lack of research on the variation of truck value of time with respect to carrier and shipper operating characteristics. (Shippers generate the need to move freight, and carriers accommodate that need.) Just as passenger-vehicle value of time varies by user characteristics and trip purpose, the value of time for freight movers also seems to depend on carrier characteristics and shipment attributes. Factors such as the carrier operations (for hire or private, truckload or less than truckload), driver pay type, and shipment characteristics (such as commodity value or shipper characteristics) are recognized as potential factors influencing the freight mover value of time.

Kawamura (2000) lists three methods used in studies to determine freight mover value of time. The first method is a cost-based approach (or factor cost) that divides the value of time into its constituent cost elements. The largest portion of the hourly cost is the truck driver wage and compensation, with vehicle depreciation and inventory costs representing a much smaller share of the hourly cost. (The vehicle operating costs should be accounted for separately and not included in the value of time.) The second method is the revenue-based approach in which the freight mover value of time is estimated as the increase in carrier revenues derived from 1 hour of travel time savings. The third method is the SP survey, which uses data from motor carrier managers and shippers to estimate the value of freight-mover time based on their choice among hypothetical travel scenarios.

Freight value-of-time estimates from the cost-based approach is based on the hourly opportunity (or direct) cost of the truck driver and inventory, excluding vehicle operating costs. (Vehicle operating costs such as fuel, tires, and maintenance should be accounted for separately in benefit-cost and other analyses, though some studies do report vehicle-related expenses or the total marginal costs of truck operation as the value of time.) The cost-based approach produces more-conservative estimates because the value of time includes only the costs of driver time and inventory (also sometimes the time-based vehicle depreciation cost) and does not take into account the value of time from the shipper's perspective. Cost-based estimates should, however, include the inventory cost, which is calculated by using an hourly discount rate, and the value of the shipment. The inventory costs are generally a very small portion of the value of time and do not reflect damage or the perishability of the shipment.

The revenue approach calculates the value of time as the net increase in profit from the reduction in travel time by making assumptions about the level of utilization for the time savings. Although the revenue method seems to be rarely used, compared to the cost-based and stated preference methods, two studies—Hanning and McFarland (1963) and Waters et al. (1995)—report ranges for the value of time by using the revenue approach. Hanning and McFarland (1963) estimated the value of truck time as $17.40 to $22.60 (1998 dollars), while Waters et al. (1995) find a wide range for the value of truck time, from $6.10 to $34.60 per hour. Kawamura (2000) notes that using the revenue-based approach is potentially problematic because "actual behavioral changes under a policy or program are determined by the perceived value of time, the benefit-loss calculations based on this method will be inaccurate except in the cases in which truck operators possess a perfect knowledge of the marginal profit."

With data collected from an SP survey on congestion pricing, Kawamura (2000) found the mean value of truck time to be approximately $30.00 (converted to 2008 dollars). The value of time for California operators varied by carrier and operation types, but not necessarily with respect to shipment weight. Additional findings from Kawamura (2000) are shown in Table B.5. This table shows that carriers whose drivers are paid by the hour have a higher value of time than do carriers who have fixed-salary drivers. In addition, for-hire carriers have a higher value of time than do private operators.

Table B.5. Findings from SP Survey

Truck Operator Type	Value of Time[a]
All trucks	$30.91
Private carrier	$23.25
For-hire carrier	$36.98
Truckload operations	$33.02
Less-than-truckload operations	$29.85
Hourly paid drivers	$33.55
Other pay type	$19.95

Source: Kawamura 2000.

[a] Converted to 2008 dollars.

Smalkoski and Levinson (2005) implemented an adaptive SP survey for carriers and shippers in Minnesota and analyzed their willingness to pay for operations permits during the spring load-restriction period. The mean value of time was \$49.42, with a 95% confidence interval of \$40.45 to \$58.39. The authors were unable to produce value-of-time estimates for different carrier groups, but like Kawamura, they observed that for-hire firms seem to have a "considerably" higher value of time than do other groups.

The FHWA Freight Management and Operations publications have reported the value of time for freight as a range between \$25 and \$200 per hour. The high end of the FHWA range is based on the Small et al. (1999) truck value-of-time estimated range of \$144 to \$192 per hour. Given the likely idiosyncrasy of the estimates from the SP data collected by Small et al. (1999), the upper end on the range for freight mover value of time may be closer to between \$75 and \$100 (with the overall range of truck value of time between \$25 to \$100), and likely not as high as \$200, on average.

The Southern California Association of Governments adopted a value of \$73/hour for use in freight studies based on the FHWA publications. Similarly, after reviewing the literature on the truck value of time, the Puget Sound Regional Council, together with the freight working group at the Washington State Department of Transportation (DOT), adopted truck value-of-time estimates of \$40/hour for light trucks, \$45/hour for medium trucks, and \$50/hour for heavy trucks (Outwater and Kitchen 2008).

Value-of-time estimates derived with a cost-based approach have consistently placed the value of time for freight at around \$25 to \$30/hour, which is primarily based on driver compensation and benefits, with a small fraction of the hourly cost from vehicle depreciation and inventory costs. If one were to include additional shipper value of time costs (in addition to the direct driver time and time-related operating costs), the freight-mover value of time may be closer to \$40 or \$50 per hour and up to \$75 per hour for some freight corridors.

Guidance and Recommended Rates

This section describes the U.S. DOT Departmental Guidance on the Valuation of Travel Time in Economic Analysis (1997b). The U.S. DOT guidance is the basis for the FHWA Highway Economic Requirements System (HERS) value-of-time estimates. This guidance is also used in the FHWA Highway Freight Logistics Reorganization Benefits Estimation Tool (2008).

The empirical basis for the U.S. DOT Guidance on the Valuation of Travel Time in Economic Analysis (1997b) is the clustering of estimates for passenger travelers at around 50% of the hourly wage rate. The U.S. DOT guidance provides the recommended values for the value of time as a percentage of the hourly wage, differentiating values for local passenger personal travel, local passenger business travel, intercity passenger personal travel, intercity passenger business travel, and truck-driver travel. Acknowledging the variation in the value of time estimates found in the literature, the U.S. DOT provides plausible ranges for conducting sensitivity analyses. The values of travel time recommended by U.S. DOT are shown in Table B.6. The value of travel time as a percentage of the wage rate is converted to a dollar value by 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-based approach, with 100% of the full driver compensation recommended for the truck-driver value of time.

HERS uses the value of time for seven vehicle classes: two passenger-vehicle classes and five truck configurations. The value of time is computed by using the U.S. DOT guidance for driver and occupant time plus estimates on the vehicle depreciation cost per hour and the freight inventory cost per hour. Variation in the truck value of time for the different vehicle classes is primarily due to the average vehicle occupancy assumption applied to the driver compensation for each vehicle class. These values are shown in Table B.7.

Table B.6. U.S. DOT Recommended Values of Time in 2008 Dollars

Type of Travel/Traveler	Value of Time (per person-hour as a percentage of wage rate)	National Hourly Wage (or Hourly Median Household Income)	Value of Time (dollars per person-hour)
Passenger travel			
Personal (local)	50% (35%–60%)	\$25.12	\$12.55 (\$8.79–\$15.07)
Personal (intercity)	70% (60%–90%)	\$25.12	\$17.60 (\$15.07–\$22.61)
Business	100% (80%–120%)	\$29.20	\$29.20 (\$23.28–\$34.92)
Freight movers			
Truck drivers (local and intercity)	100%	\$23.30	\$23.30

Table B.7. Value of Time from HERS

Criteria	Automobile		Truck				
	Small	Medium	4-Tire	6-Tire	3- to 4-Axle	4-Axle Combination	5-Axle Combination
Business travel							
Value per person	$29.20	$29.20	$29.20	$23.30	$23.30	$23.30	$23.30
Average vehicle occupancy	1.43	1.43	1.43	1.05	1.00	1.12	1.12
Vehicle depreciation	$1.40	$1.87	$2.45	$3.41	$9.22	$8.25	$7.93
Inventory						$0.79	$0.79
Business travel value per vehicle	$43.16	$43.62	$44.20	$27.88	$32.52	$34.35	$34.02
Personal travel							
Value per person	$12.55	$12.55	$12.55				
Average occupancy	1.43	1.43	1.43				
Percentage personal	89%	89%	75%				
Personal-travel value per vehicle hour	$17.95	$17.95	$17.95				
Average value per vehicle hour	$20.72	$20.77	$24.51	$27.88	$32.52	$35.14	$34.82

Source: HERS-ST 2005 Technical Report.

Note: Costs were converted to 2008 dollars using U.S. DOT guidance for value per person and HERS cost indexes for other cost items.

HERS computes the inventory costs for four- and five-axle combination trucks by applying an hourly discount rate to the average payload value. The payload value is estimated by the average payload weight multiplied by the average shipment value—expressed in dollars per pound for truck shipments. Although the payload for a four-axle combination truck would be lower than the payload for a five-axle combination truck, the value of the commodity shipped may be higher. Thus, the inventory costs for these two truck configuration classes are set to the same value. The inventory costs for lighter trucks (three- to four-axle and six-tire trucks) are assumed to be negligible, and personal vehicles are assumed to not be transporting goods. The HERS inventory costs do not include spoilage costs, damage, or inventory depreciation—only the cost of holding the inventory during transport (HERS 2005, p. 5.5.5). Vehicle depreciation costs are the average dollar value that a vehicle's value declines for each hour of use, adjusted so that mileage-based usage is accounted for separately in the vehicle operating costs.

The HERS value-of-time method for trucks has been adopted for use in the FHWA Highway Freight Logistics Reorganization Benefits Estimation Tool, with modifications made to the inventory-cost method. In the freight logistics tool, the analyst can specify up to five commodities and their value and relative share of freight moving through the corridor. Total inventory cost is then the weighted average reflecting the mix of commodities shipped on the particular roadway.

The U.S. DOT guidance on the value of time is given as a percentage of the wage rate per person-hour. The dollar value per person-hour can be converted to value per vehicle hour by multiplying the value per person-hour by the average vehicle occupancy (AVO) for each user group. Data from the 1995 National Household Travel Survey is used for the passenger travel AVO assumption used in the HERS value-of-time estimates. The AVO for the four-axle and five-or-more-axle combination trucks is based on a study of team drivers. The six-tire truck and three- to four-axle truck AVOs are assumed values.

Although the value-of-time estimates found in the literature take on a range of values, there is a clear relationship between the passenger value of time and wage rate. Several studies also find that the value of time during peak periods is higher than during off-peak periods. The trip purpose, particularly during the morning commuting period, influences the value of time. The recommended values shown in Table B.8 are based on the strongest relationships empirically demonstrated in the literature. These values largely follow the current U.S. DOT guidance. Many regional agencies or state DOTs may have their own values of time that reflect the local wage rates.

With the same hourly rates as in Table B.8 for calculating the hourly value of time from the U.S. DOT guidance, the dollar value of time per person-hour is presented in Table B.9. The dollar value of time per person-hour can be converted to

Table B.8. Passenger Traveler Value of Time as Percentage of Average Wage Rate

Trip Purpose, Time of Day	Value of Time (as percentage of wage rate)	Range of Values for Sensitivity Analysis
Peak period (morning commute)	75%	50%–90%
Peak period (p.m.)	60%	40%–70%
Leisure, other trip purpose	50%	30%–60%
Intercity travel	70%	60%–90%
Business travel	100%	80%–120%

Table B.10. Freight-Mover Value of Time

Freight-Mover Group	Value of Time (dollars per hour)	Range of Values for Sensitivity Analysis
Light truck (Single unit or 6-tire truck)	$30	$30–$55
Medium truck (3- to 4-axle truck)	$50	$40–$75
Heavy truck (4-axle and 5-or-more-axle combination)	$60	$40–$80

value per vehicle by using average vehicle occupancy assumptions to scale the dollar value per person-hour.

The freight-mover value of time, shown in Table B.10, should be based on 100% of the truck-driver wage and benefits, plus the hourly inventory costs. Hourly inventory costs can be calculated as the value of commodities shipped in a corridor divided by the hourly discount rate.

Once the value of time for each user group is developed, the vehicular volume for each user group may be identified so that the value of an increase in reliability can be determined for each group. Volume counts by vehicle class (or truck share of the total volume) are commonly reported and tabulated from traffic recorder data. Truck share of the total volume is often captured from loop-detector data, particularly in freight corridors. Truck volume data can also be derived from Highway Performance Monitoring System data for sample segments.

The 2003 U.S. DOT guidance suggests creating a weighted average for automobile travel by assuming that 94.4% of vehicle miles are personal trips and 5.6% of vehicle miles are business related. Household travel surveys conducted by state DOTs, regional MPOs, or the 2008 National Household Travel Survey are other sources for determining the volume by user group or by trip purpose.

Table B.9. Passenger–Traveler Value of Time

Trip Purpose, Time of Day	Value of Time (dollars per person-hour)	Range of Values for Sensitivity Analysis
Peak period (morning commute)	$18.80	$12.60–$22.60
Peak period (p.m.)	$15.00	$10.00–$17.60
Leisure, other trip purpose	$12.60	$7.50–$15.10
Intercity travel	$17.60	$15.10–$22.60
Business travel	$29.20	$23.40–$35.00

Note: Business travel hourly rate is based on wage and compensation; other trip purposes are based on national median household income following U.S. DOT guidance.

Applying the Methodology

With the options theoretic approach, the costs of unreliability or the benefits of potential reliability improvement strategies can be assessed. By converting uncertain performance metrics to certainty-equivalent values, valuation of reliability improvements can be achieved by simply applying appropriate values of time to the certainty-equivalent delay measure. This can be done for multiple user groups and trip purposes to the extent that the composition of the traffic stream can be determined. To implement this approach, some judgments must be made:

1. The statistical nature of unreliability must be known or assumed. It must be determined whether the unreliability occurs because of events that cause speeds to be distributed lognormally, or by extreme value type, or other distributions. In some cases, it is easier to represent the distribution of the events rather than the highway performance metric (such as speeds or travel times). This is the case in situations in which highway performance metrics are not collected comprehensively over a long period of time, but in which data are available on the events that cause unreliable travel conditions. Formal statistical tests for the goodness of fit, such as the Kolmogorov–Smirnov test, can be used to verify the distribution of the data, in addition to the use of descriptive statistics and visual inspection (e.g., histograms).
2. A time horizon for the evaluation effort must be defined that is appropriate to the reliability measurement process. If a finite horizon to the evaluation is appropriate, then an options formulation can be selected that has a finite life. If a long time horizon characterizes the process that generates unreliability, a perpetual options

formulation may be more appropriate. Thus, one might evaluate recurring congestion phenomena by using short-life options. Rare events (such as bridge failures, flood events, etc.) may require a longer or even perpetual option life assumption.

3. It must be determined whether the unreliability is to be valued only at the end of an assumed time horizon or whether it is to be valued whenever (during the option's life) the unreliability is to occur. European option formulations are appropriate for the former, and American options formulations are appropriate for the latter.
4. After the appropriate framework for valuation is determined, data must be assembled. These data should identify the necessary probability distributions.

In summary, the options formulation will be determined from the frequency of the phenomena addressed by the strategy, the data availability for the roadway and event type being evaluated, and the statistical distribution displayed by the data. For typical recurring events and for very rare events, the choice of options formulation may be obvious. In the case of rare events, speed data will often not exist, and the options formulations for recurring events will not be appropriate.

Given an identified treatment or policy to improve reliability and the necessary options formulas and data, the unreliability processes can be converted into certainty-equivalent measures and treated as deterministic, rather than probabilistic. Application of the appropriate values of time then provides a method for comparing the value of unreliability with and without implementation of the treatment or policy to improve reliability. The reliability benefit from a particular treatment or policy is then determined by comparing the value of unreliability without the treatment to the value of unreliability with the treatment.

The change in the total value of unreliability is determined by calculating the present value of the benefit from implementing the treatment. To conduct a benefit-cost analysis of the treatment or policy, the benefit from the strategy is then compared to the present value of the cost of implementation and the annual maintenance or operations costs of the treatment or policy. The annual outlays associated with the treatment or policy must be discounted to their present value, just as the annual benefits from improvement reliability are discounted to their present value. Strategies with the highest benefit-to-cost ratio will provide the greatest level of benefits when compared to the strategy implementation and maintenance costs for the lifetime of the project. When comparing alternative treatments and policies, the evaluation should use the same discount rate for computing the present value of the treatment benefits and costs and use similar time frames.

Comparison of Methodologies for Valuation of Travel Time Reliability

The options theoretic approach is a new approach for the valuation of travel time reliability. The typical approaches to the valuation of travel time reliability are based on discrete choice models that use SP or RP data. Given the limited number of natural experiments that allow for the collection of RP data, the majority of this work has tended to focus on SP survey data. Comparing the options theoretic method to RP and SP approaches is useful, given that most of the research in this area has been conducted using the RP-SP empirical approaches. This section presents the following:

- A discussion of some conceptual and practical considerations of relying on the RP-SP approach. Some of these considerations call into question the practical utility of the RP-SP approach.
- A numerical comparison of the value of reliability of the options approach and that estimated by the RP-SP approach. For the latter, the estimates produced by Small et al. (2006) are used. With their data, the necessary parameters to implement the options theoretic approach are computed with the same speed distribution and values of time in their paper.

Conceptual Considerations in Relying on RP or SP Methods

Numerous aspects of the RP-SP approach make reliance on this method problematic in practice. Some of the contrasts between the options approach and RP and SP approaches are the following:

- The RP and SP approaches are not economical to apply, requiring costly studies for application. Putting aside any general skepticism about the reliability of SP procedures in particular, even this method is relatively costly to implement and subject to the same statistical issues and biases that creep into interview-based contingent valuation, conjoint, and similar analyses.
- The RP and SP approaches are not agnostic procedures free of functional form assumptions akin to those of the options approach. In particular, these approaches implicitly adopt utility function specifications that are usually asserted, rather than demonstrated. The function form is usually linear in its arguments (or some nonlinear specification to introduce risk aversion). This is analogous, in a mathematical sense, to the Black–Scholes approach, which employs assumptions about risk, too. In its simplest expression, Black–Scholes assumes risk neutrality, but has been shown to be robust to the assumption of risk aversion.

- The RP and SP analyses usually also postulate a fairly specific characterization of the context of unreliability—for example, that it arises out of a particular manifestation of a scheduling–cost problem, and so forth. The options theoretic approach is no more restrictive; it simply postulates that there is a willingness to pay for insurance (hypothetically) that compensates drivers for not experiencing below-average speeds that are, in turn, drawn from a lognormally distributed delay process.
- A major difference is that the options theoretic approach allows separation of the value-of-time issue from the "real" unreliability issue. Because the existing travel models carry values of time internally for other purposes (mode choice and traffic assignment), the RP and SP approaches (typically confounding time–time savings valuation and traffic variability) are harder to integrate into the modeling suite. In contrast, the options approach allows unreliability to be introduced directly into traditional, volume-delay specifications used in travel model platforms. Given that the primary empirical input of the options approach is speed-distributional information, it imposes light additional burdens on the modeler. The required data on speed variations are plentiful, easily calculated from loop-detector histories, and can be made idiosyncratic to individual network links. For the same reason, the options approach is friendlier in microsimulation model settings.

Numerical Comparison

A numerical comparison demonstrates that the options theoretic approach yields values of unreliability similar to the RP-derived estimates of Small et al. (2006).

The additional complexity and cost of measuring and implementing measures derived from RP and SP would be worthwhile, perhaps, if the simpler and less-demanding options approach yielded vastly different measures. In fact, however, the measures are virtually indistinguishable. This is demonstrated below by comparing an options measure to that derived in Small et al. (2006). This work is a highly regarded implementation of the RP-SP approach.

Small et al. (2006) used a mixed logit model with both RP and SP data from the unique setting of California's SR-91 express lanes. This setting is unique because a driver using the congested general-purpose lanes can pay a toll and enjoy both a faster speed of travel and (an assumed) zero variability in travel speed. This allowed the authors to estimate both the value of travel time savings and the value of unreliability. Using the RP data, they measured the value of travel time at $21.46/hour (93% of the average wage rate). The study was conducted under 4-hour a.m. peak conditions, which expose general-purpose lane users to considerable volatility in speeds and travel times. Under the conditions in place, the Small et al. model yielded a value of unreliability of $19.56 per hour. When applied to the 10-mile segment of SR-91, the value of unreliability was then measured to be $0.52 (for the 10-mile segment).

The Small et al. (2006) paper provides enough information to enable measuring the volatility of speeds in a manner compatible with the options theoretic approach. Specifically, the median speed on the general-purpose (free) lanes is reported to be 53 mph. The corresponding 20th percentile speed (imputed from the 80th percentile travel time, in minutes) is 46 mph. These speed data, combined with the assumption of a lognormal distribution of speeds, yield a log mean speed of 3.9703 and the log standard deviation of speed of 0.1683. With use of the log standard deviation and the assumption of a 5% discount rate (to which the calculations are very insensitive), the put option value can be calculated for an option whose life lasts long enough for the traveler to traverse the 10-mile facility.

All that remains to be done is to hypothesize the "speed guarantee" appropriate to this setting. In this report's characterization of unreliability, the average speed experience of travelers, measured over time, is taken as the speed against which they measure unreliability and so is the desired "guaranteed" speed. Unfortunately, Small et al. (2006) did not know the average speed experience at the various times their RP sample traveled. What they knew was the median speed over the entire 4-hour a.m. peak (53 mph). However, various speed guarantees in the options formula can be tested to see what speed guarantee corresponds to Small et al.'s revealed $0.52 value of reliability over the 10-mile facility. That speed is 57 mph.

Alternatively, by using the 53-mph peak-period median value as the guaranteed speed (though not the correct datum for the options approach), the value of reliability calculated by the options approach is $0.29. Measured either way, it is clear that the options approach and the RP-SP approach yield quite consistent values. Indeed, Small et al. (2006) also estimated an SP model, which produced a value of reliability much smaller than the estimate based on RP. Given the computational cost and flexibility of the options approach, it is clear that it is a valuable method of evaluating travel unreliability.

Conclusions for the Options Theoretic Approach

This appendix presents an options theoretic approach for the valuation of travel time reliability. Options theory is a well-established methodology from the field of financial economics used for the valuation of assets in the presence of uncertainty. Although options theory in finance deals with the dollar value of financial instruments, real options deal with stochastic variables when quantities are measured in terms of real units, such as time or actual commodities.

Given the novel approach developed in this research, an extensive review of the options theoretic approach was performed by a number of expert reviewers. Experts on options theory and finance were consulted; they provided multiple rounds of review of the appropriateness and validity of the approach. Expert reviewer comments largely focused on the mapping of the travel time reliability option formulation to the analogous elements in the Black–Scholes formula. Use of an insurance option for travel time variability is a rather original application of options theory for the valuation of travel time reliability, as suggested by the reviewers. However the use of real options and these techniques is not new in the context of transportation. The reviewer comments and responses are summarized below. Given the unfamiliarity with such methods and questioning of the approach because of its highly mathematical nature, it is suggested that a workshop or conference highlighting the use of various financial techniques in the transportation field will help to advance the understanding and application of these methods.

The options theoretic approach for the valuation of travel time reliability is an option formulation that determines the option value for travel time reliability in terms of the travel time that roadway users would be willing to sacrifice to obtain a speed guarantee. With the certainty-equivalent of delay, practitioners can compute the value of reliability for multiple user groups, by using well-established values of time with the deterministic value associated with travel time reliability.

An advantage of the options theoretic approach is that it is a robust and compact method that can be tailored to reliability analysis for specific roadways and the observed travel time variability on them. Unlike SP surveys, the options theoretic approach is not based on fixed idiosyncratic data. The options theoretic approach can be generalized to travel time variability experienced on other roadways or in other regions. It uses readily available traffic data. This method converts a stochastic variable (travel time) into a certainty-equivalent measure that can be treated deterministically in the evaluation of a project or operational treatment.

A limitation of the options theoretic approach is that the formula is inappropriate for analyses in which travel time variability cannot be characterized by a lognormal distribution. Determining which options formulation should be used for specific analyses (particularly for rare events) poses a potential challenge to the implementation of this methodology by public agencies, particularly if analysts are unfamiliar with travel time distributions and benefit–cost evaluation frameworks.

In Appendix C, the rare-event formulation for incorporating the valuation of reliability into investment decisions is presented. The rare-event approach was developed to investigate an approach for the valuation of travel time reliability for rare events, and as an approach for optimal investment decision making, given the uncertainty related to low-probability, high-consequence events.

Summary of Reviewer Comments and Responses

Comment 1

One can create many different classification schemes within the field of options and financial derivatives. However, in view of the need to impute dollar values to improvements in travel time reliability in Project L11, the literature suggests three relevant classes:

1. Financial options: These are concerned with valuing a financial asset given the underlying price, the strike price, the time to expiration, the volatility (variability), and the risk-free interest rate.
2. Real options: These relate to the valuation of one or more contingencies that unfold over time, such as a decision to proceed with Phase 2 of a project after making a positive feasibility determination under Phase 1.
3. Valuing insurance contracts: These refer to what a buyer of insurance is willing to pay for an insurance contract based on the present value of expected loss.

Each of these approaches is indicative of how one might value improvements in travel time reliability. None by itself appears to be strictly applicable, and none may be possible without using supplemental techniques to evaluate how road users trade off reductions in the variability in travel time against reductions in average travel time and out-of-pocket costs.

Response 1

The comment presents a useful taxonomy for the types of options. Our travel time reliability option formulation is derived from options representations of insurance. In other words, the basic insight of the approach is that one can think of unreliability as analogous to the occurrence of an undesirable outcome in some random event context (e.g., an accident that impairs the value of a car). In an auto insurance context, one can think of the insurance policy as a mechanism for compensating the driver for any lost value due to an accident during the life of the contract. Carrying this notion over to travel time reliability, one can imagine that an insurance policy could be crafted that compensated the driver for the unexpected occurrence of speeds below the expected (average) speed. Such a policy does not exist for daily vehicle travel, although such policies do exist for long trips (e.g., an accident that impairs the value of a car). In an auto insurance context, one can think of the insurance policy as a mechanism for compensating the driver for any lost value due to an accident during the life of the contract. Carrying this notion over to travel time reliability, one can imagine that an insurance policy could be crafted that compensated the driver for the unexpected occurrence of speeds below the expected (average) speed. Such a policy does not exist for daily vehicle travel, although such policies do exist for long trips (e.g., overseas travel insurance). So, if one accepts that the concept of speed insurance makes sense, then the Black–Scholes formulation we are using makes sense, and one can calculate the speed-equivalent "premium" to be assured compensation for encountering speeds less than the mean (expected) speed.

Comment 2

The question is whether the Black–Scholes option pricing equation can be used to value a decrease in the variability of travel times over a specified road segment. As I read your report I had two questions in mind: First, is the Black–Scholes model applicable? Second, have you applied it correctly? My answers are yes and yes.

Response 2

We agree with the reviewer that the Black–Scholes model is applicable to the problem of travel time variability, and we believe that this model has been appropriately applied.

Comment 3

How to justify applying any interest rate (growth rate) to travel speed (or time) in the way used in the model and how to select the value of this interest rate for travel speed (or time)?

Response 3

A finite and fixed option life (insurance contract life) is necessary to derive a value of the insurance premium or option value. The assumption to apply an interest rate (growth rate) is arbitrary (although less so than assumptions of other approaches that assume that all that matters in measurement of reliability is the probability of tail events).

Comment 4

It appears that the value of r is arbitrarily set; and there does not seem to be any justification for it. The example sets the value of r to be 5% (or 3%). A 3% to 5% interest rate is commonly used when considering money because this range is close to the historical interest rates people could get by putting their money in something like a bank account with guaranteed interest rate. However, it is not clear how to justify the assumption that the travel speed will grow at any rate with certainty over $T - t$ time along the target road segment. If we can properly justify applying a guaranteed interest or growth rate r to travel speed, then the value of r will need to be determined carefully because the result of the model depends heavily on the value of r.

Response 4

The value of the interest rate used in the formulation should be the real, annual riskless rate of return. This rate varies somewhat with macroeconomic conditions but should reflect the real discount rate the market is applying to value funds received in the future versus today. This is also called the "time value of money" in finance parlance. The reviewer is correct that the interest rate in the implementation of the Black–Scholes formula should be a low, single-digit annual rate in the vast majority of macroeconomic settings.

Comment 5

"Real options" is a specific branch of options evaluation. It does not concern financial assets, but rather, other tangible assets in which the value of the option depends upon one or more contingent events. Examples are raising tolls at such time when traffic volumes reach a certain level, investing in the next stage of drug development assuming preliminary drug trials are successful, pursuing a line of research once a positive feasibility determination has been made, and developing the next component of a modular electronics platform once the market for additional modules has been established. In each of these examples, the value is conditional upon an event occurring in the future or upon a condition state being realized. The term "real options" for the most part has a specific meaning among those who are expert in this branch of financial analysis. It is possible that the semantic elasticity of the term "real" options allows it to be applied to valuing travel time reliability. However, one of the country's leading experts on real options whom we consulted does not think this approach is applicable to valuing travel time reliability.

Response 5

The reviewer is correct that the term "real options" is commonly used in a capital budgeting context and that this setting involves real (versus financial) assets. Others, however, make the distinction between whether the option is purchased or arises naturally in the course of decision making under uncertainty. Still others distinguish between whether the option is tradable or not. We know of no one else who has studied travel time reliability using the options approach, so it is not clear what is the proper terminology to use. However, Professor Lenos Trigeorgis, a well-known expert in the field of real options analysis, applied the real options term in an analogous setting, that is, a decision to increase flexibility of production processes as a defense against exchange rate variability. (In this case, value arose from increasing flexibility.)

Comment 6

The original option model was developed to determine the price of traded financial options such as call options, which give the right to buy shares of common stock at a fixed price in the future, or put options, which confer the right to sell shares of common stock at a fixed price in the future. The classic derivation depends on the ability to form so-called arbitrage portfolios of traded securities that hedge out the stochastic component of the prices. In the Black–Scholes case, the other key assumption is that the markets are complete, which roughly means that traded securities can span the uncertainty. The original option pricing model has been extended along different dimensions in a variety of ways. For example, the original model has been modified to handle different stochastic assumptions regarding the underlying securities and deal with complicated derivative structures. In addition, the range of application has been extended to value real options, such as the option a mining firm has to open or close a mine. It has also been applied to value certain features of insurance contracts. However, in this case, successful applications relate to the valuation of embedded financial options in insurance and annuity contracts rather than the basic insurance per se. For example, a policyholder under an equity-indexed annuity may participate in the upward moves of the S&P 500 Index and also benefit from downside protection in case the market value falls below an initial investment. These features are routinely valued by using a combination of call and put options on the S&P Index. A standard insurance contract, such as a reinsurance policy on a house, has a payout that resembles the payout on a put option. In the case of the fire insurance contract, the premium is paid up front, and the benefit is equal to the fire damage if any. The fire damage can be viewed as the difference between the value of the house before the fire minus the value after the fire. In the case of a European put option on a financial security, the investor pays the option premium at inception and receives a benefit equal to the difference between the option strike price and the market price of the security when the option matures. While the two contracts are similar in some aspects, they are priced in different ways using very different paradigms. The insurance contracts are priced by actuarial methods that are based on historical statistics and underwriting. The put option is priced using a Black–Scholes type model.

Response 6

Real-world contracts (mortgages, insurance, options on tradable securities, etc.) have features that do, indeed, complicate the valuation exercise. However, it has long been recognized that an insurance contract is fundamentally a put option. Actuarial complexities arise because of the need to measure such things as the distribution of life expectancy, accident rates, etc., and to consider and contain adverse selection distortions. Our modeling of the value of insurance against traveling slower than the expected speed is focused on determining the underlying value of such insurance if it existed. We are *not* modeling how rates would be set if I were imagining starting a commute-trip insurance business. It is the underlying value of the risk (not the operating challenges of insurers, etc.) that is of interest.

Comment 7

Reliance on normal/lognormal distribution—again this is fairly standard in option theory in order for the pricing to be tractable. The appendix would benefit from greater demonstration that this assumption is appropriate for the types of data likely to be used. In particular, formal tests (e.g., a Kolmogorov-Smirnov test) could be employed to evaluate the assumption and identify the sensitivity of the results to departures from this assumption.

Response 7

The authors agree with and appreciate the comments of this reviewer. The only response we offer concerns the reliance on assumption of lognormality in the simpler (recurring events) setting. Although it is true that little formal testing of the lognormality of speed data goes on, it is a widely appreciated feature in practice. Vehicle counting systems, such as PeMS, TRAK, and others, are installed in thousands of locations on U.S. highways. These systems produce large quantities of high-resolution traffic volume and speed data, and the lognormality of the distribution of speed is accepted as commonplace. This does not mean that testing for compliance with this assumption should not be done, of course. Analysts can be instructed to use statistical testing methods to confirm the distribution of their data.

Additional citations were added to the appendix to support the appropriateness of our method in the transportation context. For example, SHRP 2 L03 cites Rakha et al. (2006), which confirms the use of lognormal distribution for speed in the context of travel time reliability.

Comment 8

By assuming that "recurring and rare phenomena arise out of processes with very different stochastic properties," the authors are proposing using a mixture of distributions to characterize events that affect time travel reliability. One of the difficulties in using mixtures is identifying the point at which the distributions should be joined; there is no discussion of this in the appendix. The justification for using mixtures is that while recurring events, for which there is often ample data for analysis, might be well characterized by a normal distribution, rare events tend to fall into an extreme tail that would result in an overall distribution that has very fat tail.

Response 8

The authors appreciate and agree with these comments. Ignoring the prospect of rare events, and using pure Gaussian assumptions instead, is at the heart of many financial and engineering catastrophes, including long-term capital, and elements of the current financial crisis. One of the reasons that we distinguish between recurring and rare events in our discussion is to draw attention to the rare-event issue. Unfortunately, implementation of strategies to protect against rare events in a cost-effective way is very difficult because of the problem of characterizing the event distribution and the complexity of mathematically representing the proper investment strategy. This is especially challenging in the setting of highway infrastructure development and operation. We feel the best we can do in a paper such as this is to highlight the issue, offer the skeleton of a methodology, and provide citations to (the very few) papers that hint at how to embed an investment strategy in a rare-event setting.

Comment 9

My main comment concerns the travel time reliability valuation issues. Although the proposed methodology for measuring the value of reliability using option values is innovative. The use of this methodology for this issue is new. From a scientific point of view this is very interesting. But in my opinion, the research does not fully address the question of whether the approach can be applied for transportation phenomena. Therefore, this approach presents a risk. To "prove" that the methodology will yield appropriate values for probabilities of travel times will require a lot of empirical research and comparison with methodologies currently applied elsewhere in the world (Norway, the Netherlands, United Kingdom, etc.). Without such work, it is very risky to incorporate the methodology as *the* standard procedure to be applied.

Response 9

The thrust of this comment is that it urges us to compare the options theoretic approach with stated- and revealed-preference approaches to "prove" the appropriateness or validity of the results obtained from the options theoretic approach. Comparing the approaches is a useful suggestion because most folks working in this area are toiling away to develop unreliability valuations using the latter two empirical approaches.

The contrasts between the two approaches are the following:

1. The RP and SP approaches are probably impractical methods for widespread application of reliability valuation. This is because they are not economical, requiring separate studies for each application. Even putting aside my general skepticism about the SP techniques, even that approach is relatively costly to implement and subject to the same statistical issues and biases that creep into interview-based contingent valuation, conjoint and similar analyses.
2. The RP and SP approaches implicitly adopt utility function specifications that are certainly debatable in their mathematical form (usually linear in its arguments or some nonlinear specification to introduce risk-aversion). Hence, they are no more agnostic than the Black–Scholes approach which technically assumes risk-neutrality, but have been shown to be robust to the assumption of risk-aversion.
3. The RP and SP analyses usually also postulate a somewhat specific characterization of the context of unreliability—for example, that it arises out of a particular manifestation of a scheduling-cost problem, etc. The options theoretic approach is no more restrictive; it simply postulates that there is a willingness to pay for insurance (hypothetically) that compensates drivers for not experiencing below-average speeds that are, in turn, generated from draws from a lognormally distributed delay process.
4. A major difference (which I see as an advantage of the options theoretic approach) is that the value of the real option allows separation of the value-of-time issue from the real unreliability issue. Since the existing travel models carry values of time internally for other purposes (mode choice and traffic assignment), the RP and SP approaches (having confounded time valuation and traffic variability), are harder to integrate into the modeling suite. In contrast,

the options approach allows unreliability to be introduced directly into traditional, volume-delay specifications used in travel model platforms. Since its primary empirical input is speed-distributional information, it imposes light additional burdens on the modeler. The required data on speed variations is plentiful, easily calculated from loop-detector histories, and can be made idiosyncratic to individual network links. For the same reason, the approach is friendlier in micro simulation model settings.

Comment 10

Because the experts we consulted differ on the validity of applying Black–Scholes to valuing reductions in travel time variability, SHRP 2 Reliability staff held a number of supplemental conversations to determine under what circumstances Black–Scholes might continue to be useful. Both a member of SHRP 2 staff and one of the reviewers suggested that the options theoretic approach might be useful for ranking different ways to improve travel time reliability even though one cannot be confident that calculated values from Black–Scholes have absolute meaning.

Response 10

We believe that the measurement technique proposed is much more consistent and transparent than one-off SP or RP findings. The value of travel time is already a necessary input to the travel demand modeling process; our work simply extends the application of those time values to time-certain equivalents of variables measures. Empirically, experienced travel modelers such as Blaine have observed that traffic assignment became more realistic when our measure of the "impedance" of volatility was included in link impedance specifications (for freeways).

Comment 11

Reliability Project L11 brings to the attention of practitioners and decision makers an analytic method that often is superior to traditional discounted cash flow or discounted present value analysis. This is a valuable silver lining of this research and represents a contribution to the field even if a consensus cannot be reached on the validity and applicability of the options theoretic approach to imputing the economic value of improvements in travel time reliability.

Response 11

This method is a contribution to the field, and we also feel that the approach provides advantages over the SP and RP methods, as detailed in this appendix.

Recurring-Event Reliability Valuation Example

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.–10:00 a.m.). This facility is 10 miles long, running north and 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 B.5. The large dip in speed at 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 were implemented. This would help the agency to perform a benefit-cost analysis for the strategy and decide whether it is worth implementing.

Solution

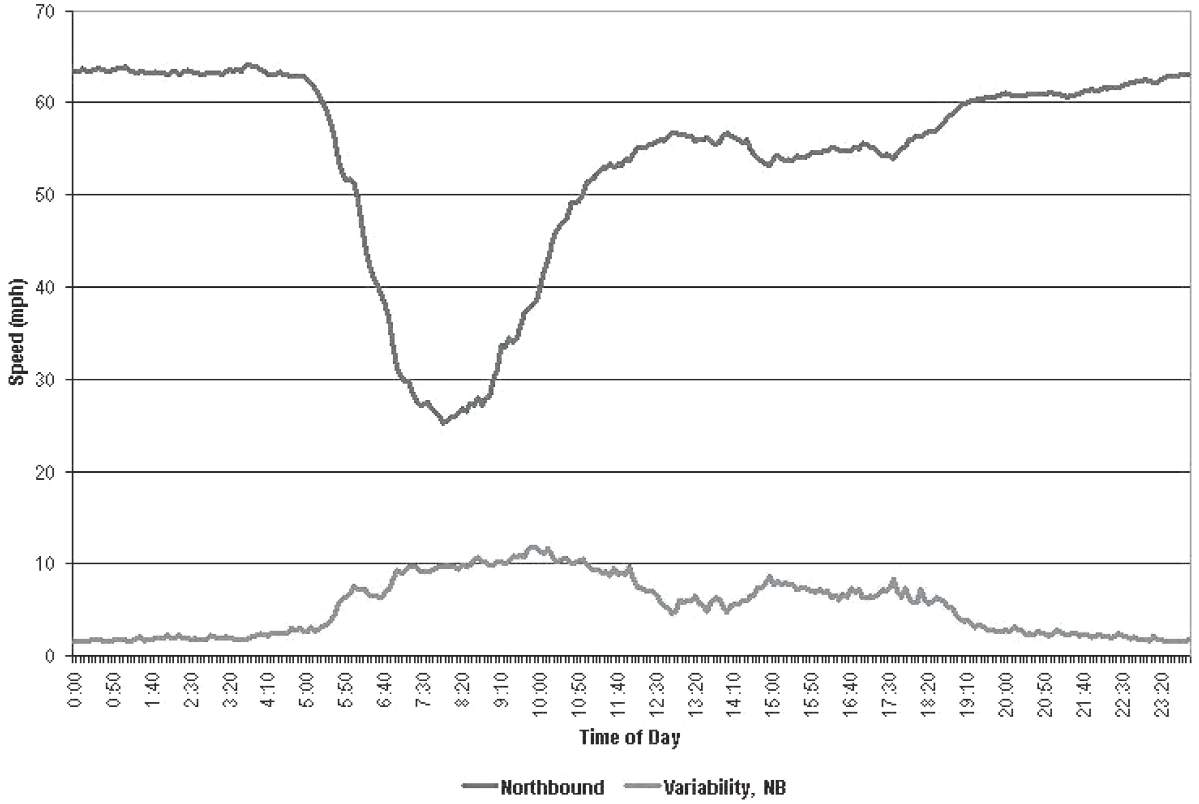
The variability in the a.m. peak period in the northbound direction on the facility generates costs that are borne by the users of the facility. The cost of the travel time variability can be converted to a certainty-equivalent value, which indicates the additional time motorists are willing to spend on the facility if only the variability in travel times could be eliminated. This certainty-equivalent value of unreliability can then be converted to real-dollar values by applying the user's value of time.

- Data needs
  - High-resolution speed data; and
  - Volume data by vehicle type.
- Cautions
  - Applicable to data for which travel time variation can be suitably characterized by the lognormal distribution.

The steps involved in the calculation are outlined below.

Step 1: Characterize the Recurring Congestion Problem

A. Obtain speed data for each 5-minute interval (or other appropriate interval) (Table B.11).
B. Calculate the average speed and the standard deviation of the log of speed.



Note: NB = northbound.

Figure B.5. Diurnal speed and speed variability.

C. Construct the lognormal distribution with the log mean and log standard deviation of the speed to confirm that the speed data are lognormally distributed.

Step 1A

Table B.11. Speed Data at 5-Minute Intervals

Date	Time (a.m.)					
	6:00	6:05	6:10	....	9:50	9:55
1/2/2007						
1/3/2007						
.....						
.....						
.....						

Step 2. Calculate the Certainty-Equivalent Value of Unreliability

A. Choose the appropriate option formulation (European put or American put option).

B. Determine the risk-free interest rate to be used in the analysis.

C. Calculate the contract length, based on the lowest 1% speed.

D. Calculate the certainty-equivalent value of reliability for the roadway by using the options formula.

E. Convert the certainty-equivalent value from mph to minutes per mile.

Step 2A

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

- The European put option gives us 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 give 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 lognormally, as is the speed data on a facility leading to a fitting application.

Step 2B

A value of 5.00% risk-free interest rate is chosen. Thus, $r = 0.05$.

Step 2C

The contract length $(T-t)$ is calculated as the travel time to cover the segment under consideration at the lowest 1% speed, which is determined by 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.

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

Step 2D

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

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

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

where

V_T = the desired speed = 32.67 mph, and

I = the 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:

$$N(d_1)=N(0.18175)=0.4279$$
$$N(d_2)=N(-0.18174)=0.57211$$

$$\begin{aligned}P(V_T,t)&=Ie^{-r(T-t)}N(d_2)-V_TN(d_1)\\&=32.67e^{-0.05(0.000086)}(0.57211)-32.67(0.4279)\\&=4.71\text{ mph}\end{aligned}$$

A commuter is willing to accept a reduction of 4.71 mph in his or her average speed to eliminate the travel time variability.

Step 2E

The new average speed at which the commuter is willing to travel if unreliability is eliminated = 32.67 − 4.71 = 27.96 mph.

- Time to cover 1 mile at old average speed $=\frac{1}{32.67}\times$ 60 minutes.
- Time to cover 1 mile at new average speed $=\frac{1}{27.96}\times$ 60 minutes.
- ∴ The certainty-equivalent time per mile that the user is willing to "pay" to eliminate unreliability is given by $P(V_T, t)=\left(\frac{1}{27.96}-\frac{1}{32.67}\right)\times 60=0.31$ minutes per mile.

Step 3. Evaluate the Change that Affects Unreliability

A. Estimate the expected reduction in speed variability achieved through the implementation of the strategy.

B. Calculate the certainty-equivalent value for the new scenario.

Step 3A

"Smart" systems, including collision-warning systems and systems that automatically adjust cruise-control speed from the relative distance of the car ahead, can reduce speed variability and travel time unreliability as they become widely adapted in vehicles. It is estimated that the new system would reduce the speed variability, α, by 50%.

Assumptions for the new scenario:

- Vehicle volume remains constant over time.
- Unknown speed (V_T) = 32.67 mph.
- Guaranteed speed (I) = 32.67 mph.
- $\alpha=0.5\times 0.3635=0.1817$.

Step 3B

The European put option and a 5.00% risk-free interest rate are chosen. Thus, $r=0.05$. The lowest 1% speed is now 20.18 mph because of the change in the travel time variability. Therefore, the new contract length is given by

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

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

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

Perform intermediate and final option value calculation:

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

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

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

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

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

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

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

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

$$= 2.37 \text{ mph}$$

Thus, the new certainty-equivalent value in minutes per mile is

$$P(V_T, t) = \left(\frac{1}{30.3} - \frac{1}{32.67}\right) \times 60 = 0.14 \text{ minutes per mile.}$$

Step 4. Calculate the Road-User Value of Reliability Change

A. Determine the value of time for different vehicle classes.
B. Calculate the value of the reliability improvement for each vehicle class.
C. Calculate the value of reliability improvement for the average a.m. peak hour.
D. Calculate the total annual value of the reliability improvement over the length of the highway for all user groups only for the average a.m. peak hour.

Step 4A

In Table B.12, volume is equal to the average a.m. hourly volume (over 4 hours for a three-lane facility).

Table B.12. Value of Time for Different Vehicle Classes

Vehicle Class	Volume	Value of Time ($/minute)
Single occupancy	11,484	0.30
High occupancy	2,871	0.60
Truck	1,595	0.83

Value of reliability improvement

- Single-occupancy vehicles = 11,484 × 0.30 × (0.31 – 0.14) = $585.68 per mile.
- High-occupancy vehicles = 2,871 × 0.60 × (0.31 – 0.14) = $292.84 per mile.
- Trucks = 1,595 × 0.83 × (0.31 – 0.14) = $225.05 per mile.

Step 4B

- Total length of the highway = 10 miles.
- ∴ Total value of reliability improvement for the average a.m. peak hour = ($585.68 + $292.84 + $225.05) × 10 (miles) ≈ $11,036.

Step 4C

- Total annual value of reliability improvement = 252 weekdays/year.
- ∴ Total value of reliability improvement per year (average a.m. peak hour) = $11,036 × 252 days ≈ $2,781,000.

The annual value of reliability improvement could be compared to the annual costs of the strategy or improvement in a benefit-cost analysis.

It is important to note that these savings are for the average a.m. peak hour only and not for the entire day. This example could be repeated for other periods of the day when the speed and variability can be appropriately aggregated, as was done for the a.m. peak period in this example.

APPENDIX C

Valuation of Travel Time Reliability for Rare Events

Valuing Reliability for Rare Events

In this appendix, options theory from financial economics is again applied to the problem of unreliability, this time in the context of rare events and the decision to invest given a low-probability but high-consequence event. Some events that influence the performance of the highway network are considered to be rare events. For example, an important challenge for highway agencies is how to mitigate interruptions in service owing to road closure by avalanche, flooding, or bridge failure. Valuing unreliability generated by rare events is influenced by the following considerations:

- The occurrence of rare events is not believed to be accurately characterized by random draws from a normally distributed variable. The rare-event distributions are more complex mathematically, making it more difficult to perform the necessary option value calculations.
- Longer time periods often must be examined to properly identify the parameters of the statistical distributions that characterize the event probabilities.
- Transportation network unreliability may not be directly associated with rare events because a long history of system performance data may not exist.
- The impacts caused by rare events may be more complex than those that affect the variability of speed on a few network segments. Some segments may be closed for extended periods of time. Thus, the travel delays that occur may result in travel path diversions, rather than simply changing the variability of speed on the segments that are affected.
- The time horizon for the transportation agency to make plans for dealing with rare events is often much longer than the time horizon for dealing with a recurring event.

These considerations do not always arise. Events that are not normally distributed may contribute to unreliability on a regular basis. However, most rare events are associated with phenomena such as severe flooding, rare weather events, structural failures, and other events that occur infrequently.

Using Extreme Value Functions to Characterize Rare Events

A class of distributions known as extreme value (EV) distributions is thought to represent the incidence of rare events better than do normal distributions. EV distributions tend to have probability density functions that are quite asymmetric. Much of the weight of the distribution is clustered at low-outcome values. In addition, EV distributions tend to have long tails that are fatter than the upper tail of a normal distribution. These EV distributions represent a situation in which, on most days, an event does not occur that affects reliability in a significant way. However, on rare occasions, an event does occur that affects reliability in a dramatic fashion.

The EV distributions used to characterize rare events are referred to as Type I, II, and III distributions and are also known as Gumbel, Fréchet, and Weibull distributions, respectively. Each of these distributions is a variation of the generalized extreme value (GEV) distribution, differing only in their parameter values, but having very different shapes:

- The Gumbel distribution is unbounded and can have its mass either in the lower or upper portion of the distribution.
- The Fréchet distribution, in contrast, has most of its mass at low values, has a lower limit, and has an unlimited upper tail.
- The Weibull distribution has most of its mass in the upper tail of the distribution and takes on a maximum value.

The GEV probability density function formulation is presented in Equation C.1. It has three parameters: location (μ), scale (σ), and shape (ξ), which can be used to distinguish the three distribution types. Similar to the mean and standard deviation of a normal distribution, the location parameter μ determines the "location" of the distribution and shifts the distribution to the right or left, without changing its shape. The scale parameter

σ determines the spread of the distribution. The shape parameter ξ controls the shape of the distribution—in particular, the tail behavior of the distribution.

$$f(x;\mu,\sigma,\xi)=\frac{1}{\sigma}\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{(-1/\xi)-1} e\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]\right\} \tag{C.1}$$

where

$$1+\xi(x-\mu)/\sigma>0$$

and

μ = location parameter
σ = scale parameter
ξ = shape parameter

and where

x is a random variable, distributed GEV

$$P(I,t)=e^{-r(T-t)}\left\{\begin{array}{l} I\left(e^{-h^{-1/\xi}}-e^{-H^{-1/\xi}}\right) \\ -V_0\left(\begin{array}{l}(1-\mu+\sigma/\xi)\left(e^{-H^{-1/\xi}}-e^{-h^{-1/\xi}}\right) \\ -\dfrac{\sigma}{\xi}\Gamma\left(1-\xi,h^{-1/\xi},H^{-1/\xi}\right)\end{array}\right)\end{array}\right\}$$

where

$$H=1+\frac{\xi}{\sigma}\left(1-\frac{I}{V_0}-\mu\right)$$

$$h=1+\frac{\xi}{\sigma}(1-\mu)$$

and where

μ = the location parameter of the estimated EV function
σ = the scale parameter of the estimated EV function
ξ = the shape parameter of the estimated EV function
$\Gamma(\ )$ = the incomplete gamma distribution

Figure C.1 illustrates the standard shapes of the respective distributions for $\mu = 0$, $\sigma = 1$, and $\xi = -0.5$ (Weibull), $\xi = 0.5$ (Fréchet), and $\xi \to 0$ (Gumbel). Because these are the standard distributions, they are located over zero and have a standard scale parameter of 1, with the lower bound for the Fréchet distribution at −2 and the upper bound for the Weibull distribution at +2. For rare events, the Fréchet or Gumbel distributions have the most-appropriate shapes in that most of the mass will occur at the lower tail of the distribution and the extreme observations will occur in the upper tail. In practice, the Gumbel distribution is the one that is most widely used to characterize rare events because it can be estimated with a two-parameter specification (location and scale). The Gumbel probability density function is presented in Equation C.2.

$$P(I,t)=e^{-r(T-t)}\left\{\begin{array}{l} I\left(e^{-h^{-1/\xi}}-e^{-H^{-1/\xi}}\right) \\ -V_0\left(\begin{array}{l}(1-\mu+\sigma/\xi)\left(e^{-H^{-1/\xi}}-e^{-h^{-1/\xi}}\right) \\ -\dfrac{\sigma}{\xi}\Gamma\left(1-\xi,h^{-1/\xi},H^{-1/\xi}\right)\end{array}\right)\end{array}\right\} \tag{C.2}$$

where

$$H=1+\frac{\xi}{\sigma}\left(1-\frac{I}{V_0}-\mu\right)$$

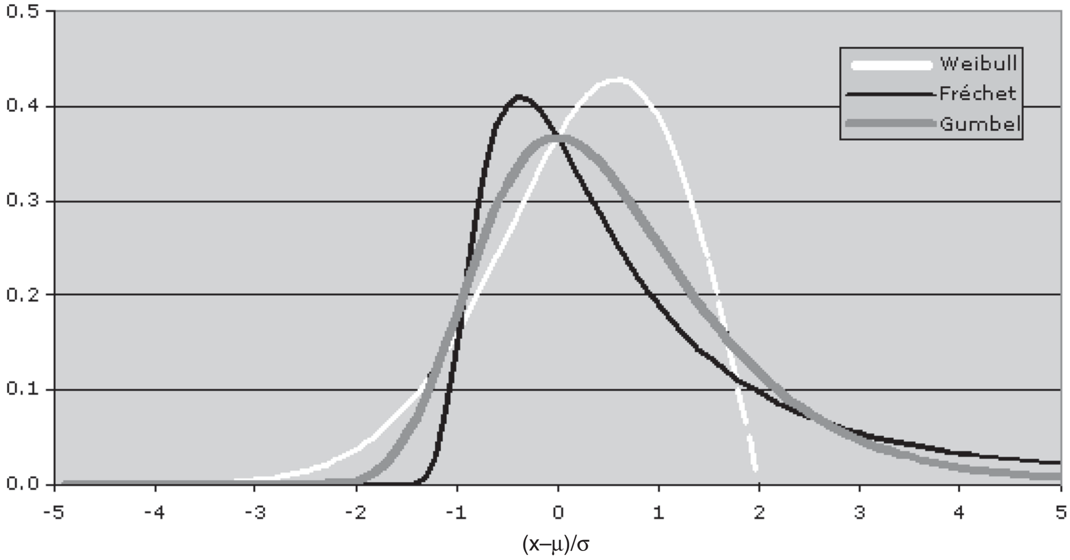


Figure C.1. Typical EV distributions.

$$h = 1 + \frac{\xi}{\sigma}(1 - \mu)$$

and where

μ = the location parameter of the estimated EV function
σ = the scale parameter of the estimated EV function
ξ = the shape parameter of the estimated EV function
$\Gamma(\,)$ = the incomplete gamma distribution

The location, scale, and shape parameters of EV distributions are estimated by special fitting procedures applied to the random variable. The parameter *x* represents the event frequency or system performance data that are distributed. These could include data such as speed (delay) data for a long time period. The procedures for estimating the parameters are available in Stata and similar, comprehensive statistical software packages or in standalone software such as MathWave. The location and scale parameters for the Gumbel distribution can be estimated with the Gumbel distribution fitting options from these statistical software packages or by using standalone software.

Valuing Unreliability for Processes Characterized by EV Distributions

Valuing options when the value of the process of interest follows an EV distribution is conceptually similar to the process described earlier for lognormally distributed values. However, the mathematics is more complicated, and the role of time in the methodology is more pronounced because the option's life occurs over a longer period of time.

The precise formulation of the valuation formula depends on the data available and the unreliability process being examined. In the case in which the speed metric is a distributed EV, and the valuation at the end of the option life is appropriate (similar to the lognormal case), a closed form of a European put formulation is available (Markose and Alentorn 2005). The value of the put can be calculated for a European put option with a strike price (speed guarantee) of *I* and a life (evaluation interval) of *t* with Equation C.3.

$$f(x;\mu,\sigma)_{Gumbel} = \frac{1}{\sigma} e^{\frac{-(x-\mu)}{\sigma}} e^{-e^{\frac{-(x-\mu)}{\sigma}}} \qquad \text{(C.3)}$$

where

μ = location parameter
σ = scale parameter

and where

x is the random variable of interest

This formulation may be useful in situations in which speed variability is due entirely to a rare event that occurs within a relatively short interval. For example, this might apply to a normally uncongested country road where an accident occurs, causing speed reductions (delays) that represent an EV distribution. Sufficient data would be needed to estimate the location, scale, and shape parameters for the EV distribution. Conceptually, the valuation of unreliability would then proceed in a manner completely analogous to the manner described earlier in which speeds are distributed lognormally.

Illustrative Example of European Put Option

A more-typical case occurs when the events that precipitate unreliability are known to be a distributed EV, but there is no record of associated traffic metrics. This can be because insufficient data are collected or because speed is not a sufficient measure of the impact of the events on network reliability. In this case, the event distribution is estimated from information about the event rather than from a roadway performance metric such as speed. This means that a second step can link the events to travel time performance.

This situation is illustrated with the European EV put formulation in a setting of avalanche closures. Avalanches have characteristics of rare events in that for most days and months in the winter, no avalanches occur, but periodically, avalanches of varying intensity and extensiveness occur. If an avalanche event is a distributed EV, then Equation C.3 can provide the certainty-equivalent value of closure duration under various conditions of control or mitigation of the avalanche impacts.

The other relevant feature of this example is that the traffic count data, although collected with high frequency in the vicinity of the avalanche, do not fully convey the traffic unreliability associated with the avalanche. Specifically, without considerable additional effort, one cannot determine the useful traffic performance metrics associated with the avalanche. Thus, the unreliability valuation exercise must be broken into two pieces. First, the duration of avalanches can be analyzed in an options framework to derive a certainty-equivalent delay from the (presumed) EV-distributed duration data. Thus, highly variable and rare-event data can be reduced to a deterministic indicator. Second, a separate study (not performed here) linking closure duration to traffic delay can then be applied to the certainty-equivalent closure duration for monetizing the benefits of a strategy or treatment.

The illustrative example presented here is of an avalanche closure for Snoqualmie Pass on I-90 in the State of Washington. The rare-event nature of a road closure caused by an avalanche is determined by examining the number of hours of pass closure per month (for December through April) by using data from a 13-year historical series of avalanche closures for the I-90 eastbound direction of Snoqualmie Pass.

With the parameters of the Gumbel EV distribution estimated from the closure data, one can consider the certainty-equivalent value associated with strategies that offer various "guarantees" of protection from rare-event closures (such as traffic management, staging of snow-removal equipment, etc.). One such strategy might allow the agency to reduce the average monthly closure duration by 5 hours. Another more-aggressive strategy might aim at reducing most of the rare-event outcomes and the closure duration by 25 hours—effectively eliminating the closure duration for all but the most significant events. In a manner similar to the insurance analogy used to illustrate valuing unreliability associated with recurring events, one could calculate the European put option for various such "insurance" levels.

Figure C.2 illustrates how the European put option values vary with the closure delay guarantee (duration reduction). This exhibit illustrates that the certainty-equivalent value of the uncertainty about closure delay is highest when the closure reduction is greatest. The certainty-equivalent value declines to zero when no reduction is provided by the strategy. At the 25-hour guarantee level, the certainty-equivalent value offered by the associated strategy is equivalent in value to 12 hours of monthly delay. At the 5-hour level, the certainty-equivalent value is equal to approximately 3 hours of monthly delay.

With information on the relationship between average monthly delay and the cost of unreliability (the monetized cost of traffic delay), there is now a basis for valuing the severity of different monthly closure durations and for evaluating remediation strategies. Note that the example in this figure was developed to illustrate a principle and should not be used for policy guidance. There may be other formulations of the data and associated options that should be considered.

Often, there is an additional complexity of the reliability problem associated with rare events; that is, truly rare events play out over very long time periods and can occur at any time in the interval—not just at the end of the interval. This makes the use of the European option inappropriate, because this option assumes a finite horizon and exercise at the end of the interval. In such cases, it is more logical to use an American perpetual-life option.

Coupling a perpetual-life option with EV distributional assumptions complicates the arithmetic of the unreliability-valuation process considerably. Only a handful of published papers address this concept. Work by Koh and Paxson (2006) has been adapted to value decisions to invest in rare-event ventures. This work provides some guidance for placing a value on unreliability associated with rare events that may play out over a long period of time. However, the adaptation likely can be better refined for traffic-related concerns with further research.

The approach taken by Koh and Paxson assumes that one embarks on a program to produce benefits or reduce costs while recognizing that potential benefits of the strategy are highly uncertain. Only a few events occur even after having had the strategy (option) in place for a long time. The Koh and Paxson example is similar in spirit to highway situations in which there is insufficient information to parameterize the network performance (e.g., speed) distribution directly, but one knows that rare events affect network performance.

Sufficient data must be available to parameterize the EV distribution, but only for the rare-event process. The connection between the rare-event process and the economic consequences

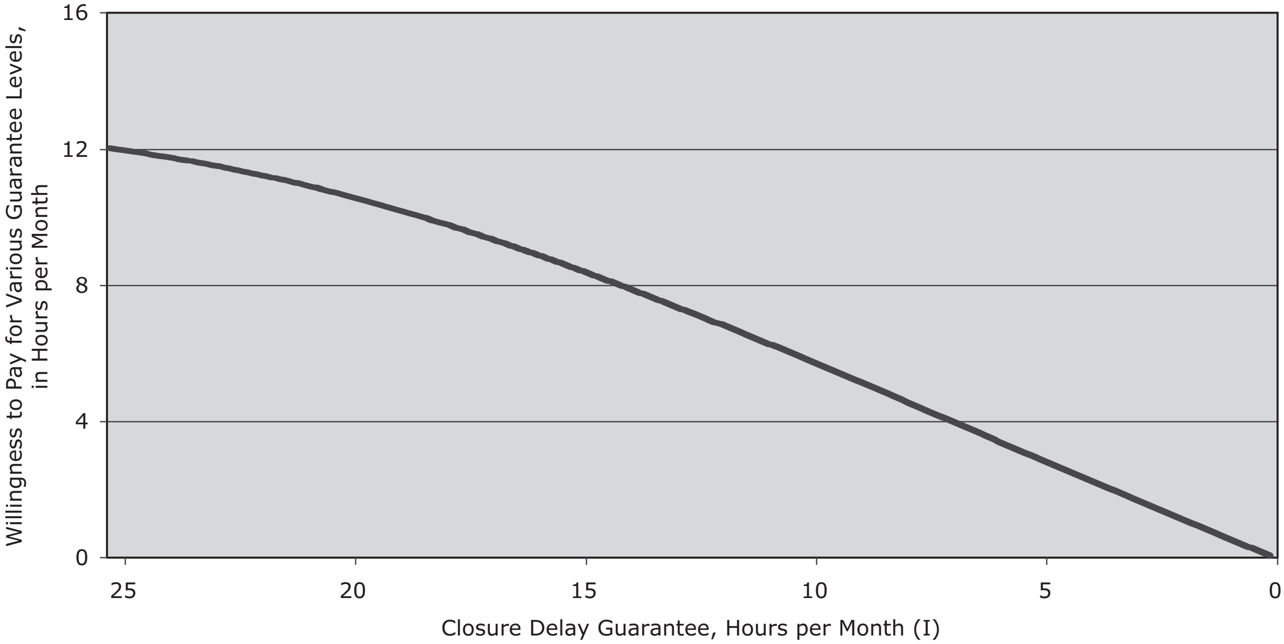


Figure C.2. Illustrative example of European put option for avalanche closure delay.

of the event occurring is determined by characterizing the value of the event process separately. Koh and Paxson do this by postulating a Wiener process, with a log mean and log standard deviation. The Koh and Paxson method also allows the cost, *K,* of facilitating the mitigating strategy to be incorporated, so that the option is a project value (net benefit) concept. Incorporating project valuation directly into the options theoretic framework with the GEV is a potentially valuable way to derive certainty-equivalent economic values of highway management strategies.

There is limited literature on the use of perpetual-life American options, so the Koh and Paxson paper is particularly interesting. The mathematics become doubly complex because of both rare-event and perpetual-option considerations. The Koh and Paxson option is a perpetual-life American call option. However, put-call parity allows the use of this formulation by restating the problem slightly. Equation C.4 presents the Koh and Paxson method for the Gumbel EV distribution.

$$F(V;K,x,\pi,s)_{Gumbel}=\frac{V^{\beta}\left(e^{\frac{-(x-\mu)}{\sigma}}e^{-e^{\frac{-(x-\mu)}{\sigma}}}\right)^{\beta}}{\beta\left(\frac{K\beta}{\beta-1}\right)^{\beta-1}}\ \text{if } V<V^{\star}\ \text{or}$$

$$=V\left(e^{\frac{-(x-\mu)}{\sigma}}e^{-e^{\frac{-(x-\mu)}{\sigma}}}\right)-K\ \text{if } V\geq V^{\star}$$

where

$$\beta=\frac{1}{2}-\frac{\pi}{s^{2}}+\sqrt{\left(\frac{\pi}{s^{2}}-\frac{1}{2}\right)^{2}+\frac{2r}{s^{2}}}>1 \qquad \text{(C.4)}$$

and where

$F(\ )$ = the present discounted value function of the option
V = the present discounted value of the event when it occurs
K = the present discounted value of the cost investing to mitigate impacts
x = the number of events, $x > \mu$
π = the mean of the process that generates V, $\pi > 0$
s = the standard deviation of the process that generates V, $s > 0$
r = risk-free interest rate
$V^{\star}$ = the value of the event below which it is worth continuing to wait to invest K
μ = location parameter for the Gumbel distribution
σ = scale parameter for the Gumbel distribution

The formulation in Equation C.4 can be used to evaluate the cost of rare events (and their mitigation). For example, suppose that a transportation authority is considering investing in a project that would protect a segment of highway from the effects of avalanches in the segment right-of-way. The agency wishes to know whether it is worthwhile to do so. Specifically, the agency wants to know how to compare the value of mitigation (*V*) and the cost of mitigation (*K*) associated with the project.

Put in more formal terms, the agency wishes to know what the certainty-equivalent benefit would be under various scenarios of the value, *V,* of the avalanche closures, and the cost, *K,* of mitigation. The agency would proceed as follows:

- Historical information on the frequency of avalanche events would be used to derive the values of the scale and location parameters of the Gumbel EV.
- Any uncertainty about the present value of the event would be addressed by providing information about π and s.
- The number of simultaneous events sought by the strategy is entered as x.

The formula in Equation C.4 is then solved for *F*( ) for various values of *V* (the mitigation value) and *K* (the project cost). By reviewing Equation C.4, it can be determined that the project value function, *F*( ) varies in the following way with these parameters:

- The greater is *V,* the greater is the project value.
- The greater is *K,* the lower is the project value.
- The greater is the uncertainty, *s,* about the value *V,* the greater is the project value.
- The greater is the number of events, *x,* that can occur at one point in time, the lower the project value. This is because the probability of many simultaneous rare events is low.

This method has been applied to the previously used case of avalanche mitigation in the Snoqualmie Pass in Washington State. With data from a 13-year history of avalanche events in the area, a GEV-Gumbel distribution was fit, and the location and scale parameters obtained. Figure C.3 shows the GEV-Gumbel probability density function for the number of avalanche closures per month for the months of December through March for the eastbound direction. The estimated GEV-Gumbel distribution is displayed in Figure C.4.

Data on the duration of the closure associated with avalanches were also obtained and used as a proxy for the parameters of the Wiener process. The resulting data and options formulation allow the analyst to characterize the certainty-equivalent net benefits associated with mitigating avalanches at cost *K.* Figure C.5 illustrates the project value $F(V)$ corresponding to a \$10 million cost of mitigation, *K,* for values of *V* (with $r = 0.09$, $\pi = 0.05$, and $s = 0.1$). As the value of the benefit of the mitigation (*V*) increases, so too does the project value $F(V)$.

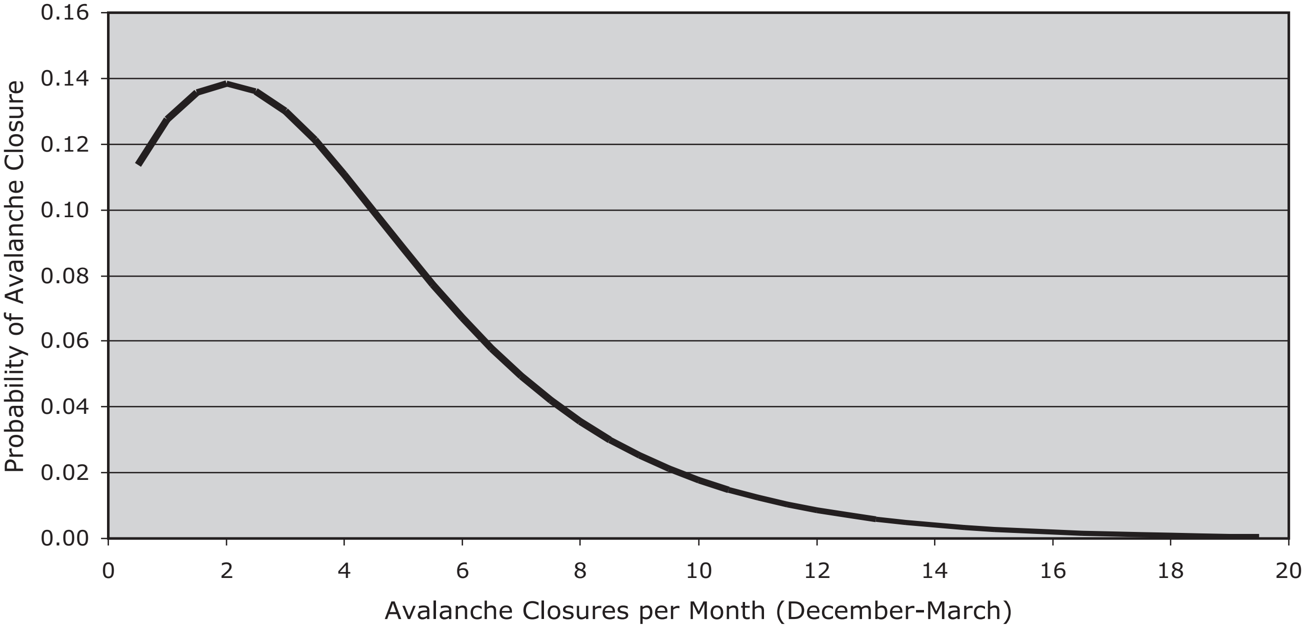


Figure C.3. Gumbel probability density function for avalanche closures per year, I-90 eastbound.

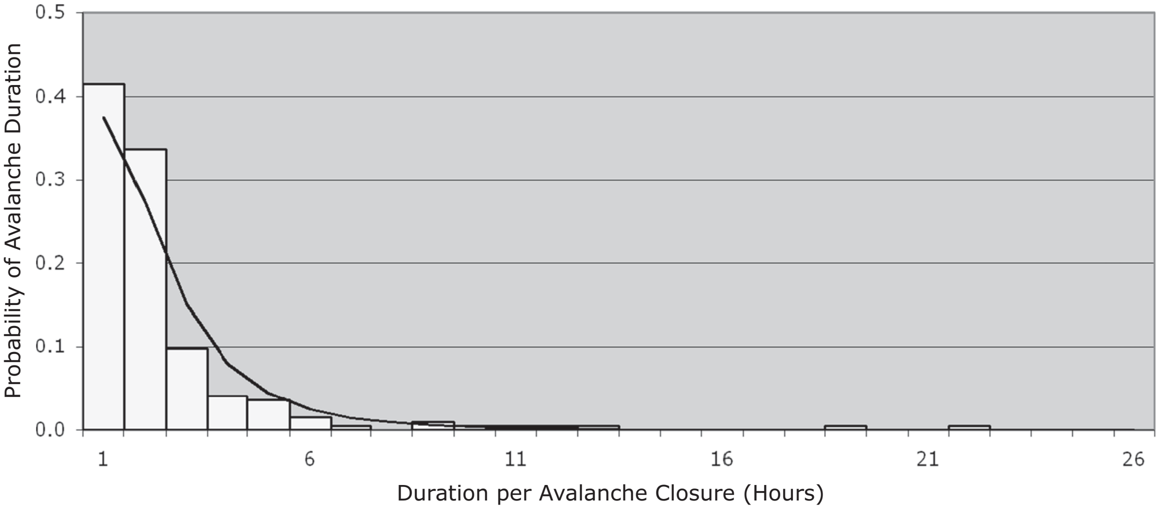


Figure C.4. Estimated Gumbel distribution for duration per avalanche closure.

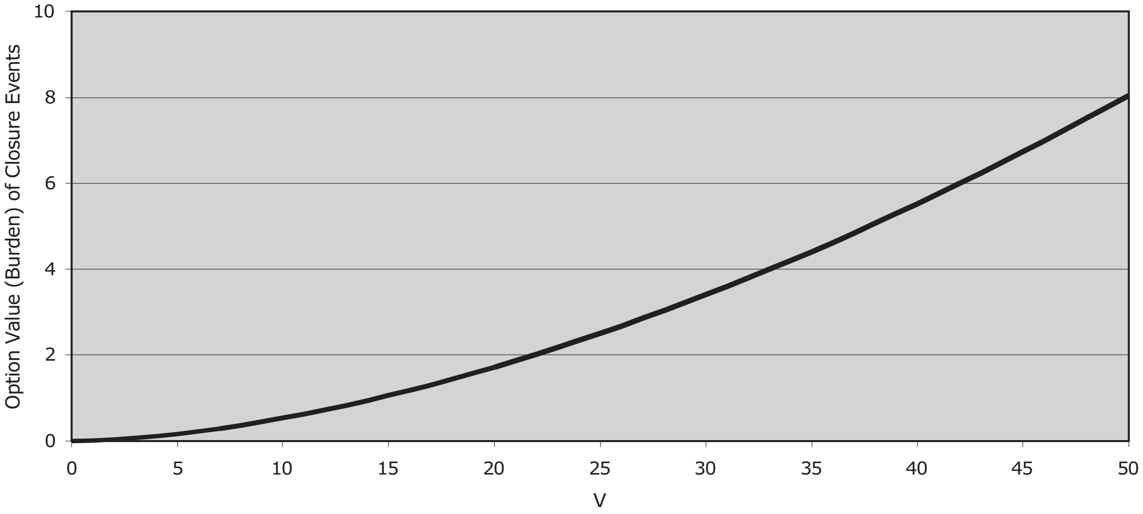


Figure C.5. Example of option value, F(V)*, for avalanche closure events.*

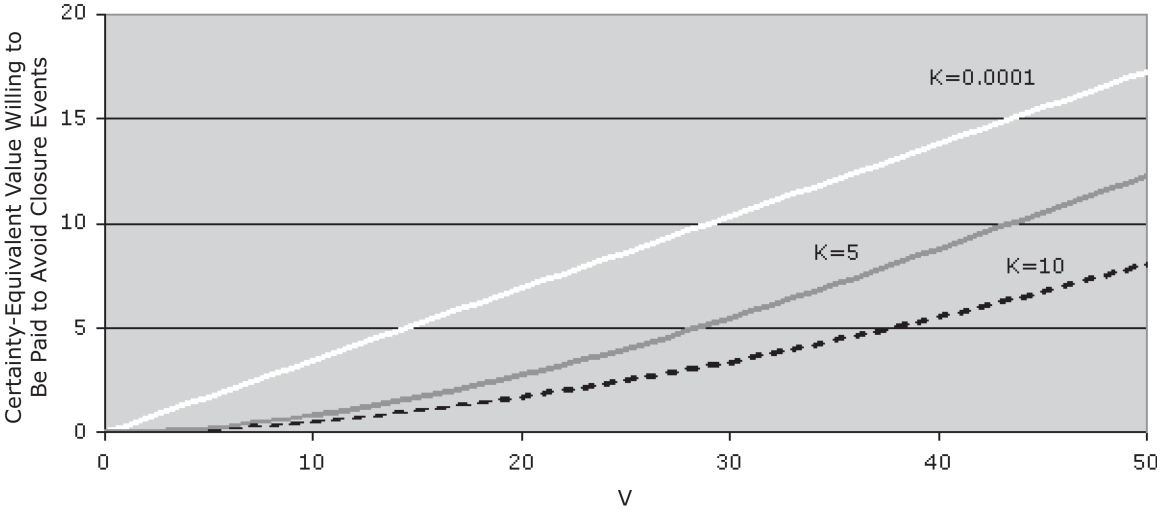


Figure C.6. Certainty-equivalent benefit for different mitigation costs, **K.**

In Figure C.6, $F(V)$ is shown for three different values of K, expressed in millions of dollars. For $K = 0.0001$, $F(V)$ is essentially a gross benefit calculation given that a very low value for the cost of mitigation has been used to calculate the certainty-equivalent benefit. As the cost of the mitigation increases, say from $K = 5$ to $K = 10$ as shown below, $F(V)$, also expressed as millions of dollars, decreases. Figure C.7 demonstrates the relationship between the project value and the number of avalanche closures. This figure is for illustrative purposes only, because the Gumbel was estimated only for the avalanche incidence on one pass (I-90) and may not represent the incidence of conditions that cause avalanches on multiple passes. However, it reveals the expected result: a project or strategy intended to remediate multiple avalanches does not have high value because multiple avalanches are such a rare event.

The Koh and Paxson (2006) approach is very flexible; it allows for the case in which events are meaningful only if multiple instances occur simultaneously. For example, a highway network might have three alternative passes at risk of avalanche, but significant delays occur only if all three passes experience an avalanche. The Koh and Paxson formulation can be used to examine what the project value is for different quantities of simultaneous avalanches.

As shown in Equation C.4, the greater the number of events, x, that can occur at one point in time, the lower the project value. This is because the probability of many simultaneous rare events is low. In the example of avalanche closures, the highest values of $F(V)$ occur for values of x near the location parameter from the Gumbel distribution—around two or three closures per month. As the number of closures per month, x, increases, $F(V)$, the project value, declines.

In the case of a perpetual-horizon evaluation using the Koh and Paxson approach (using an EV distribution and a perpetual-life American option), the present value of benefits

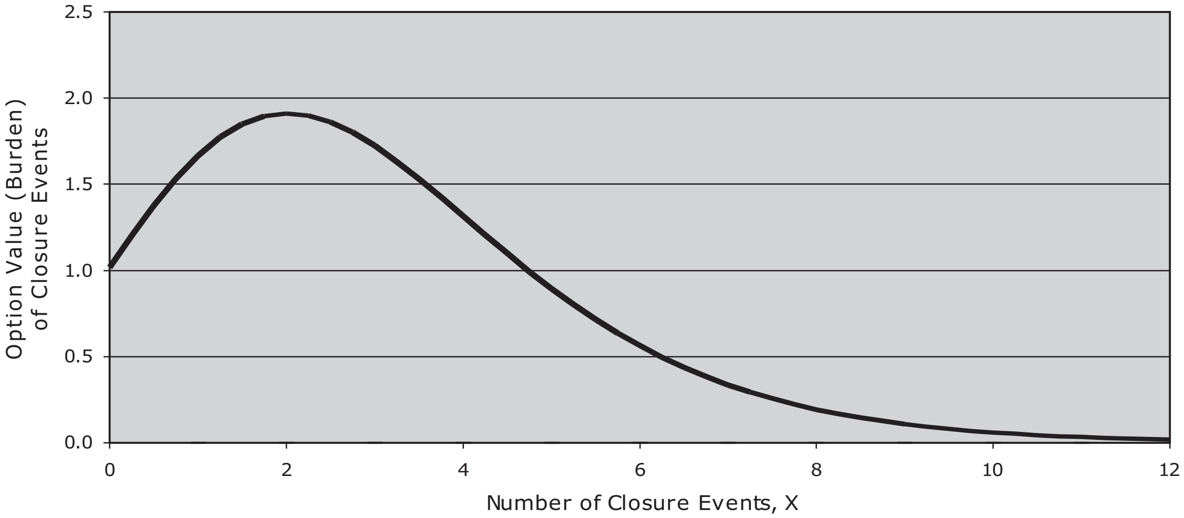


Figure C.7. Sensitivity of **F(V)** *to number of avalanche closures per month.*

and costs are incorporated (as *V* and *K*, respectively) directly into the project option value function. The reason for this is that the timing of the unreliability process is allowed to occur any time within the perpetual life of the option. Thus, the certainty-equivalent value of the costs of the unreliability (or the benefits of remediating those costs) is associated with the (stochastic) event timing. Although it would be desirable to model such circumstances more simply (i.e., separating the project valuation from the rare-event process), a closed-form representation of an American put option using rare-event distributions and a perpetual life is unknown at this time.

In this appendix, an approach first proposed by Koh and Paxson (2006) has been extended to the context of transportation investment decision making under uncertainty caused by rare events. The method relies on EV distributions for rare events to help guide investment, incorporating not only the uncertainty surrounding the frequency of the event, but also the uncertain timing of such an event in a way that addresses the discounted expected benefits (savings) due to the investment. Although the options theoretic approach is more standard under the assumption of log-normal distribution, these rare events can cause considerable disruption to the transportation network, and methods should be improved to help make the necessary investments to mitigate the effects of rare events.

Rare-Event Reliability Valuation Example

Issue

A transportation agency in the northeastern region of the United States oversees a section of a network on which typical rain conditions have minimal impact on highway network performance. However, an extremely rare hurricane event would overwhelm and damage this section of roadway, imposing significant trip and schedule delays on users of the network. The planners have proposed that the agency install and maintain a pumping system for the affected network section that will pump out the water in the rare event that the hurricane rainfalls flood the roads.

The agency would like to compare the investment cost and expected losses. The exact size and burden of these hypothetical delays is not known because damaging hurricanes in the region are rare. Analysts have examined the possible range of user travel and economic impacts with standard capital planning models. They have calculated the future stream of costs from a damaging hurricane and converted the estimated costs to present value by using a discount rate that reflects their uncertainty of the timing and damage associated with the event. The present value of the damage calculated by this method equals $100 million ("impact cost") and would be borne by the agency or the public, or both, without a mitigation strategy. The present value of the costs of installing the pumping system is $101 million.

The agency now has to ask the question, is it worth (the present value) $101 million to mitigate (the present value of) $100 million in impact cost? Given the current state of disparity between the investment cost and the expected losses, traditional capital investment models indicate that investment in the pumps would not be a rational decision by the agency. This methodology, however, does not incorporate the uncertainty of the event in a formal way.

Solution

The options theoretic approach could be used to calculate the certainty-equivalent value of the uncertainty related to the occurrence and number of hurricanes.

- Data needs: Information or data on the likelihood of hurricane events in the region are needed to construct a distribution of hurricane events.
- Cautions: Given the nature of rare events, it is unlikely that the probability distribution for the rare event can be estimated from historical data.

The steps involved in the calculation are outlined below.

Step 1: Characterize the Rare Event

The incidence of the disruptive hurricanes that cause these effects is infrequent and not easily predictable. Historical evidence suggests that in this particular region, hurricane incidence can be characterized by a GEV (event) statistical distribution type known as the Gumbel distribution.

A. Obtain data or information on the likelihood of future hurricane events in the region.
B. Estimate parameter values from the Gumbel distribution to describe the expected probability distribution for hurricane events. Be certain that the rare event can be characterized by the Gumbel distribution.

Step 1A

- Location parameter = $\mu = 1.67$; and
- Scale parameter = $P(V_T, t) = 0.88$.

Step 1B

The probability distribution using the Gumbel probability density function is given by

$$f(x;\mu,\sigma)_{Gumbel} = \frac{1}{\sigma} e^{\frac{-(x-\mu)}{\sigma}} e^{-e^{\frac{-(x-\mu)}{\sigma}}}$$

$$= \frac{1}{0.88} e^{\frac{-(x-1.67)}{0.88}} e^{-e^{\frac{-(x-1.67)}{0.88}}}$$

where

x is the random variable of interest (number of hurricanes during the lifespan of the strategy/policy)

Step 2: Calculate Certainty-Equivalent Value of Uncertainty Associated with Rare Events

Here, the investment opportunity is to spend \$101 million to avoid \$100 million in costs per hurricane event. Equation C.4 can be used to derive the certainty-equivalent value of uncertainty associated with the occurrence of hurricanes.

Use Equation C.4 to calculate the certainty-equivalent value of uncertainty associated with rare events. Default values for the interest rate and the mean and standard deviation for the process that generates V are based on those used by Koh and Paxson (2006). Because the Koh and Paxson formulation embeds the option value into an investment framework, the interest rate is 9% to reflect a risk premium and inflation.

STEP 2A

For the given example,

V = the total present discounted value of the cost incurred
= Expected cost per event × Expected number of events
= \$100 million × x

V^* = the value of the event below which it is worth continuing to wait to invest K

K = the present value of cost invested to mitigate impacts
= \$101 million

r = risk-free interest rate = 9%

π = the mean of the random process that generates $V = 0.05$

s = the standard deviation of the random process that generates $V = 0.10$

The certainty-equivalent value of uncertainty is given by

$$F(V; K, x, \pi, s)_{Gumbel} = \frac{V^{\beta}\left(e^{\frac{-(x-\mu)}{\sigma}}\, e^{-e^{\frac{-(x-\mu)}{\sigma}}}\right)^{\beta}}{\beta\left(\frac{K\beta}{\beta-1}\right)^{\beta-1}} \text{ if } V < V^*$$

$$= V\left(e^{\frac{-(x-\mu)^{-e^{\frac{-(x-\mu)}{\sigma}}}}{\sigma}}\right) - K \text{ if } V \geq V^*$$

where

$$\beta = \frac{1}{2} - \frac{\pi}{s^2} + \sqrt{\left(\frac{\pi}{s^2} - \frac{1}{2}\right)^2 + \frac{2r}{s^2}} > 1$$

$$V^* = \frac{K\beta}{\left(e^{\frac{-(x-\mu)^{-e^{\frac{-(x-\mu)}{\sigma}}}}{\sigma}}\right)(\beta-1)}$$

x = the number of hurricanes during the lifespan of the strategy/policy.

The probability of occurrence of two hurricanes is highest as shown by the Gumbel distribution in Step 1B.

For $x = 2$

$$\beta = \frac{1}{2} - \frac{\pi}{s^2} + \sqrt{\left(\frac{\pi}{s^2} - \frac{1}{2}\right)^2 + \frac{2r}{s^2}}$$

$$= \frac{1}{2} - \frac{0.05}{0.1^2} + \sqrt{\left(\frac{0.05}{0.1^2} - \frac{1}{2}\right)^2 + \frac{2 \times 0.09}{0.1^2}}$$

$$= 1.68$$

$$V^* = \frac{101 \times 1.68}{\left(e^{\frac{-(2-1.67)^{-e^{\frac{-(2-1.67)}{0.88}}}}{0.88}}\right)(1.68-1)} = \$719 \text{ million}$$

Since ∵ $V < V^*$

$$F(100, 101, 2, 0.05, 0.1)_{Gumbel}$$

$$= (2 \times 100)^{1.68}\left(e^{\frac{-(2-1.67)}{0.88}}\, e^{-e^{\frac{-(2-1.67)}{0.88}}}\right) \Big/ 1.68\left(\frac{101 \times 1.68}{1.68-1}\right)^{1.68-1}$$

$$= \$17.09 \text{ million.}$$

Step 3: Perform Analysis to Decide Whether to Implement Strategy or Policy

A. Calculate the total cost of implementing the strategy or policy.

B. Calculate the total benefits as a result of implementing the strategy or policy.

C. Perform the analysis to decide if it is worth implementing the strategy or policy.

STEP 3A

Total cost of installing the pumping system = \$101 million.

STEP 3B

- Present value of damage per hurricane event calculated by using capital planning methods = \$100 million.
- Option value of investment opportunity associated with occurrence of two hurricane events per year = \$17.09 million.
- Total benefits = 2 × \$100 million + \$17.09 million = \$217.09 million.

STEP 3C

Because the benefits are most likely to be more than the cost in the case of two hurricanes, it is worth the investment to install the pumping system.

APPENDIX D

Sample Problem: Quantifying the Economic Benefit of Improving Travel Time Reliability

Issue

SR-520 (the Evergreen Point Floating Bridge) is an east–west facility that connects I-5 in Seattle with Bellevue, Washington, and other suburbs to the east. This facility (shown in Figure D.1) has a cross section of two lanes per direction. The ramp meters for traffic entering eastbound SR-520 from Montlake and Lake Washington Boulevards have operated during the evening commuting period since 1986. Since then, eastbound traffic conditions (in what had traditionally been the reverse commute direction) during the 6:00 a.m. to 9:00 a.m. peak period have worsened. This has occurred because of the population growth of Bellevue and the business development (e.g., Microsoft) east of Lake Washington. Until late 2001, however, eastbound on-ramp meters were not active during the morning commuting period. To alleviate increasingly heavy morning congestion and to reduce merge-related accidents, the Washington State DOT decided to lift the time restrictions for the operation of the eastbound on-ramp meters. Since August 6, 2001, these ramp meters have operated during weekday morning commuting times.

Description of Problem

This sample problem presents a methodology for determining how the activation of these two on-ramp meters for eastbound SR-520 traffic has affected travel time reliability during the morning peak period. Six months of weekday travel time data at 5-minute intervals from before and after the initiation of morning ramp metering were analyzed. Travel times during the before period (January 1, 2001–June 29, 2001) were compared with travel times during the after period (January 1, 2002–June 28, 2002). This comparison included travel time measurements taken during each weekday in a comparable 6-month period before and after activation of these two on-ramp meters to minimize the effects of seasonal variation.

Eastbound travel times were measured on weekdays between 6 a.m. and 9 a.m. Speeds were then calculated with data from the approximately 4-mile length of SR-520 from I-5 to the east side of the Evergreen Point Floating Bridge. Figure D.2 illustrates the speed data collected in 2001 and 2002.

Solution

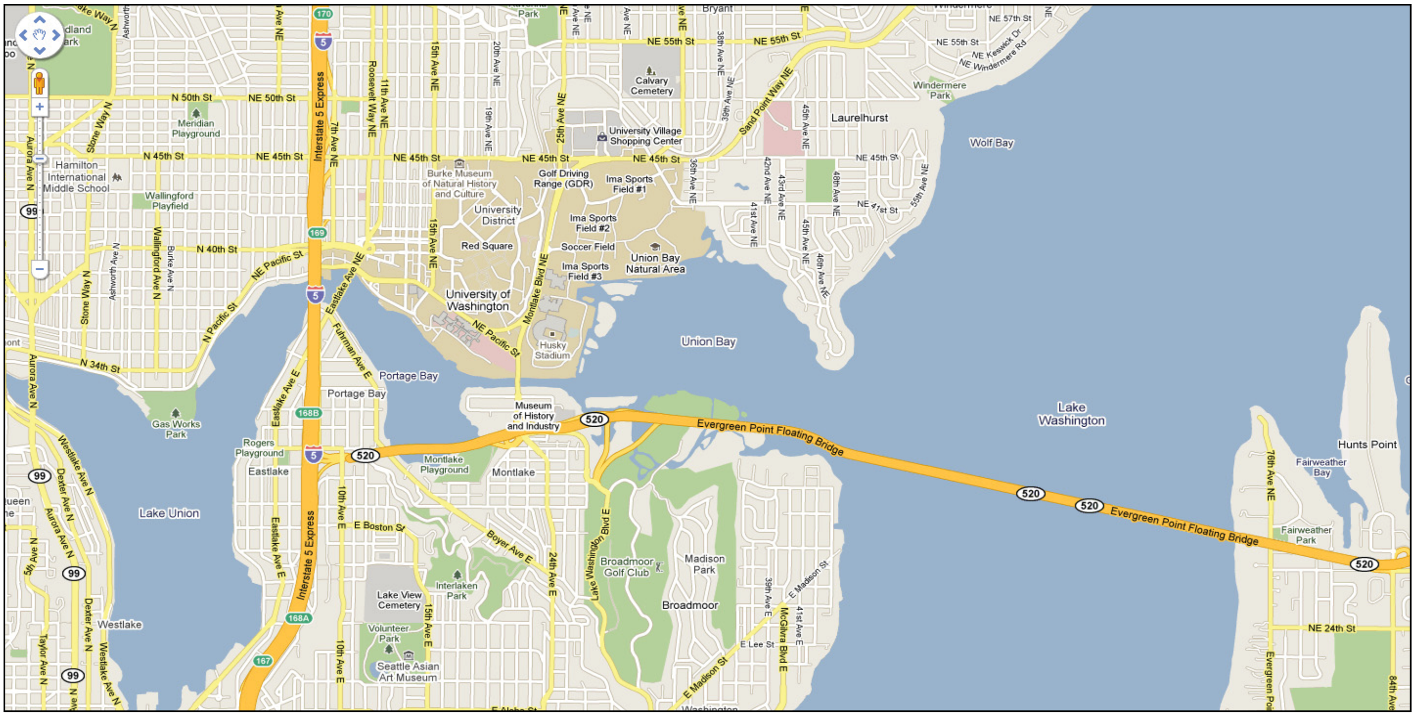
The travel time variability during the a.m. peak period in the eastbound direction on SR-520 generates a cost that is borne by users of the facility. This cost can be converted to a certainty-equivalent value, which describes the additional time that motorists are willing to spend on the facility if the variability in travel times is eliminated. This certainty-equivalent value of unreliability can then be converted to a dollar value by applying the user's value of time. The resulting annual monetary value that results from improving travel time reliability can be compared with the cost of implementing the ramp meters to derive a benefit-to-cost ratio for the treatment. The reliability improvement calculated in this sample problem was then compared with improvements achieved at other locations where ramp meters have been installed.

- Data needs
    - ○ Speed data collected at 5-minute (or 15-minute) time intervals; and
    - ○ Volume data collected by vehicle type.
- Cautions
    - ○ This procedure is applicable to data for which the variation in travel times can be characterized by a lognormal distribution.

Procedure to Quantify Economic Benefit of Improving Travel Time Reliability

Six steps were followed to solve this problem.

Step 1: Characterize the recurring congestion problem.
Step 2: Calculate the certainty-equivalent value of unreliability.



Source: Map data © 2013 Google.

Figure D.1. SR-520 (Evergreen Point Floating Bridge) study area.

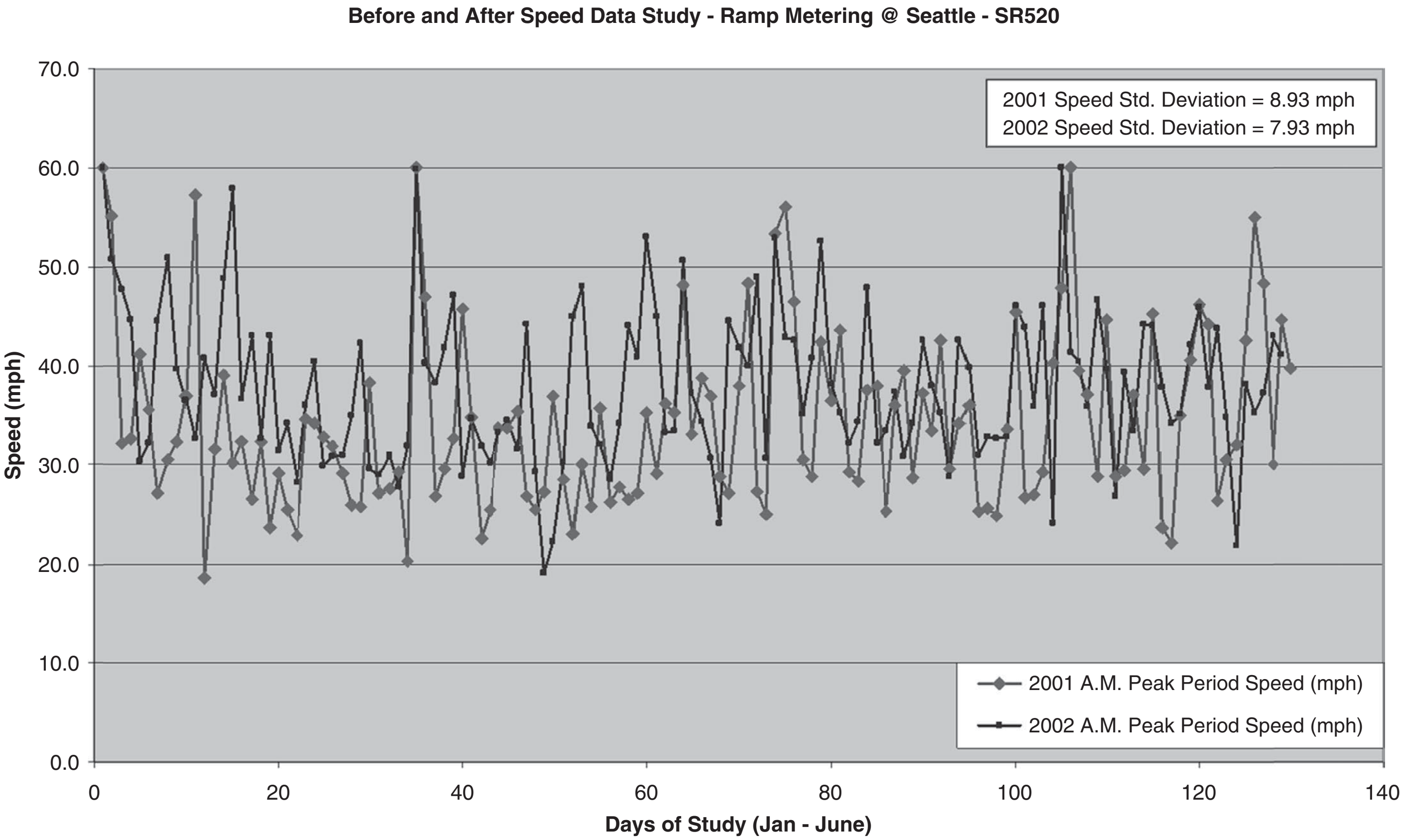


Figure D.2. 2001 and 2002 speed data for eastbound SR-520 from I-5 to east of Evergreen Point Floating Bridge.

Step 3: Evaluate the treatment that reduces unreliability.
Step 4: Calculate the value of the reliability improvement to the road user.
Step 5: Calculate the reliability measures and the benefit-to-cost ratio.
Step 6: Compare results with other similar treatments.

Step 1: Characterize the Recurring Congestion Problem

A. Obtain speed data and calculate data parameters.
B. Calculate the average speed and the standard deviation of the log of speed.
C. Construct a lognormal distribution with the log mean and log standard deviation of the speed to confirm that the speed data are lognormally distributed.

Step 1A

Obtain speed data and calculate data parameters. The following parameters were calculated from the speed data. Refer to Figure D.2 for the speed data used in the calculations.

- 2001 95th percentile speed = 23.65 mph.
- 2002 95th percentile speed = 27.91 mph.
- 2001 average speed = 32.41 mph.
- 2002 average speed = 36.39 mph.
- 2001 and 2002 free-flow speed = 60 mph.
- 2001 and 2002 corridor length = 4 miles.

Table D.1 shows the eastbound SR-520 freeway volumes for the 3-hour weekday a.m. peak period (from 6 a.m. to 9 a.m.) before and after implementation of the ramp metering.

Table D.2 shows the assumed value of time for each vehicle class. These values are based on recommendations from the FHWA Highway Economic Requirements System.

Step 1B

Calculate the average speed and the standard deviation of the natural log of speed for 2001 conditions.

$$\text{Average speed } (\bar{X}) = \frac{\sum S_i}{N}$$

where
S_i = speed during interval i, and
N = total number of intervals.

Table D.1. Vehicular Volumes

Vehicle Class	2001	2002
Passenger car	6,516	6,921
Truck (3% of total volume)	202	214

Table D.2. Value of Time for Different Vehicle Classes

Vehicle Class	Value of Time ($/minute)
Passenger car	0.30
Truck	0.83

For this, $I = 32.41$ mph

$$\text{Average ln speed } (\mu) = \frac{\sum \ln(S_i)}{N}$$

For this example, $\mu = 3.51$

Standard deviation of ln speed or speed volatility (α) =

$$\sqrt{\frac{1}{N}\sum(\ln(S_i) - \mu)^2}$$

$\alpha = 0.2451$

Step 1C

Construct a lognormal distribution using the log mean and the log standard deviation of the speed to confirm that the speed data are lognormally distributed. Figure D.3 shows the distribution for this example.

Step 2: Calculate the Certainty-Equivalent Value of Reliability

A. Choose the appropriate option formulation (European put or American put).
B. Determine the risk-free interest rate to be used in the analysis.
C. Calculate the contract length on the basis of the 95th percentile speed.
D. Calculate the certainty-equivalent value of reliability for the roadway by using the options formula.
E. Convert the certainty-equivalent value from mph to minutes per mile.

Step 2A

Choose the appropriate option formulation (European put or American put). For this example, the European put option was used for the following reasons:

- The European put option provides the traveler's value of reliability 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

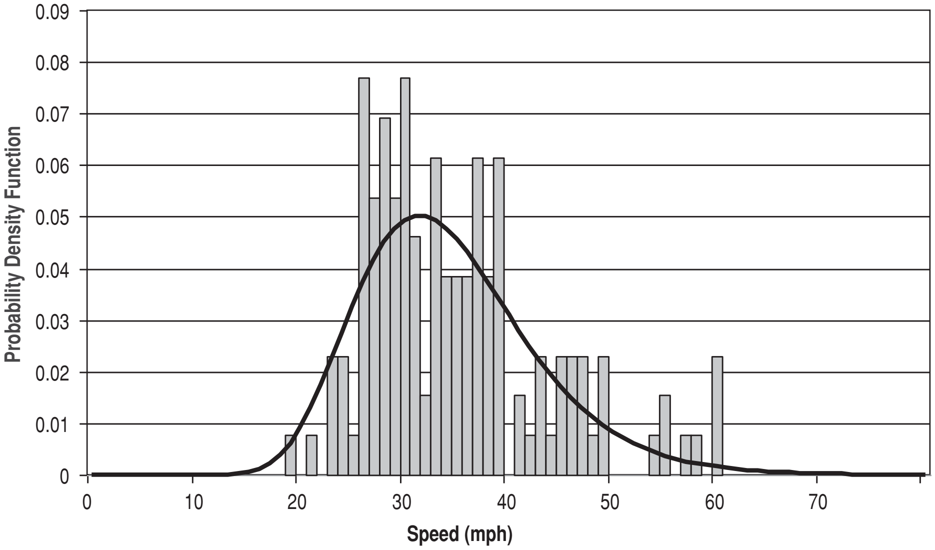


Figure D.3. Lognormal distribution of 2001 speeds (weekends excluded from data).

determine the commuter value of unreliability for a period of time appropriate for the evaluation of a strategy.
- The European put option is selected because this option is formulated with a finite time horizon and is exercised at the end of the option life (i.e., once the traveler has traversed the bridge segment).

STEP 2B

Determine the risk-free interest rate to be used in the analysis. (A risk-free interest rate identifies the rate at which one is guaranteed a return on investment.)

- A value of 5.00% risk-free interest rate was assumed. Thus, $r = 0.05$.

STEP 2C

Calculate the contract length on the basis of the 95th percentile speed. The contract length, $(T - t)$, is calculated as the travel time to cover the segment at the 95th percentile speed, which is determined by using the mean log speed and the standard deviation of the log speed. For this example, the lowest 5% speed is 23.65 mph, and the segment length is 4 miles. The contract length is expressed in years because the interest rate is an annual rate.

$$T - t = \left(\frac{\dfrac{60}{23.65}}{365 \times 24 \times 60} \right) \times 4 = 0.0000193 \text{ years}$$

STEP 2D

Calculate the certainty-equivalent value of reliability for the roadway by using the options formula. The certainty-equivalent value of reliability $T - t = \left(\frac{60/13.22}{365 \times 24 \times 60} \right) \times 10$ is calculated by first calculating three parameters: $P(V_T, t)$, d_1, and d_2. $P(V_T, t)$ is calculated by using the formula for volatility in finance, which represents the standard deviation of the log speed, divided by the square root of the contract length. The variables d_1 and d_2 are two points on the cumulative lognormal distribution. $N(d)$, $N(d_1)$, and $N(d_2)$ are thus probabilities that the cumulative probability will be less than d_1 or d_2, respectively. In the Black–Scholes formula, $N(d_2)$ is the probability that the option will be exercised, and $N(d_1)$ is called the option delta, which measures how the option value changes with volatility.

$$\sigma = \frac{\alpha}{\sqrt{(T - t)}} = \frac{0.2451}{\sqrt{0.0000193}} = 55.78$$

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

The desired speed = 32.41 mph (2001 average speed).

V_T = the guaranteed speed (equivalent to the 2001 average speed) = I = 32.41 mph.

Thus,

$$d_1 = \frac{\ln\left(\frac{32.41}{32.41}\right) + \left(0.05 + \frac{55.78^2}{2}\right)(0.0000193)}{55.78\sqrt{0.0000193}} = 0.12256$$

$$d_2 = d_1 - \sigma\sqrt{(T - t)}$$
$$= 0.12256 - 55.78\sqrt{0.0000193} = -0.12255$$

Evaluate the standard normal distribution at d_1 and d_2:

$$N(d_1) = N(0.12256) = 0.4512$$

$$N(d_2) = N(-0.12255) = 0.5488$$

The certainty-equivalent value of reliability is

$$\begin{aligned} P(V_T, t) &= Ie^{-r(T-t)}N(d_2) - V_T N(d_1) \\ &= 32.41e^{-0.05(0.0000193)}(0.5488) - 32.41(0.4512) \\ &= 3.16 \text{ mph} \end{aligned}$$

From this calculation, a commuter is willing to accept a reduction of 3.16 mph in his or her average speed to eliminate travel time variability.

STEP 2E

Convert the certainty-equivalent value from mph to minutes per mile. The new average speed at which the commuter is willing to travel if unreliability is eliminated = 32.41 − 3.16 = 29.25 mph.

Time to cover 1 mile at the initial average speed = $\frac{1}{32.41} \times$ 60 minutes. Time to cover 1 mile at the new average speed = $\frac{1}{29.25} \times 60$ minutes.

∴ The certainty-equivalent time per mile that the user is willing to "pay" to eliminate unreliability is given by

$$P(V_T, t) = \left(\frac{1}{29.25} - \frac{1}{32.41}\right) \times 60 = 0.20 \text{ minutes per mile.}$$

Step 3: Evaluate the Treatment That Reduces Unreliability

A. Calculate a new set of speed data parameters after implementation of the treatment, which is reflected in the 2002 data.

B. Calculate the certainty-equivalent value for the after (2002) scenario.

STEP 3A

The new set of speed data parameters (after implementation of the treatment) is calculated as follows:

Assumptions for the new scenario:

- The new average speed (V_T) = 36.39 mph (the 2002 average speed).
- The guaranteed speed (equivalent to the 2002 average speed) (I) = 36.39 mph. I = the guaranteed speed as calculated.

Standard deviation of ln speed or speed volatility (α) = $\sqrt{\frac{1}{N}\sum(\ln(S_i) - \mu)^2}$

$\alpha = 0.2094$ for this example.

The lognormal distribution calculated with the log mean and the log standard deviation of the speed is shown in Figure D.4 to confirm the speed data are lognormally distributed.

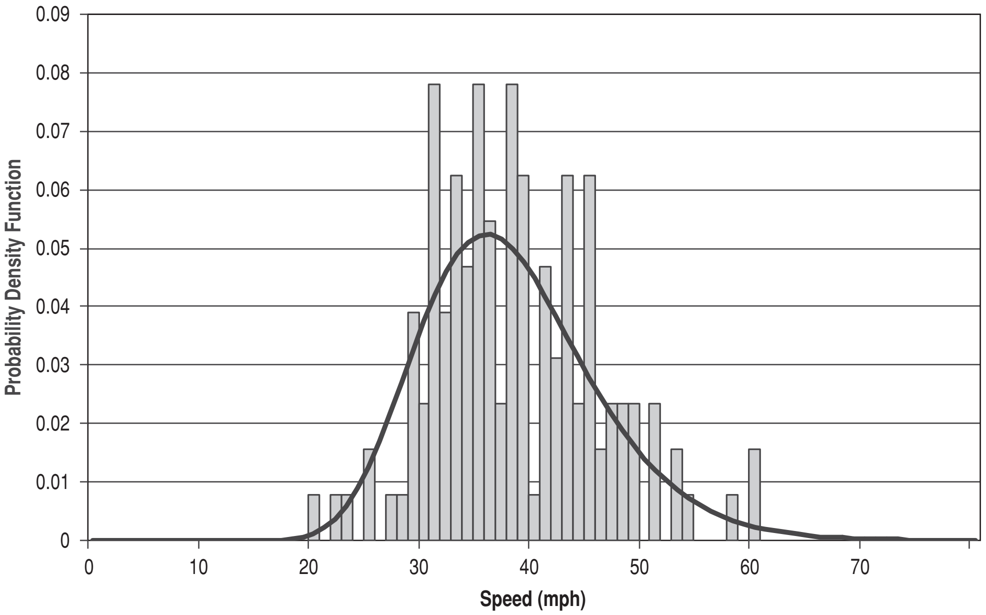


Figure D.4. Lognormal distribution of 2002 speeds (weekends excluded from data).

Step 3B

Calculate the certainty-equivalent value for the after (2002) scenario. The European put option and a 5.00% risk-free interest rate are chosen. Thus, $r = 0.05$.

The 95th percentile speed is now 27.91 mph. Therefore, the new contract length is given by

$$T - t = \left(\frac{\frac{60}{27.91}}{365 \times 24 \times 60} \right) \times 4 = 0.0000164 \text{ years}$$

Sigma is calculated by 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:

$$\sigma = \frac{\alpha}{\sqrt{(T-t)}} = \frac{0.2094}{\sqrt{0.0000164}} = 51.76$$

The intermediate and final option value calculations are performed:

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

$$d_1 = \frac{\ln\left(\frac{36.39}{36.39}\right) + \left(0.05 + \frac{51.76^2}{2}\right)(0.0000164)}{51.76\sqrt{0.0000164}} = 0.10469$$

$$\begin{aligned} d_2 &= d_1 - \sigma\sqrt{(T-t)} \\ &= 0.10469 - 51.76\sqrt{0.0000164} = -0.10469 \end{aligned}$$

$$N(d_1) = N(0.10469) = 0.4583$$

$$N(d_2) = N(-0.10469) = 0.5417$$

The certainty-equivalent value of reliability is

$$\begin{aligned} P(V_T, t) &= Ie^{-r(T-t)}N(d_2) - V_T N(d_1) \\ &= 36.39e^{-0.05(0.0000164)}(0.5417) - 36.39(0.4583) \\ &= 3.03 \text{ mph} \end{aligned}$$

The new average speed at which the commuter is willing to travel if unreliability is eliminated = 36.39 – 3.03 = 33.35 mph.

Time to cover 1 mile at old average speed $= \frac{1}{36.39} \times 60$ minutes.

Time to cover 1 mile at new average speed $= \frac{1}{33.35} \times 60$ minutes.

Thus, the new certainty-equivalent value in minutes per mile is $P(V_T, t) = \left(\frac{1}{33.35} - \frac{1}{36.39} \right) \times 60 = 0.15$ minutes per mile.

The reduction of the certainty-equivalent value from 0.20 minutes per mile (before the ramp meter installation) to 0.15 minutes per mile (after the ramp meter installation) means that after the implementation, the commuter is willing to accept less reduction in speed in exchange for eliminating variability. The commuter is willing to do this because variability has decreased (reliability has improved) after the implementation of the ramp meters.

Step 4: Calculate the Value of the Reliability Improvement to the Road User

A. Determine the value of time for different vehicle classes.
B. Calculate the value of the reliability improvement for each vehicle class.
C. Calculate the value of the reliability improvement for the average a.m. peak period.
D. Calculate the total annual value of the reliability improvement over the length of the highway for all user groups for the average a.m. peak period only.

Step 4A

The value of time for different vehicle classes is shown in Step 1A.

Step 4B

The value of the reliability improvement for each vehicle class during the 3-hour a.m. peak period is shown below:

- Passenger vehicles = 6,921 × ($0.30/minute) × (0.20 – 0.15 minutes/mile) = $103.82/mile.
- Trucks = 214 × ($0.83/minute) × (0.20 – 0.15 minutes/mile) = $8.88/mile.

Step 4C

The value of the reliability improvement for the 3-hour a.m. peak period is calculated as

- Total length of the highway = 4 miles.
- ∴ Total value of the reliability improvement for the 3-hour a.m. peak period = ($103.82 + $8.88) × 4 (miles) ≈ $450.80.

Step 4D

The total annual value of the reliability improvement is

- The total number of days considered = 252 weekdays/year.
- ∴ Total value of the reliability improvement per year (for the 3-hour a.m. peak period) = $450.80 × 252 days ≈ $113,601.60.

Step 5: Calculate the Reliability Measures and the Benefit-to-Cost Ratio

A. Calculate before and after buffer index (BI) and planning-time index (PTI).
B. Calculate the benefit-to-cost ratio.

Table D.3. Buffer Indices and Planning Time Indices

Reliability Measure	Before (2001)	After (2002)
PTI	2.54	2.15
BI	0.37	0.30

Step 5A

Calculate the reliability measures. The BI and the PTI were calculated by using the collected speed data. By definition, the BI is estimated by computing the 95th percentile travel time minus the average travel time divided by the average travel time. The PTI is obtained by the ratio of the 95th percentile travel time to the ideal or free-flow travel time.

The following are the required input data:

- 2001 95th percentile travel time = 605.8 seconds.
- 2002 95th percentile travel time = 513.4 seconds.
- 2001 average travel time = 442.1 seconds.
- 2002 average travel time = 393.8 seconds.
- 2001 free-flow travel time = 238.8 seconds.
- 2002 free-flow travel time = 238.8 seconds.

Table D.3 shows the computed PTI and BI values from the data collected during 2001 (before) and 2002 (after).

The results show a clear reduction in both the PTI and the BI after the eastbound ramp meters were implemented in late 2001 during the a.m. peak period to alleviate congestion.

Step 5B

Calculate the benefit-to-cost ratio. This last step in estimating the monetary value of travel time reliability consists of comparing the total annual value of reliability improvement (Step 4D) with the implementation cost for the ramp-metering system. It is assumed that the lifetime of the ramp-metering system is 5 years.

From the literature (RITA, U.S. Department of Transportation 2013; Maccubbin et al. 2008; Hadi and Sinha 2005), it is estimated that the average unit capital cost for the installation of a ramp meter is approximately $30,000 and that the maintenance and operating cost per year is $2,200. Assuming an annual interest rate of 3%, the total cost of installing and maintaining the two ramp meters over a 5-year period is estimated to be $78,403. The net present value of the reliability improvement over 5 years yields $520,264 in savings.

Thus, the benefit-to-cost ratio is estimated to be 6.6:1. These calculations are summarized in Table D.4. It should be

Table D.4. Summary of Benefit-to-Cost Ratio Calculations

Inputs			
	per ramp meter		
Installation Cost	30,000		
Annual O&M	2200		
Real Discount Rate	3%		
	Basic Present Value Calculation		
Year	**Cost (Evaluation Year Dollars)^a**	**Travel Time Reliability Benefits (Evaluation Year Dollars)^b**	**Net Benefits (Evaluation Year Dollars)**
1	$64,400	$113,602	$49,202
2	$4,400	$113,602	$109,202
3	$4,400	$113,602	$109,202
4	$4,400	$113,602	$109,202
5	$4,400	$113,602	$109,202
Total-NPV	$78,403	$520,264	$441,861
Benefit-Cost Ratio		6.63575341	

[a] Cost reflects two ramp meters

Year 1 Cost = Installation and O&M in Year 1.

[b] Benefits reflect the value travel time reliability improvement; other benefits are not included.

Assumptions:
No change in future year volumes.
No extrapolation of benefits to future years.

Note: O&M = operations and maintenance.

noted that this is a rough estimate that considers the benefits of the morning peak period only and is provided for illustrative purposes. If the safety benefits and the reduction in fuel emissions were considered, a higher benefit-to-cost ratio could be calculated. In addition, the ramp delay experienced by some users is a disbenefit. A simple benefit-cost calculation does not reflect changes in volume or travel time variability in future years.

Step 6: Compare Results with Similar Treatments

As a final step in this analysis, a literature review was conducted to estimate the benefit of other ramp-metering projects designed to improve travel time reliability. Direct assessments of reliability improvements were not found. (Hence, the importance of the methodology in this document is confirmed.) However, other indirect measures, such as improvements to mobility and safety are described below (from Appendix F):

- Efficiency: The benefit-to-cost ratio of the Minneapolis–St. Paul, Minnesota, ramp-metering system was found to be 15:1 (RITA, U.S. Department of Transportation 2013).
- Mobility
    - A ramp-metering study in Salt Lake Valley, Utah, showed that with an 8-second metering cycle, mainline peak period delay decreased by 36%, or 54 seconds per vehicle (RITA, U.S. Department of Transportation 2013).
    - Freeway volume declined by 9% and peak-period throughput decreased by 14% after ramp meters were experimentally turned off in the Minneapolis–St. Paul area (Maccubbin et al. 2008).
    - Five ramp-meter pilot projects were tested on the A40 motorway in Germany. The results showed that congestion decreased by more than 50% during peak periods, and traffic incidents at the ramps decreased by 40% (Mirshahi et al. 2007).
    - Ramp meters in the Netherlands have helped to regulate traffic flow on highways, led to measured speed increases, and allowed for capacity increases of up to 5% (FHWA, U.S. Department of Transportation 2006).
    - Ramp meters at the Oakland–Bay Bridge toll facility in San Francisco, California, resulted in an overall average travel time decrease of 16.5% and a site-specific travel time savings of between 2.5 and 3.5 minutes per vehicle (Clark 2007).
- Safety
    - Crash frequency increased by 26% after the ramp-meter system on Minneapolis–St. Paul freeways was deactivated (RITA, U.S. Department of Transportation 2013).
    - A survey of traffic management centers in eight cities found that ramp meters reduced the accident rate by between 24% and 50% (Maccubbin et al. 2008).
- Energy and environment: Ramp meters saved between 2% and 55% of the fuel expended at each ramp in a simulation study in Minneapolis–St. Paul (RITA, U.S. Department of Transportation 2013).

APPENDIX E

Strategy Framework for Agency Management, Organization, and Resource Allocation

Agency Institutional Requirements

In this appendix, specific institutional treatments for Category 1—agency management, organization, and resource allocation—are identified to improve travel time reliability on the basis of the SHRP 2 L06 project findings (Parsons Brinckerhoff et al. 2011 and 2012). The key drivers that affect agency development levels are different from the future alternative scenarios (optimistic, mediocre, and pessimistic) presented in Chapter 5. The agency development (maturity) level is defined in terms of institutional organization and how systems operations and management (SO&M) activities are handled. Three development levels are identified as follows:

- Development Level 1: Ad Hoc. SO&M activities are accommodated on an ad hoc and informal basis, usually as part of maintenance or capital project arrangements in response to congestion problems.
- Development Level 2: Rationalized. SO&M is considered a distinct activity with adjustments in arrangements, resources, and roles to better manage each of the SO&M features.
- Development Level 3: Mainstreamed. There has been real institutional change, and improving travel time reliability through SO&M has been adopted as a core mission, with appropriate formal and standardized agreements aiming to support continuous improvement of the implemented programs.

Advancement up the ladder of these three development levels will be influenced by the following key institutional drivers:

- Anticipated major traffic impacts (e.g., Olympics, auto races);
- Unanticipated major weather events (e.g., snowstorms, hurricanes, tornadoes);
- Financial incentives (e.g., funds dedicated toward intelligent transportation systems); and
- New regional political configuration (e.g., metropolitan planning organizations [MPOs], local governments).

Agencies that experience one of these key drivers are likely to move to another level. Events such as these can present a window of opportunity that can help move agencies toward Development Level 3 (which represents the ideal agency organization). The institutional treatments presented in this section should be viewed as applicable to all three alternative future scenarios, and the level of implementation of each treatment is determined by the impact of each scenario on the institutional key drivers.

In summary, agencies could aim to grow from Development Level 1 to Development Level 3 in all three future scenarios. The treatments to be implemented are the same, but the circumstances and the intensity of each institutional key driver are different. The recommended strategies for Category 1 for all three future scenarios are shown in Table E.1.

Category 1 Strategies

SO&M Awareness

It is important that agency staff and leadership understand the impacts and benefits of the SO&M structure and to establish a goal for improving and maintaining reliability. Greater awareness can be achieved through informational programs, visible leadership, establishing a formal core program, coordinating actions among several partners (public safety, other state agencies and local governments), and setting performance measurement, analysis, and procedural improvement goals.

Therefore, an organization and its members need to accept reliability as a goal, understand and take responsibility for their strategies, and actively deploy resources to protect and enhance reliability to meet customer needs.

Table E.1. Summary of Key Treatments for Category 1 Institutional Strategies

Strategy	Treatment	Strategy Level of Development		
		1: Ad Hoc	**2: Rationalized**	**3: Mainstreamed**
Culture and leadership				
SO&M awareness	Undertake educational program regarding SO&M as customer service	Value of SO&M not yet widely appreciated: The impacts and benefits of SO&M strategies are not well understood or quantified by agency staff or leadership. Therefore, there is limited support for staffing and funding resources devoted to SO&M, especially in competition with other presumed state DOT priorities.	Role of SO&M in providing service improvements widely understood: Technical appreciation of potential performance leverage on recurring and nonrecurring congestion relative to other programs exists within the agency. The role of SO&M is appreciated by policy makers and key stakeholders.	SO&M fully appreciated: SO&M is fully appreciated in terms of value and potential within the agency and understood at policy, professional, and public levels.
	Exert visible senior leadership	Lack of management priority: No visible leadership exists among CEOs or senior and middle staffs at the agency level to mainstream SO&M.	Visible senior support agencywide: Top management is visible in supporting and articulating SO&M leverage, cost-effectiveness, and risks across disciplines in the DOT.	Visible senior support agencywide: SO&M is understood and supported by stable career leadership as a key mission.
	Establish formal core program	SO&M as a set of ad hoc activities: Vague mission regarding SO&M, and SO&M activities are parts of other programs. There is no DOT-wide strategy, budget, accountability, and so on.	SO&M as a formal mission and program with supporting policy: SO&M activities are established as a formal program with all program attributes of capital and maintenance, tailored to the special needs of operations.	New state DOT business model: New state DOT business model accepts maintaining operational level of service as a program objective and is fully mobilized programmatically for continuous improvement.
	Rationalize state DOT authority	SO&M ambitions limited by legacy assumptions: The DOT role, especially in field, is based on accepting existing or presumed legal constraints or traditions for the roles of partners in areas relating to incident response and traffic management.	Effective span of control needs identified: The DOT works with partners to identify common interests and means of rationalizing roles that meet a range of interests.	Effective span of control negotiated: Roles of public- and private-sector players rationalized (through legislation, regulation, and new contractual agreements).
	Internalize continuous improvement as agency mode or ethic	Limited progress orientation: Lack of ideal performance measurement often is used as an excuse for “business as usual” approaches.	Adoption of continuous progress concept: The DOT is broadly committed to improving SO&M in terms of both technologies and procedures on a continuous, incremental basis.	Continuous improvement internalized: The presumption is that continuous improvement is desirable and sustainable.

(continued on next page)

Table E.1. Summary of Key Treatments for Category 1 Institutional Strategies (continued)

Strategy	Treatment	Strategy Level of Development		
		1: Ad Hoc	**2: Rationalized**	**3: Mainstreamed**
Organization and staffing				
SO&M structure	Establish top-level SO&M executive structure	Leadership, subordinate, and top-level accountability absent: All core programs require equivalent status and level of influence in statewide and district program development.	SO&M at top level of program management: The status of the operations organization is equivalent in reporting relationships and chain of command, organizational unit levels, authorities and responsibility—at both the central office and districts.	Integrated, with organizational equivalency: A top-level management position with SO&M orientation is established in the central office and districts.
	Establish appropriate organizational structure	Functions fragmented and unclear: SO&M units are fragmented and responsibilities unclear at central office division or branch level and at district level. Coordination and provision of service to districts is difficult.	Functions consolidated and aligned: The functions and related responsibilities and authorities have been clarified and established (ITS, systems operations, traffic engineering, TMCs, contracting, asset management, etc.).	Integrated: An efficient and appropriate organizational structure has been established.
	Identify core capacities	Needed core capabilities unknown: There is no identification of needed core capabilities; staffing plan or job specifications and key capacities may be missing or simply not recognized as being needed.	Aligned capabilities and training: SO&M has been professionalized via identification of needed core capabilities, a program to develop and retain the needed capabilities, and a clear succession path.	Key positions filled: SO&M has been professionalized.
	Determine and allocate responsibility, accountability, and incentives	Accountability vague and conflicting: There is little, if any, accountability for the service impacts of SO&M activities—within TMCs and districts—or between districts and central office management.	Responsibilities clarified within SO&M: Clarified performance accountability in the chain of command is based on program, unit, and individual responsibilities related to SO&M effectiveness.	SO&M responsibilities clarified within all DOT units: The DOT accepts accountability for its SO&M activities (recognizing that DOT does not control all the variables that affect performance).
Resource allocation				
SO&M as a high-priority budget item	Develop program-level budget estimate	Ad hoc project funding: SO&M strategy applications are often at the project level and funded on an ad hoc, unpredictable basis, or buried in other projects (capital or maintenance) and subject to their priorities.	Criteria-based program-level needs estimated: There are cost estimates for a staged statewide program, including capital, operating, and life-cycle maintenance costs with clear priorities.	Sustainable budget line item: The agency has a needs-related and prioritized staged program.
	Introduce SO&M as a top-level agency budget line item	Outside of standard budgeting process: Funding levels for SO&M are unpredictable; there is often no knowledge of the level of funding for comparison with potential benefits or in comparison with other programs.	Consolidated program budget developed: SO&M-related costs are aggregated for full accounting that includes capital, operating, and staffing.	Sustainable budget line item: SO&M becomes a first-tier budget item.

(continued on next page)

Table E.1. Summary of Key Treatments for Category 1 Institutional Strategies (continued)

Strategy	Treatment	Strategy Level of Development		
		1: Ad Hoc	2: Rationalized	3: Mainstreamed
	Develop acceptance of sustainable resourcing from state funds	SO&M lacks clear position in state funding: Resources are suballocated from other program categories.	SO&M costs as eligible use of state funding categories: SO&M is included in state transportation budgeting procedures as a stand-alone category.	State budget for operations: SO&M becomes a separate budget category for state funding.
	Develop methodology for trade-offs	SO&M cost-effectiveness ignored across programs: SO&M is not consistently considered in the conventional highway project development process for both budget and investment trade-offs.	Criteria-based program: Related cost-effectiveness is a major factor in resource allocation.	Rational performance-based investment: The trade-off between SO&M and capital expenditure is considered as part of the planning.
Partnerships				
Public–private partnerships	Agree on operational roles and procedures with PSAs	Informal unaligned relationships: There is a modest level of SO&M cooperation and coordination between the state DOT and PSAs.	Aligned objectives and roles: there are formal, agency-level agreements regarding roles and procedures.	Rationalized roles: Roles of agencies are organized for maximum strategy effectiveness.
	Identify opportunities for joint operations activities with local government and metropolitan planning organizations	Limited interactions with local government: There is a modest level of SO&M cooperation and coordination between state and local governments (uneven, informal).	Cooperative planning, programming, and operations: SO&M is included in the MPO regional plan and programs. Active regional task forces focus on operations issues.	Regional cooperative mechanisms in place: There is an integrated SO&M program at the regional level.
	Develop procedures that accommodate partner goals and maximize mobility (minimum disruption)	Nominal procedures applications in field unclear: There is a lack of agreed-upon concepts of operations for all strategy applications and no consistent effort to measure and improve effectiveness.	Traffic impact–oriented procedures: There is agreement among partners (public and private) on improved procedures, with performance-based benchmarking against best practices.	Aggressive procedures to maximize mobility-based performance measurement activity or outcome measurement: There is an acceptance of a performance-driven process of refinement and upgrading of procedures.
	Rationalize staff versus outsourcing activities, responsibilities, and oversight	Inconsistent approach to outsourcing: The existing outsourcing arrangements may lack consistency, performance orientation, and clear interagency understanding.	Basic business model for service delivery: Essential core agency capabilities have been identified, and a consistent statewide performance management approach to outsourced services has been developed.	APPENDIX A Clarified, rationalized business model for public–private partnerships: The DOT has a clear and sustainable business model regarding in-house versus outsourced roles and how they are managed.

Source: Parsons Brinckerhoff et al. 2011.

Note: DOT = department of transportation; CEO = chief executive officer; ITS = intelligent transportation systems; TMC = transportation management center; MPO = metropolitan planning organization; PSAs = public safety agencies.

SO&M Structure

Executive leadership (at the central office and in the field) needs to be on a parity with the leadership of other programs (capacity, maintenance, etc.) for representation in policy, resource, staffing, and related decisions. The organizational structure can potentially support efficient and effective program delivery in the field via clear and efficient disposition of responsibility and capabilities with the appropriate authority—at district and central-office levels and between them. Furthermore, SO&M requires technical specialties related to planning, engineering, transportation management centers, field operations, and contract management. SO&M is therefore a specialty requiring a broad acquaintance with both the state of the practice and with state department of transportation (DOT) administration regulations. As a service focused on system performance, much of it in real time, the SO&M program can justify its claim on resources through performance accountability at the scale of the entire DOT and its component units.

Therefore, the organization's staff need to know the goals and the tools necessary to achieve them. This could mean retaining key leaders, making structural changes within the organization, and contracting with private entities to achieve the goals.

SO&M as High-Priority Budget Item

The development of a sustainable program involving a multiyear budget and operating funds requires a rational and transparent budget process, equivalent to those used in other core programs. SO&M cannot be established as a long-term, sustainable program unless it is part of the formal budgeting process for capital, operations, and staff resources. Think: goals → budgets → strategies → tactics → evaluation → goals.

Therefore, it is essential to secure the funding and tools necessary to achieve the goals of improving travel time reliability.

Public–Private Partnerships

Effective delivery of key SO&M strategy applications requires close cooperation between DOTs and public safety agencies. This may entail shared priorities, clear roles, and consensus procedures that can be implemented through changes in conventional procedures that may support DOT objectives without compromising those of the partners. At the state of the art, most SO&M strategies involve both state and local governments. An essential component of developing a program in a multijurisdictional environment is a strong and institutionalized working relationship among state, local (parallel collaborations), and regional entities (MPOs) that supports effective regional SO&M planning, programming, and implementation.

Therefore, it is important that adjacent communities work together to enhance travel reliability. Today, there are communities that undertake projects independently because they do not have shared objectives and do not communicate with each other. It is also important to establish relationships with private entities, such as railroad authorities, truckers, and distribution centers, to coordinate and optimize the combined efforts of all parties.

APPENDIX F

Additional Description and Quantitative Benefits of Travel Time Reliability Strategies

This appendix provides further description of the strategies and treatments in Categories 2 through 5: information collection and dissemination, vehicle technologies, incident and special event management, and infrastructure improvements and demand optimization. Finally, it provides examples of treatments and impacts designed to increase travel time savings in these categories.

Additional Description of Strategies

Information Collection and Dissemination

Surveillance and Detection

A variety of surveillance and detection technologies are able to detect incidents quickly. The technologies include inductive loops, acoustic and microwave vehicle detectors, and camera systems that provide frequent still images or full-motion video. These intelligent transportation system (ITS) technologies help incident management personnel identify incidents shortly after they happen. Surveillance and detection solutions along a corridor or within a region can provide considerable long-term benefits and are critical elements for establishing a nationally available, real-time system to monitor traffic and travel conditions (ITS Joint Program Office, U.S. Department of Transportation 2009).

However, reducing the annual rate of road accidents and deaths requires more than improved vehicle and roadway technologies. Surveillance treatments also include evaluating the capability of drivers to operate a motor vehicle safely in the short and long terms. Driver behavior such as speeding, reckless driving, and alcohol or drug use are typically addressed and closely monitored by law enforcement authorities. Behavioral interventions, such as stricter crackdowns on impaired driving, additional restrictions on high-risk drivers, and automated enforcement (*Critical Issues in Transportation* 2009), have proved successful in other countries.

Probe Vehicles and Point Detection

Probe vehicles and point detection (Global Positioning System [GPS], video detection, radar, transponders, Bluetooth mobile access code [MAC] Readers, Doppler radar, and video image processors [VIPs]) include technology devices that are used by roadway agencies for vehicle detection to provide near-real-time travel time estimation. The application of each technology varies among agencies according to each agency's knowledge of the technology (Franca and Jones 2010).

Doppler radar works by measuring changes in frequency and wavelength of moving targets. This sensor is usually installed on a pole or a mast along the roadway and is capable of detecting the speed of vehicles moving toward or away from the radar. Doppler radar provides direct speed measurements and is typically insensitive to inclement weather.

A VIP system typically consists of one or more cameras mounted on a pole, a microprocessor-based computer for digitizing and processing the imagery, and software for interpreting the images and converting them to traffic-flow data. VIP systems are able to monitor multiple detection zones and provide information on several aspects of travel data (e.g., speed, volume, and vehicle length). However, rain, snow, and wind gusts are known to affect sensor performance. Vehicle shadows and occlusions are other weaknesses of VIP systems.

GPS is a worldwide tracking system based on satellites that orbit the earth. GPS receivers are able to establish a vehicle's position, speed, and direction from satellite information. Continuous vehicle position information is provided because vehicle direction and speeds are measured in real time. The receiver is usually placed inside the vehicle, and a dedicated data link (e.g., wireless or cell phone network) is required to identify vehicle direction of travel and speed. GPS receivers need to have a clear sky to receive signals from the satellite system, and the connection can be lost when vehicles travel through tunnels, mountains, trees, and so on.

Transponder systems are equipped with identification tags on the vehicle and a roadside reader. When a vehicle is within the detection range of the reader, the tag communicates information about the vehicle's speed, position, and direction to the roadway central office through a dedicated data link such as a wireless network. A radio frequency identification (RFID) system is an example of a transponder system. Bluetooth MAC Readers have a similar architecture that can detect and log a Bluetooth wireless device's addresses. Matching the presence and times of detection of these addresses at successive receivers allows for the calculation of travel time and assessment of travel routes (origins and destinations). Unlike speed detectors that record speed at a single location, Bluetooth technology directly samples travel time through a corridor. One disadvantage is that transponder systems (antennas, readers, and checkpoint stations) tend to have a higher cost than do video detection and radars (point detection).

Pretrip Information

Providing information on planned disruptions in advance, whether for construction zones or special events, can greatly increase reliable travel, because travelers can better plan for their trips and adapt in terms of route and timing. Event transportation management systems can help control the impact of congestion at stadiums or convention centers. In areas with frequent events, large changeable destination signs or other lane-control equipment can be installed. In areas with occasional or one-time events, portable equipment can help smooth traffic flow. The key strategies for this subcategory relate to the preparation and dissemination of pretrip information.

National Traffic and Road Closure Information

The Federal Highway Administration (FHWA) National Traffic and Road Closure Information website provides real-time information on weather, road, and traffic conditions for travelers and freight shippers nationwide. Pretrip information is available for all 50 states, and a collection of local websites is also provided by state as well.

Planned Special Events Management

Special events cause congestion and unexpected delays to travelers by increasing traffic demand or reducing roadway capacity (e.g., street closures for parades). Advanced planning and coordination of events allow agencies to develop and deploy the operational strategies, traffic control plans, protocols, procedures, and technologies needed to control traffic and share real-time information with other stakeholders on the day of the event. These capabilities allow agencies to manage and control traffic proactively to accommodate the increased travel demand generated by the event and to use the available roadway capacity in the most efficient and effective manner (Kittelson & Associates, Inc. forthcoming).

Real-Time Information

Advanced communications have improved the dissemination of information to the traveling public. Motorists are now able to receive relevant information on location-specific traffic conditions in a number of ways, including mobile and web services, highway advisory radio (HAR), and 511 systems. In the future, in-vehicle signing would include static sign information (e.g., stop, curve warning, guide signs, service signs, and directional signs) and dynamic information (e.g., current signal status, which includes highway intersection and highway–rail intersection status and local conditions warnings identified by local environmental sensors). It would include short-range communications between field equipment and vehicles and connections to the traffic management subsystem for monitoring and control. It would also include the capability for maintenance and construction, transit, and emergency vehicles to transmit sign information to vehicles in the vicinity so that in-vehicle signing can be used without fixed infrastructure in work zones, around incidents, and in areas where transit operations affect traffic. The information that drivers obtain in real time as they travel is highly valued by drivers and can have a positive impact on the reliability of trips for individual travelers. Travelers can take a detour, change destination, or communicate their situation to others in the case of time-sensitive commitments. The ability of traveler information to improve trip reliability will increase as technology and avenues for transmitting traveler information improve. Additional information about traveler information systems can be found in *NCHRP Synthesis 399: Real-Time Traveler Information Systems* (Deeter 2009).

Pretrip Information by 511, Real-Time Navigation Systems, Websites, Subscription Alerts

Pretrip information provides data to motorists through the Internet, television, or radio. Many cities have advanced traveler information systems that are growing in sophistication. These systems incorporate close-to-real-time information from cameras and traffic reports and provide data through the Internet (Dowling 2009). Close-to-real-time information may have delivery delays of 30 minutes or more, and this technology is still developing.

Many agencies also use phone systems and traffic hotlines such as 511 to collect and distribute information about roadway conditions. Furthermore, many agency websites (e.g., 511.org in San Francisco, California, and 511.ksdot.org in Kansas City, Kansas) are starting to provide service to cell phones, which allows people to also obtain information on the go (Kittelson & Associates, Inc. forthcoming).

Road Weather Information Systems

Road weather information systems (RWIS) reduce the disruptive impacts of weather, using technology to promote safety, increase mobility, improve productivity, and protect the environment. Adverse weather conditions pose a significant threat to the operation of the nation's roads. Under extreme conditions, such as snowstorms, travel times can increase significantly. RWIS are now critical components of many agency winter maintenance programs. Accurate and timely road weather information helps maintenance managers react proactively before problems arise, thereby improving safety while also reducing costs (ITS Joint Program Office, U.S. Department of Transportation 2009).

FREIGHT SHIPPER CONGESTION INFORMATION

Freight shipper congestion information refers to real-time information along significant freight corridors. ITS technologies such as dynamic message signs (DMSs), variable message signs (VMSs), GPS, and RFID are used to provide travel time information to freight operators. As an example, these technologies are evaluated by FHWA (Kittelson & Associates, Inc. forthcoming) along segments of I-5 (California, Oregon, and Washington) and I-45 (Texas). It should be noted that the FHWA national corridor-monitoring data from transponders (through partnership with the American Transportation Research Institute) are not available or used for real-time monitoring. Many trucks are tracked by GPS, which is a great probe source. The challenge is to gain access to these data (which are private) and use them to provide real-time information.

Weigh-in-motion (WIM) technology is another treatment to relieve congestion for freight shippers. Even though WIM does not provide real-time information to truck drivers, it does allow agencies to reduce the freight screening time in weigh stations and, therefore, reduce truck queues entering and leaving the stations. In addition, data archived from WIM systems can be used to estimate truck volumes at stations (and adjacent highways) and to better plan truck routes.

Roadside Messages

Roadside messages consist of DMSs, also known as variable message signs, that display information to travelers while they are driving. DMS devices provide overhead or side-of-roadway warning and regulation, and routing and management information. These technologies are intended to affect the behavior of drivers by providing real-time traffic information related to travel times, incidents, weather, construction, and special events. DMSs are ITS solutions that provide safety and mobility benefits in urban, suburban, rural, and work zone settings. The use of DMSs is becoming more prevalent and is a very effective way to convey expected travel conditions to travelers (Kittelson & Associates, Inc. forthcoming; ITS Joint Program Office, U.S. Department of Transportation 2009; Dowling 2009).

Vehicle Technologies

Vehicle–Infrastructure Integration

Vehicle–infrastructure integration (VII) is a new technology concept that will provide full communication between vehicles and highway infrastructure. It combines technologies, such as advanced wireless communications, onboard computer processing, advanced vehicle sensors, GPS navigation, smart infrastructure, and others, to help vehicles identify threats and hazards on the roadway, and it communicates this information over wireless networks to give drivers alerts and warnings. Some of the informational products are route guidance, traffic advisories, and in-vehicle signing.

Several states, including California and Michigan, are evaluating ITS technology communication advances. Such technology is expected to improve travel time reliability by providing real-time information to roadway users and agencies about road conditions, traffic, weather, and detours (Kittelson & Associates, Inc. forthcoming).

Driver Assistance Products

Driver assistance systems can help make driving safer by recognizing potentially dangerous situations. Such systems are typically based on sensors and cameras connected to a central vehicle information system that provides warnings to the driver or directly intervenes in the driving process by braking or accelerating. These systems can be classified as side assist, front assist, brake assist, blind corner monitor, and parking and rear assist.

Advanced crash avoidance technologies are needed. ITS can help to eliminate a large number of crashes and reduce the severity of crashes. Unprecedented levels of safety, mobility, and efficiency will be made possible through the development, integration, and deployment of a new generation of in-vehicle electronics, vehicle and infrastructure automation, and selective automated enforcement, which include determining whether drivers are fit to drive. Active safety technology includes forward and rear collision avoidance, intersection collision avoidance, and lane-departure prevention.

All of these technologies aid drivers and allow vehicles to perform better and safer. Performance of in-vehicle systems can be further improved by connecting them with the infrastructure that provides information on road and traffic conditions. In addition, infrastructure-based warning and guidance technology can help improve safety for all vehicles, even those that are not specially equipped. The following is a list of other driver assistance products:

- Curve-speed warning;
- Adaptive cruise control;
- Self-aiming headlights;

- Vision enhancement systems (night or fog assistance);
- Rollover and stability control;
- Traction control;
- Lane-departure warning; and
- Work zone, pedestrian-crossing, and rail–highway intersection warnings.

Incident and Special Event Management

Pre-Event Strategies

Safety service patrols, which preceded the emergence of ITS technologies, are now frequently incorporated into traffic incident management programs. The patrol vehicles and staff, supported by an array of other ITS components, can significantly reduce the time to detect, respond to, and clear incidents. Safety service patrols are considered one of the most essential components of a successful traffic incident management program. Recently, safety service patrols have become an effective component of work zone management systems, especially for long-duration work zones. The Virginia Department of Transportation (DOT) safety service patrol assists stranded motorists with disabled vehicles and provides traffic control during traffic incidents and road work. Reductions in incident-related delay also lead to fuel savings and emissions reductions.

Postevent Strategies

Automatic Crash and Incident Detection and Notification

Getting emergency response teams as quickly as possible to the scene of a crash or other injury-producing incident is critical to saving lives and minimizing the consequences of injuries. To achieve this timely medical care, public safety providers will expect to receive timely notice of the incident, including its severity and precise location, routing guidance to the scene and to the hospital, and to be aware of and able to convey the nature and degree of the injuries, entrapments, hazardous materials spills, and fires.

Automatic location information from wireless enhanced 911 or telematics services can expedite public safety notification and response incidents. Traffic-sensitive route planning software within public safety computer-aided dispatch systems can identify which public safety response unit is closest among those available and appropriate for a specific incident. Route guidance software can efficiently direct the unit to the scene, aided by traffic-signal preemption and other traffic-control mechanisms to speed up the response. Coordination with in-vehicle systems allows public safety operators to arrive with knowledge of the potential victims and the situation, including cargo, if commercial vehicles are involved. At the scene, direct auto and video communication with the trauma center provides the public safety team with instructions on immediate treatment.

On-Scene Incident Management

Traffic incident management is defined as the coordinated, preplanned use of technology, processes, and procedures to reduce the duration and impact of incidents and to improve the safety of motorists, crash victims, and incident responders. Public safety agencies (police, fire and rescue, and emergency medical services) are the primary responders to traffic incidents. Transportation agencies usually play a secondary, supportive role. Incident management techniques deal with the coordinated work of public safety agencies and transportation agencies to ensure rapid and appropriate incident detection, response, traffic control, and clearance (Cambridge Systematics, Inc. et al. 2013, Dowling 2009). Today, insufficient attention is paid by the first responders (fire, police, etc.) to traffic operations management. First responders are mostly concerned with protecting the site and managing any injuries or fatalities.

Work Zone Management

The objective of work zone management is to move traffic through work zones safely with as little delay as possible. Today, work zone management is concerned with protecting the workers and the work zone, not necessarily with minimizing traffic impacts. Incentives on the part of agencies and contractors are generally small, and there is little real-time monitoring of performance. Work zones on freeways are estimated to account for nearly 25% of nonrecurring delay (Cambridge Systematics, Inc. and Texas Transportation Institute 2005).

ITS applications in work zones include the temporary implementation of traffic management or incident management technologies. These temporary systems can be stand-alone or be supplemental to existing systems during construction. Other applications control speed limit displays or notify travelers of changes in lane configurations, travel times, and delays through the work zones. Systems for work zone incident management can also be used to detect incidents rapidly and determine the appropriate degree of response needed, thereby limiting the amount and duration of additional capacity reductions. ITS solutions for work zone management include components such as smart work zones, traveler information and portable DMSs, dynamic lane-merge systems, variable speed limit systems, and portable traffic management systems that include surveillance and detection, and safety service patrols. ITS may also be used to manage traffic along detour routes during full road closures as a result of reconstruction projects (Potts et al. forthcoming; ITS Joint Program Office, U.S. Department of Transportation 2009).

Examples of work zone management applications in the United States include Colorado DOT's traffic incident management program for several long-term construction projects (the T-REX project in Denver and the COSMIX project in Colorado Springs), and North Carolina DOT's real-time work zone information system on I-95 north of Fayetteville in 2002 (Dowling 2009). Also, Caltrans has a software package for work zone management designed to address traffic impacts.

Infrastructure Improvements and Demand Optimization

Geometric Design Treatments

Bottleneck Removal (Weaving, Alignment)

The improvement or elimination of weaving sections can be accomplished through changes in striping or lane assignments, the use of medians to physically separate traffic flows, reconfiguring ramps to add or restrict movements, and realigning ramps to increase weaving distance or eliminate a weaving conflict. Weaving sections reduce vehicle speed, capacity, and reliability in addition to contributing to safety deficiencies. Improving weaving sections may increase roadway capacity to a degree similar to basic freeway sections or ramp merge and diverge areas.

Horizontal and vertical alignment modifications primarily apply to older facilities (arterials and freeways) that were designed and built before modern roadway design standards were established. Sharp horizontal or vertical curves affect the speed profile of vehicles and, anecdotally, can lead to sudden braking that increases the probability for a breakdown (Kittelson & Associates, Inc. forthcoming).

Geometric Improvements (Interchange, Ramp, Intersections)

Geometric improvements refer to spot reconstruction or minor geometric widening performed within the existing paved area. They are considered as low to moderate in cost and less significant than a major capital improvement project. Spot geometric design treatments, such as auxiliary lanes, flyovers, improved weaving section designs, interchange modifications, and minor alignment changes, can be part of an active traffic management package of measures. Every major metropolitan area of the United States has examples of spot geometric design treatments used to alleviate freeway bottlenecks (Kittelson & Associates, Inc. forthcoming; Dowling 2009).

Flyovers apply to interchange ramps and major through or turn movements at arterial intersections. They are generally considered a spot treatment to address a high-volume movement as opposed to full reconstruction or lane widening of a facility.

Alternative left-turn treatments at intersections refer to nonconventional intersections. This includes intersections at which left-turn movements are converted to other intersection movements to reduce the left-turn signal phase. Continuous-flow intersections shift the left turn several hundred feet downstream to eliminate the left-turn signal phase.

Interchange modifications include changes to the interchange type, ramp configurations, and traffic control of the ramp terminals.

Access Management

Access management includes driveway location, raised medians, channelization, and frontage roads. The intent of access management is to provide access to adjacent properties while maintaining a safe and efficient transportation system. Access management is an effective means to improve urban street capacity and performance. Access control includes raised medians, two-way left-turn lanes, driveway consolidation, and signal spacing (Kittelson & Associates, Inc. forthcoming; Dowling 2009).

Driveway consolidation (reducing the number of driveways on a roadway) has been shown to improve the travel speed along a roadway. Research has shown that directional free-flow speed decreases about 0.15 mph per access point, and the Florida DOT has determined that poorly designed driveways can reduce arterial travel speed by up to 10 mph (Dowling 2009).

An issue that often arises when retrofitting roadways to limit access points is opposition from business owners who depend on the access points that are being closed, restricted, or relocated. Cost is another implementation challenge, particularly if right-of-way needs to be purchased.

Raised medians are installed to reduce turning movements and manage access to land uses along a corridor. A full barrier completely limits turning maneuvers (except right turns) and the number of interruptions to traffic flow. Alternatively, limited access barriers can provide opportunities for drivers to make left-turn movements when safe and appropriate. Raised medians improve flow and performance by redirecting midblock left-turning movements to signalized intersections.

Another strategy is to channelize or separate right-turn movements to minimize impedances to through movements.

Signal Timing, ITS

Poor signal timing accounts for 5% to 10% of all traffic delay (Cambridge Systematics, Inc. and Texas Transportation Institute 2005). Optimizing signal timing is the single most-cost-effective measure for improving arterial capacity and performance. Signal timing is as important as the number of lanes on a roadway in determining the capacity and performance of an urban roadway.

TRANSPORTATION MANAGEMENT CENTERS

Transportation management centers (TMCs) are centralized facilities that gather traffic information through cameras, loop detectors, radars, and so on, to manage traffic conditions. One of the main goals of a TMC is to optimize network operations by taking into account the variation of demand throughout the day. TMCs are common in large metropolitan areas such as New York, Chicago, and Los Angeles and help agencies to better respond to traffic incidents and other sources of congestion. Despite the versatility of a TMC, its high implementation cost is a barrier in smaller urban areas. Feasibility studies identify the appropriate components to implement in the TMC facility (e.g., small urban areas may not need the transit automated vehicle location (AVL) component) and make it possible to implement a TMC in smaller urban areas.

In Europe, many countries have implemented regional TMCs. These regional TMCs are helping European roadway agencies improve travel time reliability along and across their roadway network borders. As a result of cultural shifts within European transport agencies, drivers are viewed as consumers for whom reliable travel is one of the important services agencies are able to provide. For example, the German government has a goal to ensure that 80% of all journeys have adequate, standardized real-time traffic and traveler information services by 2010 (Mirshahi et al. 2007, Organization for Economic Co-operation and Development 2007; Šitavancová and Hájek 2009).

SIGNAL RETIMING AND OPTIMIZATION

Optimization and coordination of traffic-signal timing minimizes vehicle stops, delay, and queues at individual and multiple signalized intersections by implementing or modifying signal-timing parameters (i.e., phase splits, cycle length, and offset), phasing sequences, and control strategies. Effective signal retiming can increase capacity and reduce signal delay, which leads to lower travel times, improved reliability, and reduced driver frustration. For optimal performance, plans for traffic-signal timing need to be updated at least every 3 to 5 years, and possibly more frequently, depending on growth and changes in traffic patterns. The cost of retiming a signal is approximately $3,000. If 25% of the approximately 265,000 signals in the United States are retimed every year, the annual cost would be roughly $200 million. Lack of resources (staff and funding) is the most-often-cited constraint for updating signal timing plans (Kittelson & Associates, Inc. forthcoming; Dowling 2009).

For example, the traffic light synchronization program in 43 cities in Texas reduced delay by 24.6% and lowered travel time by 14%. In Burlington, Ontario, Canada, signal retiming at 62 intersections lowered travel time by 7% (ITS Joint Program Office, U.S. Department of Transportation 2009). The traffic-signal operation self-assessment program sponsored by the National Transportation Operations Coalition (NTOC) in partnership with FHWA is a national effort to bring awareness to the need for additional investment in traffic-signal operations. Since 2005, a national traffic-signal report card has been published every 2 years that summarizes the results of self-assessments conducted by cities nationwide. The document evaluates how signal retiming and optimization are being conducted by the survey participants and points out outstanding needs to improve traffic-signal operations (National Transportation Operations Coalition 2007).

TRAFFIC-SIGNAL PREEMPTION AT HIGHWAY–RAILROAD GRADE CROSSINGS

The railroad traffic control system is required to provide a minimum warning time of 20 seconds to the signalized intersection control system, and such time is not always adequate to safely clear stopped vehicles from the highway–railroad grade crossing (HRGC) area. From a traffic engineer's perspective, the current traffic-signal preemption strategies are viewed as a reactive response to trains approaching a nearby HRGC in that 20 seconds is less than a typical cycle length of 90 to 120 seconds. Instead, if notifications of expected train arrivals at an HRGC could be accurately provided to the signalized intersection control system up to a cycle length before the train arrival at the HRGC, safer and more proactive preemption strategies could be adopted to provide improved safety and highway traffic operations in the HRGC area (Franca and Jones 2010).

Research on the application of low-cost ITS technologies to coordinate and optimize traffic-signal timing with train arrivals at grade crossings has been supported by the Federal Railroad Administration for the past several years. Several publications and test beds have been successfully implemented by universities and DOTs. Positive train control (PTC) systems have been recently identified as the leading edge in the future of railroad and highway operations. Positive train control systems are defined as having a focus on "integrated command, control, communications, and information systems for controlling train movements with safety, security, precision, and efficiency" (Franca and Jones 2010). PTC systems will reduce delays at HRGCs by providing advance notice of train arrival and traffic-signal preemption optimization. PTC systems are currently being tested by the major Class I railroads in the United States.

TRAFFIC ADAPTIVE SIGNAL CONTROL, ADVANCED SIGNAL SYSTEMS

Responsive traffic operation systems select a prepared timing plan based on the observed or measured level of traffic in the system. Adaptive traffic-signal control involves advanced detection of traffic, downstream signal arrival prediction, and adjustment of the downstream signal operation on the basis of that prediction. Traffic adaptive signal control systems coordinate the control of traffic signals along arterial corridors and adjust the signal phase lengths according to prevailing traffic conditions. Adaptive signal control systems use algorithms that perform real-time optimization of traffic signals in response to current traffic conditions, demand, and system capacity. Detection systems in the roadway or overhead inform the controllers of actual traffic that allows the signals to adapt to prevailing conditions. Traffic adaptive signal control can improve traffic flow under recurring congestion as well as traffic conditions caused by incidents and special events.

A few systems that are familiar to most traffic engineers include SCOOT, developed in the United Kingdom (used in Los Angeles); SCATS, developed in Australia; and OPAC and Rhodes (used in Tucson, Arizona, and Seattle, Washington), developed in the United States (Kittelson & Associates, Inc. forthcoming; ITS Joint Program Office, U.S. Department of Transportation 2009; Dowling 2009).

Advanced Transportation Automation Systems

Research is under way to develop systems that could automate all or part of the driving task for private automobiles, public transportation vehicles, commercial vehicles, and maintenance vehicles. This will likely be achieved through cooperation with an intelligent infrastructure, which may include instrumented roadways or dedicated lanes, or other infrastructure created by a public or private information provider. The primary objective would be to safely increase the capacity and flow of existing infrastructure. Infrastructure–vehicle automation will include applications such as the following:

- Automated transit systems in dedicated rights-of-way to increase the operational efficiency of transit;
- Automated precision docking of public transportation vehicles to improve service to transit users, particularly the disabled, the young, and the elderly;
- Dedicated lanes for automated trucks in urban or intercity corridors to improve goods movement;
- Automated guidance of snow-removal vehicles to increase the efficiency of winter maintenance operations; and
- Automated onboard monitoring and inspection systems for safety, weight, and cargo clearance of commercial vehicles.

Smart Freight

A variety of technology-based systems will improve the efficiency of freight flows, as follows:

- Because of inspection requirements for safety, weight, permits, and entry documents, trucks are required to stop at ports of entry, weigh stations, and borders. The use of weigh-in-motion technology, combined with electronic seals to secure cargo, and biometric driver identification can facilitate truck movements though these gateways.
- Unobtrusive inspection technologies, such as gamma ray machines, can also be used to reduce the length and impact of the inspection processes at gateways.
- The use of freight brokerages and the development of load-matching software can reduce the number of empty truck trips and reduce congestion.
- Research is under way in Europe to tag freight and use that information with control models to route freight automatically so that the goods find the most efficient way through the transportation network.
- Because drivers have a limited number of hours of service before they are legally required to stop, timely truck parking is an ongoing issue. Trucks that park on ramps and along roads are a safety concern and contribute to congestion. Programs that provide information to drivers about parking availability or allow for reservations would address this issue.

Traffic Demand Metering

Strategies for traffic demand metering aim at reducing the probability that a freeway or major roadway will break down by controlling the rate and location of additional new demand (i.e., from on-ramps, toll plazas). The metered traffic is allowed to enter the freeway or major road at a rate compatible with continuous or "sustained service flow" on the mainline. The objective of traffic demand metering treatments is to smooth out demand to better match the available capacity on the freeway and thereby significantly improve freeway performance. Traffic demand metering treatments consist of mainline metering, on-ramp metering, and peak-period ramp closures.

Metering can also improve travel time reliability. An experiment in which ramp meters were shut down for a 6-week period in Minneapolis–St. Paul, Minnesota, during 2000 indicated that travel times were nearly twice as predictable when the meters were on, as compared to the off condition (Kittelson & Associates, Inc. forthcoming). Freeway on-ramp metering can be operated in different schemes to control the manner and rate at which vehicles are allowed to enter a freeway. One-vehicle-per-green metering or a tandem metering scheme with two entry lanes are usually implemented. Since the first ramp meters in the United States were installed in the 1960s, hundreds of installations have been made with favorable operating results. Included are a number of "mainline metering" (usually implemented in bottlenecks caused by bridges or tunnels) sites, such as those on Oregon's OR-217, San Diego I-8, and Los Angeles I-710 (Kittelson & Associates, Inc. forthcoming). Postimplementation studies of peak-period freeway ramp metering have shown very little to no diversion of demand to downstream freeway ramp sections.

In Honolulu, Hawaii, as an experiment, the Lunalilo Street entrance ramp on the H-1 freeway was closed during the a.m. peak period for 2 weeks. This closure resulted in 10 minutes of travel time savings along the H-1 freeway. This experiment was followed by a pilot project to close the entrance ramp from 6:00 a.m. to 9:30 a.m. The ramp closure was made permanent in the fall of 2004 (Dowling 2009).

A study of the integrated deployment of freeway ramp metering and adaptive signal control on adjacent arterial routes in Glasgow, Scotland, found a 20% increase in vehicle throughput on the arterials and a 6% increase on freeways. Arterial traffic flows increased 13% after implementation of ramp metering and an additional 7% with the initiation of adaptive signal control (ITS Joint Program Office, U.S. Department of Transportation 2009).

Variable Speed Limits

A variable speed limit (VSL) strategy dynamically adjusts the facility speed limit by lane according to the facility operating conditions. As a facility approaches capacity at a bottleneck, the speed limit for upstream sections is reduced to decrease the shock at the bottleneck. In many applications, VSLs are embedded in traffic control systems that also adopt other measures such as lane control, ramp metering, or temporary hard shoulder running. The application of VSLs increases road safety by displaying traffic-adaptive speed limits as well as warnings in case of incidents, traffic congestion and road blockage, or bad weather conditions. It also helps homogenize traffic flow through work zones (Potts et al. forthcoming; Kittelson & Associates, Inc. forthcoming).

VSLs (speed harmonization) are widely used in a number of European countries, particularly on freeway sections in metropolitan areas with large traffic volumes where traffic-actuated speed limits are displayed by variable message signs. In the Netherlands, about half of the freeway network is equipped with traffic-control systems that display VSLs. In Germany, VSLs are currently used on approximately 750 miles (1,200 km) of freeways (approximately 10% of the network), with further increases expected in the near future.

The difference between the application of variable speed limit systems in Europe and the United States is that European systems use ITS technologies to automate changes in the posted speed limit according to traffic volume thresholds; in the United States, however, changes to the posted speed limit are typically applied by time of day or manually. The European system facilitates a rapid response to changes in traffic demand, which provides better traffic flow on the roadways (Mirshahi et al. 2007; Organization for Economic Co-operation and Development 2007; Šitavancová and Hájek 2009).

In the United States, VSLs are being used along several Interstates such as the I-70 Eisenhower Tunnel in Denver, Colorado (advisory downgrade speeds for trucks), and the I-90 Snoqualmie Pass in Washington State (regulatory speed for all traffic is based on weather conditions) (Dowling 2009).

A major challenge of VSLs is motorist compliance. Inappropriate signs and arbitrary speed restrictions, particularly at low volumes, lead to reduced compliance (Kittelson & Associates, Inc. forthcoming).

Congestion Pricing

Congestion pricing, also known as value pricing, uses variable and areawide tolls to reduce traffic volume during particular times of congestion or in particular areas of congestion. The main goal of congestion pricing (and metering) strategies is to manage demand rather than supply. These strategies can significantly improve the operations of a roadway. Congestion or value pricing is the practice of charging tolls for the use of a facility according to the severity of congestion on the facility or on a parallel facility. The objective of congestion pricing is to preserve high operating speeds by using a tolling system that encourages drivers to switch to other times of the day, other modes, or other facilities when demand is near facility capacity. The pricing scheme can be static or varied according to daily demand. Many applications of various static congestion pricing schemes already exist, including those in London and Singapore (Kittelson & Associates, Inc. forthcoming; Mirshahi et al. 2007; Organization for Economic Co-operation and Development 2007; Šitavancová and Hájek 2009). In the United States, variable pricing schemes are currently applied along managed and express lanes (i.e., SR-91 in Orange County, California, and I-95 in South Florida).

Congestion pricing is a valuable tool that can prevent a roadway system from breaking down during peak periods by sustaining good service rates. Beyond improving operations, congestion pricing can also generate revenue, which in turn, can be used for future transportation improvements.

ELECTRONIC TOLL COLLECTION

New tolling technologies can help reduce the complexity and improve the accuracy of congestion pricing in addition to expediting the tolling process. Technology such as electronic tolling helps reduce the delay associated with paying for tolls. The E-ZPass system in the northeast region of the United States and Autopass, developed in Norway, electronically debit an account as the user drives through a toll plaza.

Electronic toll collection eliminates the need for a vehicle to come to a complete or near stop to pay the toll. Some systems are able to collect tolls at full freeway speed, while others that are retrofitted to an existing manual toll-collection facility require vehicles to slow to speeds of 25 mph or less for safety reasons. Electronic toll collection may use toll tag readers, license plate recognition, cell phones, or GPS units.

Cordon Pricing (Areawide)

Cordon pricing imposes tolls for vehicles entering a central area street network during certain hours of certain days. Singapore, London, and Stockholm, Sweden, are international examples of this congestion pricing method. The toll may be reduced or waived for certain vehicle types such as those with high occupancy (Kittelson & Associates, Inc. forthcoming; Mirshahi et al. 2007; Dowling 2009).

Lane Treatments

Lane treatments consist of strategies that result in an added or dedicated travel lane for a directional movement of traffic or a specific vehicle or user type within the current section of roadway. The objective is often to improve the vehicle-moving capacity for peak directional movements during congested periods of the day. Lane treatment strategies can also be applied to increase the people-moving capacity of the facility and reduce vehicular travel demand in the case of bus-only or high-occupancy vehicle (HOV) lanes. Lane treatments apply to both freeway and arterial facilities and can be implemented on a static or dynamic basis. Lane treatments represent the most popular class of treatments for recurring bottlenecks.

Managed Lanes: HOV Lanes, High-Occupancy Toll Lanes, Truck-Only Lanes, Truck-Only Toll Lanes, HOV By-Pass Ramp

An HOV lane is reserved for the use of carpools, vanpools, and buses—in some applications, motorcycles can use them too. Most HOV lanes are implemented on freeway facilities adjacent to unrestricted general-purpose lanes. HOV lanes limit lane use to multioccupant vehicles for the entire day or for peak traffic hours. There are several types of HOV lanes, which include concurrent-flow lanes, barrier-separated lanes, contra-flow lanes, shoulder lanes, and ramp-bypass metered lanes. The intent of HOV lanes is to increase the person-moving capacity of a corridor by offering incentives for improvements in travel time and reliability. On average, HOV lanes carry a maximum of between 3,400 and 4,000 persons per lane hour. Case studies in Washington, Minnesota, Oregon, and California document benefits in terms of improved throughput of persons and improved reliability (Cambridge Systematics, Inc. et al. 2013; Potts et al. forthcoming; Kittelson & Associates, Inc. forthcoming; ITS Joint Program Office, U.S. Department of Transportation 2009; Franca and Jones 2010). An inventory of existing and planned HOV facilities is provided through the FHWA Office of Operations website for HOV facilities (FHWA, U.S. Department of Transportation 2012).

High-occupancy toll (HOT) lane facilities charge single-occupancy vehicles (SOVs) for the use of an HOV lane. Access to HOT lanes is free for transit vehicles, vanpools, and carpools. The toll charges for SOVs varies depending on the level of congestion to ensure that traffic volume does not exceed an established threshold for all vehicles in the HOV lanes so that free-flow travel conditions are maintained. Toll collection is performed electronically by using open-road tolling to allow high-speed toll collection. Tolls are charged at fixed points along the facility (ITS Joint Program Office, U.S. Department of Transportation 2009).

Changeable Lane Assignments: Reversible, Temporary Shoulder Use, Variable

Reversible lanes are used on arterial roadways, freeways, bridges, and tunnels to increase the capacity of facilities that experience strong directional traffic flows, especially during peak hours. Most reversible-lane applications on freeways are implemented by constructing a separated set of lanes along the center of the freeway with gate controls on both ends. Changeable lane-control signs may be used to inform drivers of the current status of the reversible lane (Potts et al. forthcoming; Dowling 2009).

Examples of this treatment include I-15 in San Diego, California, the Kennedy Expressway in Chicago, Illinois, I-5 and I-90 in Seattle, Washington, and the Shirley Highway in Northern Virginia. A movable barrier can be installed along undivided facilities to physically separate opposing directions of traffic flow. A reversible lane has also been used through downtown Stanley Park and the three-lane Lion's Gate Bridge in Vancouver, British Columbia, Canada (Kittelson & Associates, Inc. forthcoming; Dowling 2009).

In Europe, temporary shoulder use is implemented to reduce congestion levels. This strategy has been used with the automated VSLs in the Netherlands and Germany (Mirshahi et al. 2007).

Variable lanes at an intersection refer to the use of variable lane-use control signs that change the assignment of turning movements to accommodate variations in traffic flow. Variable turn lanes change a parking or a through lane into an exclusive left- or right-turn lane during peak periods by using dynamic lane markings and overhead variable lane-use control signs. Variable lanes have been applied in Montgomery County, Maryland, to increase the number of left-turn lanes during peak periods (Kittelson & Associates, Inc. forthcoming; ITS Joint Program Office, U.S. Department of Transportation 2009).

The use of variable lanes to add turn lanes requires adequate turning radii, adequate departure and receiving lanes, variable-mode signal phasing, and advance warning signs.

Multimodal Travel

Integrated multimodal corridors. Integrated multimodal corridors allow various partner agencies to manage the transportation corridor as a system rather than relying on the traditional approach of managing individual assets. An example of this is the use of transit signal priority, which provides an interface between transit vehicles (transit agency) and a traffic-signal system (local or state agency). This coordination helps reduce congestion and improve the productivity of the nation's transportation corridors.

The U.S. DOT launched a 5-year, multimodal integrated corridor management (ICM) initiative in 2005 to help mitigate bottlenecks, manage congestion, and allow travelers to make more-informed travel choices. In 2006, the U.S. DOT selected eight pioneer sites to partner with and define their concepts of operations and requirements for the ICM initiative. The pioneer sites include Oakland and San Diego, California; Dallas, Houston, and San Antonio, Texas; Montgomery County, Maryland; Seattle, Washington; and Minneapolis, Minnesota (*Integrated Corridor Management Systems Program Plan* 2009; Cronin et al. 2009).

Travel Reduction

RIDE-SHARE PROGRAMS

Ride-share programs involve online carpool matching and assistance to employers to match their employees with vanpools. Vanpools that meet program criteria, such as traveling at least 20 miles for a round trip are given a partial subsidy as an incentive.

TELECOMMUTING

Telecommuting refers to employees who work from home or from a satellite location on a regular basis. Of course, this type of strategy does not work for all types of employment, such as manufacturing, which requires employees to be present at the workplace.

Summary of Strategy Quantitative Benefits

The impacts of the application of the strategies and treatments are described in this appendix in terms of the anticipated travel time savings. Quantitative benefits (in terms of travel time savings or delay reduction) have not been determined for Category 1: agency management, organization, and resource allocation. However, quantitative benefits have been determined for the 18 strategies in Categories 2 through 5. Table F.1 quantifies information related to travel time reliability improvements and congestion reduction for these strategies.

Information Collection and Dissemination

Surveillance and Detection: Treatments and Impacts

Remote Verification: Closed-Circuit Television

- Safety
  - The closed-circuit television (CCTV) camera in Monroe County, New York, provided traffic operators visual feedback to examine real-time incident conditions and provide a higher and more-responsive quality of service to the traveling public (RITA, U.S. Department of Transportation 2013).
  - Traffic surveillance, lane control signs, VSLs, and DMSs in Amsterdam, Netherlands, have led to a 23% decline in the crash rate (Maccubbin et al. 2008).
- Mobility
  - The Maryland Coordinated Highways Action Response Team (CHART) program is in the process of expanding to more-automated surveillance with lane sensors. A contribution to a 5% reduction in nonrecurring congestion is reported (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - The automated traffic surveillance and control program in Los Angeles, California, in operation since 1984, has reported an 18% reduction in travel time and a 16% increase in average travel speed (Cambridge Systematics, Inc. 2002).
- Efficiency
  - Benefit-to-cost ratio of 5.6:1 for initial operations of the Maryland CHART program (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - It was estimated that the CCTV system installed by Florida DOT's District 4 advanced transportation management system in Fort Lauderdale can reduce incident-response time by 13% (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).

Driver Qualification

- Safety (Abkowitz et al. 1989):
  - According to analyses of the National Automotive Sampling System (NASS) (1981–85) and Fatality Analysis Reporting System (FARS) data (1983), 58% of heavy-truck drivers involved in accidents did not receive prior training. For fatal accidents, that number is 74%.
  - National estimates from NASS data (1981–85) show that 30% or more of truck drivers involved in hazardous cargo

Table F.1. Key Quantitative Benefits for Operational Strategies

Category and Strategy	Treatment	Key Quantitative Benefit
Information collection and dissemination		
Surveillance and detection	Remote verification (closed-circuit television)	5% reduction in travel times in nonrecurring congestion and overall 18% reduction in travel times (ITS Joint Program Office, U.S. Department of Transportation 2009; Cambridge Systematics, Inc. 2002)
	Driver qualification	Reduces nonrecurring congestion by reducing accidents (Abkowitz et al. 1989)
	Automated enforcement	Reduces travel time (Skowronek et al. 1997, Virginia HOT Lanes 2006) and improves safety (Hess and Polak 2004; Gains et al. 2005; Retting et al. 2008)
Probe vehicles and point detection	GPS, video detection, microwave radar, Bluetooth MAC Readers	No direct benefit to reducing congestion, but essential to providing reliable real-time information
Pretrip information	National Traffic and Road Closure Information	Reduces delays (early and late arrivals) by 50% (Maccubbin et al. 2008)
	Planned special events management	Reduces delay due to special events (FHWA, U.S. Department of Transportation 2005a)
Real-time information	Pretrip information by 511, websites, subscription alerts, radio	Potential reduction in travel time from 5% to 20% (RITA, U.S. Department of Transportation 2013)
	RWIS	Reduces delay by up to 12% (ITS Joint Program Office, U.S. Department of Transportation 2009; *Transportation Research Record: Journal of the Transportation Research Board, No. 2086*)
	Freight shipper congestion information, commercial vehicle operations, load-matching systems, terminals and port gates	Reduces freight travel time by up to 10% (RITA, U.S. Department of Transportation 2013; ITS Joint Program Office, U.S. Department of Transportation 2009; *Transportation Research Record: Journal of the Transportation Research Board, No. 2086*); possible increase in vehicle productivity by 10% to 24% with use of access technology and appointments at port gates
Roadside messages	Travel time message signs for travelers (DMS and VMS)	Improves trip-time reliability with delay reductions ranging from 1% to 22% (RITA, U.S. Department of Transportation 2013; Maccubbin et al. 2008; *Transportation Research Record: Journal of the Transportation Research Board, No. 2047*)
Vehicle technologies		
Vehicle–infrastructure integration	VII	Unknown benefit toward reducing congestion
Driver assistance products	Electronic stability control, obstacle detection systems, lane-departure warning systems, road-departure warning systems	Reduces accidents involving vehicles by up to 50% and reduces travel times by 4% to 10% (RITA, U.S. Department of Transportation 2013)
Incident and special event management		
Pre-event	Service patrols	Can reduce incident response time by 19% to 77% and incident clearance time by 8 min (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*)
Postevent	On-scene incident management	Reductions in incident duration from 15% to 65% reported by traffic incident management programs (Maccubbin et al. 2008; Hawkins et al. 2006)
	Work zone management	Reduces work zone–related delays by 50% to 55% (RITA, U.S. Department of Transportation 2013; Maccubbin et al. 2008)

(continued on next page)

Table F.1. Key Quantitative Benefits for Operational Strategies (continued)

Category and Strategy	Treatment	Key Quantitative Benefit
Infrastructure improvements and demand optimization		
Geometric design treatments	Bottleneck removal (weaving, alignment)	Reduces travel time by 5% to 15% (American Highway Users Alliance 2005; Freeway Bottleneck Study 2009)
	Geometric improvements (interchanges, ramps, intersections, narrow lanes, temporary shoulder use)	Increases overall capacity by 7% to 22% (Mirshahi et al. 2007)
Access management	Access management (driveway location, raised medians, channelization, frontage road)	Unknown benefit toward reducing congestion
Signal timing, ITS	TMC	Reduces delay by 10% to 50% (Vanderschuren 2009; RITA, U.S. Department of Transportation 2013)
	Signal retiming and optimization	Traffic-signal retiming programs result in travel time and delay reductions of 5% to 20% (FHWA, U.S. Department of Transportation 2005a)
	Traffic-signal preemption at grade crossings	Delays at grade crossings possibly reduced by up to 8% according to simulation models (Zhang 2000)
	Traffic adaptive signal control, advanced signal systems	Adaptive signal control systems shown to reduce peak-period travel times by 6% to 53% (RITA, U.S. Department of Transportation 2013)
	Advanced transportation automation systems, signal priority, and AVL	Reduces transit delays by 12% to 21% (RITA, U.S. Department of Transportation 2013; ITS Joint Program Office, U.S. Department of Transportation 2009)
Traffic demand metering	Ramp metering, ramp closure	An increase in mainline peak-period flows of 2% to 14% due to on-ramp metering, according to a study on ramp meters in North America (Clark 2007)
Variable speed limits	VSLs	Increases throughput by 3% to 5% (Mirshahi et al. 2007)
Congestion pricing	Electronic toll collection	Reduces delay by 50% for manual cash customers and by 55% for automatic coin machine customers, and increases speed by 57% in the express lanes (RITA, U.S. Department of Transportation 2013)
	Cordon pricing (areawide)	A decrease in inner-city traffic by about 20% from congestion pricing in London (RITA, U.S. Department of Transportation 2013)
Lane treatments	Managed lanes: HOV, HOT, truck only toll lanes	Provides reduction in travel times up to 16% (Mirshahi et al. 2007)
	Changeable lane assignments (reversible, variable)	Unknown benefit toward reducing congestion
Multimodal travel	Integrated multimodal corridors	Unknown benefit toward reducing congestion
Travel reduction	Travel alternatives (ride-share programs, telecommuting, home office, videoconferences)	Unknown benefit toward reducing congestion

Note: RWIS = roadway weather information system.

accidents had at least one prior speeding conviction in the previous 3 years and at least one additional moving violation. One in every four accident-involved drivers carrying hazardous cargo had at least one accident before the recorded one.

- ○ Studies indicate that drivers with less than 1 year of experience constitute 1% of the carrier workforce, yet account for 3% of the accidents (Jovanis et al. 1987).

Automated Enforcement: Speed, Red-Light, Toll, HOV

- Safety
  - ○ The installation of speed enforcement cameras in the United Kingdom led to a decrease in casualties by an average of 28% (Hess and Polak 2004).
  - ○ Research that analyzed data for all injury accidents in Cambridgeshire in southeastern Britain between 1990

    and 2002 indicated that the installation of a speed limit enforcement camera can be expected to lead to decreases in injury accidents by 45% (Hess and Polak 2004).
  - Research conducted by the PA Consulting Group and the University of Liverpool, England, showed a 22% reduction in personal injury collisions at sites after cameras were introduced. Overall, 42% fewer people were killed or seriously injured. At camera sites, there was also a reduction of more than 100 fatalities per annum (32% fewer fatalities) (Gains et al. 2005).
  - Research on automated speed enforcement in Montgomery County, Maryland, indicated that the proportion of drivers traveling more than 10 mph above posted speed limits declined by about 70% at locations with both warning signs and speed camera enforcement, 39% at locations with warning signs but no speed cameras, and 16% on residential streets with neither warning signs nor speed cameras (Retting et al. 2008).
- Mobility
  - A survey of I-30 motorists (a facility with HOV lanes) in 1995 determined that the transit users perceived having travel time savings of 13 minutes during the a.m. peak and 12 minutes in the p.m. peak. The I-30 carpoolers perceived that they saved 16 minutes during the a.m. peak and 13 minutes in the p.m. peak compared with the general-purpose lanes (Skowronek et al. 1997).
  - Travelers saved about 20 minutes/trip on HOT lanes on I-10 in Houston, Texas (Virginia HOT Lanes 2006).
  - In Southern California, SR-91 customers estimated that they saved nearly 30 minutes during their morning and afternoon commutes (Virginia HOT Lanes 2006).
  - Average speed during the a.m. peak on the Katy Freeway in Houston was 25 mph on the general-purpose lanes and 59 mph on the HOT lanes (Virginia HOT Lanes 2006).
- Efficiency
  - A 4-year research conducted by the PA Consulting Group and the University of Liverpool showed a positive cost-benefit of around 2.7:1 after speed and red-light cameras were introduced. In the fourth year, the benefits to society from the avoided injuries were in excess of £258 million compared to enforcement costs of around £96 million (Gains et al. 2005).
  - One study of the automated speed enforcement program in British Columbia, Canada, examined the avoided costs of speeding-related fatalities and injuries and concluded that it produced annual savings of more than Can$38 million (Rodier et al. 2007).
  - Bus operating speeds in Dallas, Texas, have more than doubled since the opening of the HOV lanes on I-30 and I-35E North during a.m. and p.m. peak hours, and because of the time savings, the operating cost of DART buses using the lane has been reduced by approximately $350,000 per year (Skowronek et al. 1997).
- Energy and environment: A study conducted by the North Central Texas Council of Governments estimated that volatile organic compound (VOC) emissions are reduced by 23.4 kg/day on I-30, 50.0 kg/day on I-35E North, and 107.6 kg/day on I-635 because of the HOV lanes on each of these facilities (Skowronek et al. 1997).
- Customer satisfaction
  - Research conducted by the PA Consulting Group and the University of Liverpool showed that 82% of people questioned support the use of speed and red-light cameras (Gains et al. 2005).
  - Research regarding automated speed enforcement in Montgomery County, Maryland, indicated that 74% of county drivers thought speeding on residential streets was a problem, and 62% supported automated speed enforcement (Retting et al. 2008).

Probe Vehicles and Point Detection: Treatments and Impacts

GPS, Video Detection, Microwave Radar, Transponders, Bluetooth MAC Readers

- Safety
  - Speed camera programs can reduce crashes by 9% to 51% (RITA, U.S. Department of Transportation 2013).
  - A 2007 National Highway Traffic Safety Administration (NHTSA) literature review documented studies of speed camera programs worldwide, which had reported crash reductions from 9% to 41% (Maccubbin et al. 2008).
  - A study of 2 years of crash data following deployment of speed cameras at study sites throughout the United Kingdom found a 35% reduction in the number of people killed or seriously injured at camera locations and a 14% decline in the number of personal injury crashes (Maccubbin et al. 2008).
- Mobility: A simulation experiment in one segment of the Baltimore–Washington Parkway in Maryland showed that ad hoc networks can provide accurate information on vehicle travel time (Kim et al. 2007).
- Efficiency: In Montana, WIM sensors were installed directly in freeway travel lanes to collect truck weight and classification data continuously at 28 sites. The study found that if freeway pavement designs were based on fatigue calculations derived from comprehensive WIM data, instead of weigh station data, the state would save about $4.1 million each year in construction costs (Maccubbin et al. 2008).

- Customer satisfaction: Fifteen months after extensive deployment of automated speed enforcement cameras in the United Kingdom, a nationwide survey found that 70% of those surveyed thought that well-placed cameras were a useful way of reducing crashes and saving lives, while 21% thought that speed cameras were an infringement of civil liberties. Public opinion surveys indicated 60% to 80% support for red-light enforcement camera programs (Lee and Chow 2009).

Pretrip Information: Treatments and Impacts

National Traffic and Road Closure Information

- Mobility: A simulation study in the Washington, D.C., area found that regular users of pretrip traveler information reduced travelers' frequency of early and late arrivals by 56% and 52%, respectively (Maccubbin et al. 2008).
- Efficiency: Modeling studies in Detroit, Michigan, and Seattle, Washington, have shown slight improvements in corridor capacity with the provision of traveler information (Maccubbin et al. 2008).
- Energy and environment: In Boston, Massachusetts, a modeling study estimated that changes in travel behavior as a result of better traveler information would result in a 25% reduction in VOCs, a 1.5% decline in nitrogen oxides, and a 33% decrease in carbon monoxide (Maccubbin et al. 2008).
- Customer satisfaction: During the 2002 Winter Olympic Games in Salt Lake City, Utah, a survey about the CommuterLink website showed that 41% of visitors and 70% of residents were aware of the website. Overall, 98% of visitors and 97% of residents who used the website said it worked well for them (Maccubbin et al. 2008).

Planned Special Events Management

- Mobility: DMSs and highway advisory radio (HAR) have been used by the Kansas Highway Patrol and the Kansas DOT to manage events at the 75,000-seat Kansas Speedway on the west side of Kansas City. For three major events in 2001, traveler information technology was used in conjunction with standard traffic control items such as cones, barrels, and signs. The technology consisted of three "smart zones" that integrate DMSs, detection devices, and surveillance cameras, as well as 12 portable DMSs and four HAR transmitters. During the first race weekend in June 2001, with approximately 45,000 fans, no significant delays entering the facility caused by traffic congestion were reported. During the second event of the season in July, no significant delays due to ingress and egress of vehicles were reported. At the third event of the season, the NASCAR weekend, traffic was expected to be at its highest levels and to suffer significant delays. With over an hour before the race started, all roadways leading into the Kansas Speedway were at free-flow conditions (FHWA, U.S. Department of Transportation 2005a).
- Customer satisfaction: Acadia National Park on the coast of Maine is one of the most visited national parks in the summer season. The Acadia National Park, Maine DOT, and other local organizations have tested traveler information in the form of real-time bus-departure signs and onboard bus announcements and real-time parking information on message boards. Both bus information systems aimed at having visitors use the free bus system called Island Explorer. In a survey of visitors in 2002, more than two-thirds said the electronic departure signs and onboard announcements helped them decide to use the Island Explorer bus. And almost half the users of the real-time parking information said it helped them decide to use the Island Explorer bus. Traveler information technologies have contributed to the overall goal of diverting visitors from personal vehicles to using public transit (FHWA, U.S. Department of Transportation 2005a).

Real-Time Information: Treatments and Impacts

Pretrip Information by 511, Websites, Subscription Alerts, Radio, Real-Time Navigation Systems

- Safety: ITS Deployment Analysis Systems (IDAS) models of the Advanced Regional Traffic Interactive Management Information System (ARTIMIS) in Cincinnati, Ohio, and Northern Kentucky estimated that traveler information reduced fatalities by 3.2% (RITA, U.S. Department of Transportation 2013).
- Mobility: Drivers who use route-specific travel time information instead of wide-area traffic advisories can improve on-time performance by 5% to 13% in the Washington, D.C., metropolitan area (RITA, U.S. Department of Transportation 2013).
    - ○ Modeling studies in Detroit, Seattle, and Washington, D.C., have shown slight improvements in corridor capacity with provision of traveler information (Maccubbin et al. 2008).
    - ○ Modeling performed as part of an evaluation of nine ITS implementation projects in San Antonio, Texas, indicated that drivers of vehicles with in-vehicle navigation devices could experience an 8.1% reduction in delay (ITS Joint Program Office, U.S. Department of Transportation 2009).
    - ○ A study conducted in Salt Lake City, Utah, shows that 511 users can reduce peak-period late arrivals by 14%

  when compared to nonusers. The combination of 511 and DMSs showed that the reductions can be up to 24% (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - Internet-user travelers saved 8.4% of travel time in the San Antonio, Texas, area (Walton et al. 2006).
  - The Vehicle Information and Communication System (VICS) in Japan has provided the latest road-traffic information to drivers through car navigation systems since 1996. The Japanese Ministry of Construction estimated that with a national deployment rate of 30%, VICS would reduce traffic congestion by 6% (Klein 2001).
- Efficiency: A simulation study in the Washington, D.C., area found that 40% of travelers who use pretrip traveler information would save $60 or more per year (RITA, U.S. Department of Transportation 2013).
- Energy and environment: A simulation study indicated that integrating traveler information with traffic and incident management systems in Seattle, Washington, could reduce emissions by 1% to 3%, lower fuel consumption by 0.8%, and improve fuel economy by 1.3% (RITA, U.S. Department of Transportation 2013).
- Customer satisfaction
  - An evaluation of an Arizona 511 telephone traveler information system found that more than 70% of users surveyed were satisfied with the enhancements (RITA, U.S. Department of Transportation 2013).
  - In Houston, real-time travel time information posted on DMSs influenced drivers' route choice. Eighty-five percent of respondents indicated that they changed their route because of the information provided. (Of these respondents, 66% said that they saved travel time as a result of the route change, and 29% were not sure.) Overall, drivers were primarily interested in seeing incident and travel time information (Maccubbin et al. 2008).

Road Weather Information Systems

- Safety
  - A wet pavement detection system in North Carolina on I-85 yielded a 39% reduction in the annual crash rate under wet conditions (RITA, U.S. Department of Transportation 2013).
  - Anti-icing systems deployed on bridges in Utah, Minnesota, and Kentucky led to crash reductions from 25% to 100%. (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - In Vantage, Washington, the deployment of an automated anti-icing system on I-90 was projected to eliminate up to 80% of snow- and ice-related crashes (Maccubbin et al. 2008).
  - A VSL system implemented along I-75 in Tennessee to control traffic during foggy conditions, and close the freeway if necessary, has dramatically reduced crashes. Although there had been more than 200 crashes, 130 injuries, and 18 fatalities on this highway section since the Interstate opened in 1973, a 2003 report noted that only one fog-related crash occurred on the freeway since installation of the system in 1994 (Maccubbin et al. 2008).
- Mobility
  - Signal-timing plans implemented in Minnesota to accommodate adverse winter weather resulted in an 8% reduction in delay (RITA, U.S. Department of Transportation 2013).
  - In Salt Lake City, Utah, the use of 511 to provide weather information resulted in a reduction of peak-period late arrivals by 11.8% (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - In Finland, an RWIS that automatically communicated actual and forecast data to road maintenance personnel was estimated to save an average of 23 minutes per deicing activity and improve traffic conditions (Maccubbin et al. 2008).
- Efficiency
  - The benefit-to-cost ratios in Oregon for two automated wind-warning systems were 4.13:1 and 22.80:1 (RITA, U.S. Department of Transportation 2013).
  - In Salt Lake City, Utah, staff meteorologists stationed at a traffic operations center (TOC) provided detailed weather forecast data to winter maintenance personnel, which reduced costs for snow- and ice-control activities and yielded a benefit-to-cost ratio of 10:1 (Maccubbin et al. 2008).
  - Benefit-to-cost ratios for RWIS and anti-icing strategies range from 2:1 to 5:1 (Maccubbin et al. 2008).
  - A Kansas DOT study found that the application of AVL to highway winter maintenance vehicles could result in a benefit-to-cost ratio ranging from at least 2.6:1, with conservative assumptions, to 24:1 or higher, with moderate assumptions (Maccubbin et al. 2008).
  - A study of a system of VSL signs in Finland controlled by weather and road conditions showed favorable results for deployment along heavily traveled road segments. The benefit-to-cost ratios ranged from 1.1:1 to 1.9:1 (Maccubbin et al. 2008).
- Energy and environment
  - Evaluation data show that anti-icing and prewetting strategies can reduce sanding applications by 20% to 30%, decrease chemical applications by 10%, and reduce chloride and sediment runoff in local waterways (RITA, U.S. Department of Transportation 2013).

  - Winter maintenance personnel from several agencies indicated that use of RWIS decreases salt use and anti-icing techniques and limits damage to roadside vegetation, groundwater, and air quality (in areas where abrasives are applied) (Maccubbin et al. 2008).
- Customer satisfaction
  - For planned special events, 94% of travelers surveyed indicated that a road-weather information website made them better prepared to travel, and 56% agreed that the information helped them avoid travel delays in a mountainous area of Spokane, Washington (RITA, U.S. Department of Transportation 2013).
  - In Idaho, 80% of motorists surveyed who used RWIS as a traveler information resource indicated that the information made them better prepared for adverse weather (Maccubbin et al. 2008).
  - Survey results in Finland indicate that 90% of drivers found weather-controlled VSL signs to be useful (Maccubbin et al. 2008).

Freight Shipper Congestion Information, Commercial Vehicle Operations, Border Technology Systems, Smart Freight, Terminals, and Port Gates

- Safety: With 25% of trucks using Commercial Vehicle Information Systems and Networks (CVISN) technology, 25,000 to 38,000 crashes were avoided nationally (Lane 2008).
- Mobility
  - A modeling study found that an appointment system for scheduling truck arrivals at cargo transfer facilities could reduce truck's in-terminal time by 48% (RITA, U.S. Department of Transportation 2013).
  - A simulation study at the Peace Bridge between the United States and Canada found that time inspection of trucks equipped with an electronic border crossing system would decrease by 14% to 66% (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - Real-time information systems can reduce travel time and costs by up to 9%, according to a simulation model (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - A simulation analysis in British Columbia, Canada, to study travel time savings of prescreening trucks showed savings up to $8.6 million in terms of travel time and up to 4% pavement load reduction (Lee and Chow 2009).
  - Time savings using commercial vehicle operations and CVISN are estimated to be 3 to 5 minutes per bypass (Brown et al. 2009).
  - In Colorado, an automated commercial vehicle prescreening system installed at three ports-of-entry check stations saved approximately 8,000 vehicle hours of delay per month (Maccubbin et al. 2008).
- Efficiency
  - Evaluation data collected from the Freight Information Real-Time System for Transport (FIRST) project estimated that savings per drayage trip to an ocean terminal would range from $21.36 to $247.57 (RITA, U.S. Department of Transportation 2013).
  - With potential cost-saving benefits ranging from $11.77 to $16.20 per air-freight shipment, the Electronic Supply Chain Manifest could save the freight industry more than $2 billion per year (Maccubbin et al. 2008).
  - In Maryland, electronic screening and credentialing systems provide a benefit-to-cost ratio ranging from 3.28:1 to 4.68:1 (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - An advanced routing and decision-making software communications program for commercial vehicles helped dispatchers organize and route time-sensitive delivery orders. The system increased the number of deliveries per driver-hour by 24% (Maccubbin et al. 2008).
  - In Washington State, it has been estimated that commercial motor carriers save $1.25 for every minute that they are not idling in weigh-station queues. Automated reporting and record-keeping technology reduces costly paperwork for the government and motor carriers (Washington State Department of Transportation 2009).
  - Use of e-seals for a dedicated ITS truck lane at the border between Washington and British Columbia resulted in a benefit-to-cost ratio ranging from 29:1 to 42:1. These lanes allow freight, equipped with transponders, to pass through the border with lower rates of inspection (Jenson et al. 2003).
  - A study of port controls and access appointment systems indicated that technology could increase vehicle productivity by 10% to 24% and access capacity by 30%.
- Energy and environment
  - In Chicago, a feasibility study indicated that automated truck-way technologies (automatic truck steering, speed, and platoon spacing control) would save travel time and reduce fuel consumption (RITA, U.S. Department of Transportation 2013).
  - In Colorado, an automated commercial vehicle prescreening system installed at three ports-of-entry check stations saved 48,200 gallons of fuel per month (Maccubbin et al. 2008).
- Customer satisfaction: Carriers surveyed indicated they were very satisfied with the ability of electronic supply chain manifest systems to duplicate paper-based systems (RITA, U.S. Department of Transportation 2013).

Roadside Messages: Treatments and Impacts

Travel Time Message Signs for Travelers, Queue-Warning Systems

- Safety
  - San Antonio, Texas, experienced a reduction of 2.8% in crashes (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - As a result of queue-warning system in the Netherlands, a reduction of 15% to 25% in primary incidents and a reduction of 40% to 50% in incidents on the system were observed (Mirshahi et al. 2007).
- Mobility
  - DMSs with delay information were found to reduce system delay by 6.7% by using models of increased traffic flow at a San Antonio, Texas, rail crossing (RITA, U.S. Department of Transportation 2013).
  - A simulation study in Detroit, Michigan, showed that DMSs combined with ramp metering would reduce vehicle delay by up to 22% (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - The ITS Deployment Analysis System (IDAS) program estimates that, on average, 11 minutes per traveler can be saved by implementing DMS systems (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - Available data show that DMSs and integrated traveler information with incident management systems can increase peak-period freeway travel speed by 8% to 13%, improve travel time (according to simulation studies), reduce crash rates, and improve trip-time reliability with delay reductions ranging from 1% to 22% (Maccubbin et al. 2008).
  - A study in six European countries showed that an average of 8% of all drivers diverted from their intended routes on the basis of the information displayed by DMSs (*Transportation Research Record: Journal of the Transportation Research Board, No. 2047*).
  - As a result of queue-warning system in the Netherlands, throughput on facilities in the system increased between 4% and 5% (Mirshahi et al. 2007).
  - Research suggests that 8% to 10% of drivers react to the information provided on DMSs in the Netherlands, which may lead to an improvement of 0% to 5% in network performance (FHWA, U.S. Department of Transportation 2006).
- Efficiency
  - In South Carolina, DMS and HAR systems made it easier for hurricane evacuees to return home during the aftermath of Hurricane Floyd (1999). Traffic volume during the evacuation, when outbound traffic used only one side of the freeway, was 44% less than traffic volume during the return trip when inbound traffic used both sides of the freeway (Maccubbin et al. 2008).
  - Positive results were found by using DMSs to display queue-warning information. In the A8 Motorway in Germany, a pilot study showed fewer accidents, reduced incidents' severity, harmonized speed, and a slight increase in capacity (Mirshahi et al. 2007).
- Customer satisfaction
  - Eighty-five percent of motorists surveyed changed their routes after viewing real-time travel time information on freeway DMSs in Houston (RITA, U.S. Department of Transportation 2013).
  - Mail-back questionnaires were sent to 428 drivers living near major freeways in Wisconsin to assess the impacts of posting travel time and traffic information on DMSs throughout the state. Of these, 221 questionnaires were returned and analyzed. The results indicated that 12% of respondents used the information more than five times per month to adjust travel routes during winter months, and 18% of respondents used the information more than five times per month to adjust travel routes during nonwinter months (Maccubbin et al. 2008).

Vehicle Technologies

Vehicle–Infrastructure Integration: Treatment and Impacts

Vehicle–Infrastructure Integration (VII)

- Safety: In Orlando, Florida, a simulation study of navigation devices found that drivers using the devices reduced their crash risks by 4% as a result of improved wrong-turn performance and the tendency of the system to select routes with improved (normally safer) facilities (Maccubbin et al. 2008).
- Mobility: A simulation study showed that VII can reduce travel time (vehicle hours of travel) by 22.5% if implemented in a network system (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).

Driver Assistance Products: Treatments and Impacts

Driver Assistance Systems

The driver assistant systems at hand are as follows: electronic stability control, obstacle detection systems, lane-change assistance systems, lane-departure warning systems, rollover warning systems, road-departure warning systems, and forward-collision warning systems

- Safety
    - A field evaluation in Michigan tested advanced cruise control (ACC) combined with forward-collision warning to form an automotive collision avoidance system (ACAS). The study found that ACAS could reduce exposure to driving conflicts leading to rear-end crashes by 8% to 23% and estimated that the combined system could eliminate about 10% of all rear-end crashes (Maccubbin et al. 2008).
    - A 1999 FHWA study suggested that lane-departure warning systems have the potential to reduce road-departure crashes by 10% for passenger vehicles and 30% for heavy trucks (RITA, U.S. Department of Transportation 2013).
    - An evaluation of electronic stability control (ESC) and crash data from the Institute for Traffic Accident Research and Data Analysis indicated that the crash rate for single-car crashes and head-on crashes decreased by about 36% when ESC was expected to be effective (RITA, U.S. Department of Transportation 2013).
    - Widespread deployment of integrated countermeasure systems could prevent more than 48% of rear-end, run-off-road, and lane-change crashes (RITA, U.S. Department of Transportation 2013).
- Mobility: In-vehicle navigation and route guidance devices can reduce travel times by 4% to 10% under normal traffic conditions or recurring traffic congestion (RITA, U.S. Department of Transportation 2013).
- Efficiency
    - A simulation study of roadways in Orlando, Florida, found that, assuming a market penetration of 30%, dynamic route guidance would allow the road network to handle a 10% increase in vehicle volumes (RITA, U.S. Department of Transportation 2013).
    - A 2007 societal benefit-cost analysis of the installation of a bundle of ACC, a collision warning system (CWS), and an advanced braking system on tractor–trailer commercial vehicles found the installation of the systems to be economically justified in two of six modeled scenarios (with benefit-to-cost ratios ranging from 1.1:1 to 1.3:1). None of the six evaluated scenarios for deployment of the technologies on all types of commercial vehicles yielded a benefit-to-cost ratio greater than 1:1 (Maccubbin et al. 2008).
    - In Japan, a guidance-vehicle system designed to lead traffic through heavy fog on freeways was projected to have a benefit-to-cost ratio ranging from 1.7:1 to 2.1:1 (RITA, U.S. Department of Transportation 2013).
    - A NHTSA modeling study indicated that forward CWS systems, lane-change or lane-merge crash avoidance systems, and road-departure countermeasure systems would yield an annual economic benefit of $25.6 billion (RITA, U.S. Department of Transportation 2013).
- Energy and environment
    - Driver response and vehicle dynamics were recorded for one ACC vehicle and two manually operated vehicles in a single lane of freeway traffic. The ACC vehicle attempted to smooth traffic flow by minimizing the variance between acceleration and deceleration extremes. Simulation models based on collected field data estimated a fuel savings of 3.6% during scenarios with frequent acceleration and deceleration (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
    - In-vehicle computer-visioning technology designed to detect and warn truck drivers of lane departure and driver drowsiness reduced fuel consumption by 15%, increased safety, and provided drivers with more comfortable working conditions (RITA, U.S. Department of Transportation 2013).
- Customer satisfaction
    - In San Antonio, Texas, 60% of drivers of paratransit vehicles equipped with in-vehicle navigation devices reported that they saved time and felt safer than when using paper maps (RITA, U.S. Department of Transportation 2013).
    - Survey data collected from tractor–trailer drivers with 1 to 3 years of experience driving with intelligent vehicle safety systems—including radar-based CWS, ACC systems, and advanced electronic braking systems—indicated that in-vehicle safety systems lowered their perceived workload by 14% to 21% over a range of driving conditions (good conditions, heavy traffic, and low visibility) (Maccubbin et al. 2008).

Incident and Special Event Management

Pre-Event: Treatment and Impacts

Service Patrols

- Safety: The Navigator incident management program in Georgia reduced secondary crashes from an expected 676 to 210 in the 12 months ending April 2004 (RITA, U.S. Department of Transportation 2013).
- Mobility
    - Several studies showed that service patrols can reduce incident-response time by 19% to 77% and incident-clearance time by 8 minutes (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
    - An analysis of nearly 10,000 incidents arising in the Hudson Valley region of New York State showed that the implementation of a freeway service patrol (FSP)

  - program would save approximately 33 vehicle hours in travel delay per incident (Chou and Miller-Hooks 2009).
  - A comprehensive evaluation of the FSP program at a San Francisco Bay Area freeway section showed that the delay savings per assisted breakdown were 42.36 vehicle hours. Savings for assisted accidents were 20.32 vehicle hours per incident and 9.35 vehicle-hours for nonassisted accidents (Skabardonis and Noeimi 1995).
- Efficiency
  - A survey conducted by the University of California, Berkeley, found that the benefits of the Los Angeles metro FSPs outweighed the costs by more than 8 to 1 in 2004 (RITA, U.S. Department of Transportation 2013).
  - Florida's road ranger program documented a savings of 1.7 million gallons of fuel across the state in 2004 due to reduced incident-related delay (ITS Joint Program Office, U.S. Department of Transportation 2013).
  - The Hoosier Helper FSP program in Northwest Indiana had a projected benefit-to-cost ratio of nearly 5:1 for daytime operations and over 13:1 for 24-hour operations (Maccubbin et al. 2008).
  - A study of two highways in Northern Virginia showed that service patrols can reduce traffic delays, and the computed benefit-to-cost ratio was 5.4:1 and 4.7:1 (*Transportation Research Record: Journal of the Transportation Research Board, No. 2047*).
- Energy and environment: A comprehensive evaluation of the FSP program at a San Francisco Bay Area freeway section showed a reduction of air pollutant emissions that included 77.2 tons of carbon monoxide, 19.1 tons of oxides of nitrogen, and 7.6 tons of hydrocarbons (Skabardonis and Noeimi 1995).
- Customer satisfaction: Satisfaction with motorist-assistance patrols ranged from 93% to more than 95% in two surveys of drivers already aware of the service in Atlanta, Georgia (RITA, U.S. Department of Transportation 2013).

Postevent: Treatments and Impacts

On-Scene Incident Management: Incident Responder Relationship, High-Visibility Garments, Clear Buffer Zones, Incident Screens

- Safety
  - The Maryland CHART highway incident management system facilitated a 28.6% reduction in average incident duration, leading to an estimated 377 fewer secondary incidents (RITA, U.S. Department of Transportation 2013).
  - In San Antonio, Texas, DMSs, combined with an incident management program, resulted in a 2.8% reduction in crashes (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - Implementation of closed-circuit television and service patrols can reduce the incident-response duration by up to 20 minutes (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - The Coordinated Highway Action Response Team (CHART) in Maryland reduced incident duration and related secondary incidents by 29% in 2002, eliminating 377 crashes within its coverage area (Maccubbin et al. 2008).
  - The expansion of the San Antonio TransGuide freeway management system had an estimated annualized crash reduction of 2.8% a year (Klein 2001).
- Mobility
  - In Georgia, the Navigator incident management program reduced the average incident duration from 67 minutes to 21 minutes, saving 7.25 million vehicle hours of delay over 1 year (RITA, U.S. Department of Transportation 2013).
  - Traffic incident management programs have reported reductions in incident duration from 15% to 65% (Maccubbin et al. 2008).
  - The Netherlands incident management program has achieved a 25% reduction in process time in 4 years (Hawkins et al. 2006).
  - On Toronto freeways, the COMPASS traffic management system saved 185 vehicles hours of delay for every million kilometers of vehicle travel (Klein 2001).
  - The expansion of the San Antonio TransGuide freeway management system had an estimated annualized delay reduction of 5.7% (Klein 2001).
- Efficiency
  - An ambulance provider in Albuquerque, New Mexico, increased its efficiency by 10% to 15% with automated vehicle location and computer-aided design (CAD) to improve route guidance (RITA, U.S. Department of Transportation 2013).
  - The Highway Emergency Response Operators (HERO) motorist assistance patrol program and Navigator incident management activities in Georgia saved more than $187 million, which yielded a benefit-to-cost ratio of 4.4:1 (Maccubbin et al. 2008).
  - The Incident Management Assistance Patrol (IMAP) program in Raleigh, North Carolina, showed a 4.3:1 benefit-to-cost ratio (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
- Energy and environment
  - The Navigator incident management program in Georgia reduced annual fuel consumption by 6.83 million gallons and contributed to decreased emissions of 2,457 tons of carbon monoxide, 186 tons of hydrocarbons, and 262 tons of nitrous oxides (RITA, U.S. Department of Transportation 2013).

  - A simulation study in Seattle showed that an incident management system with a traffic information system provided a fuel economy improvement of 1.3% (ITS Joint Program Office, U.S. Department of Transportation 2009).
- Customer satisfaction: Transportation management center staff in Pittsburgh, Pennsylvania, indicated that a real-time traffic information system used to monitor traffic density and congestion was useful and helped improve coverage for incident management (Maccubbin et al. 2008).

Work Zone Management

- Safety
  - The Illinois DOT enhanced work zone safety on I-55 by deploying an automated traffic-control system that posted traffic information and enforcement updates (number of citations issued) on DMSs located upstream of the work zone (RITA, U.S. Department of Transportation 2013).
  - A portable speed detection and warning system placed upstream from an I-80 work zone decreased the highest 15% of vehicle speeds by about 5 mph as vehicles approached a work zone lane-merge area in Nebraska (Maccubbin et al. 2008).
- Mobility
  - An automated work zone information system on a California Interstate greatly reduced traffic demand through the work zone and resulted in a maximum average peak delay that was 50% lower than expected (RITA, U.S. Department of Transportation 2013).
  - A modeling study indicated that work zone delay messages reduced maximum traffic backups by 56% and contributed to a 55% reduction in traveler delay in North Carolina (Maccubbin et al. 2008).
  - Modeling data showed that an automated work zone information system deployed on I-5 near Los Angeles contributed to a 4.3% increase in diversions and an 81% increase in average network speed (ITS Joint Program Office, U.S. Department of Transportation 2009).
- Efficiency
  - Traffic speed data in Minneapolis–St. Paul, Minnesota, collected at two Interstate work zones showed that when portable traffic management systems were deployed, work zone traffic volumes increased by 4% to 7% during peak periods (RITA, U.S. Department of Transportation 2013).
  - Based on a review of work zone ITS deployments from 17 states, the estimated benefit-to-cost ratio ranged from 2:1 to 42:1 depending upon conditions and assumptions (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - The use of ITS for temporary construction zone management in Lansing, Michigan, yielded a benefit-to-cost ratio of 1.97:1 and a net benefit of $4,874,000. The benefit-to-cost ratio was calculated by dividing the benefits of the system ($9,874,000) by the overall cost of the deployment ($5,000,000), which included $2,500,000 for opportunity costs (Maccubbin et al. 2008).
- Customer satisfaction: A survey of local residents near smart work zone systems found that more than 95% would support use of these systems in the future in North Carolina (RITA, U.S. Department of Transportation 2013).

Infrastructure Improvements and Demand Optimization

Geometric Design: Treatments and Impacts

Bottleneck Removal: Weaving, Alignment

- Safety
  - Bottleneck removal on I-15, north of the Seattle, Washington, central business district, resulted in an accident reduction of 39% (Saito et al. 2003).
  - A study conducted by the Texas Transportation Institute (TTI) on bottleneck removal showed that all sites experienced a safety benefit increase ranging from 5% to 76% with an overall average of approximately 35% (Clark 2007).
- Mobility
  - Bottleneck removals on US-59 in Houston, Texas, I-40 and I-25 in Albuquerque, New Mexico, and I-25 and I-225 in Denver, Colorado resulted in an estimated total delay reduction of 19.2 million, 14.9 million, and 9.3 million hours, respectively (American Highway Users Alliance 2005).
  - Bottleneck removal on I-17 between Union Hills Drive and Van Buren Street in Phoenix, Arizona, by adding auxiliary lanes decreased morning peak-hour travel time by 1,384 passenger-hours (6%) (Freeway Bottleneck Study 2009).
  - Bottleneck removal on I-10 between 99th Avenue and 32nd Street by widening eastbound I-10 decreased morning peak travel time by 2,555 passenger-hours (13%) (Freeway Bottleneck Study 2009).
  - Bottleneck removal on SR-51 between Cactus Road and Van Buren Street by adding auxiliary lanes decreased morning peak-hour travel time by 2,686 passenger-hours (8%) (Freeway Bottleneck Study 2009).
  - Bottleneck removal on eastbound I-10 between 24th Street and Baseline Road by constructing an eastbound collector–distributor road decreased evening peak-hour

travel time by 4,671 passenger-hours (37%) (Freeway Bottleneck Study 2009).

- Efficiency: As part of the T-Rex Project in Denver, Colorado, bottlenecks on I-25 and I-225 were removed by adding lanes on the Interstates, and Denver residents are now saving about 1.5 million gallons of motor fuel and related air pollution that is worth about $4 million per year.

Geometric Improvements: Interchanges, Ramps, Intersections, Narrow Lanes, Temporary Shoulder Use

- Safety: Thirteen case studies in Texas of minor geometric improvements showed an average reduction of 35% on injury crash rates (*Transportation Research Record: Journal of the Transportation Research Board, No. 1925*).
- Mobility: An assessment of temporary shoulder use, also called hard shoulder lane, in the Netherlands since 2003 revealed increased overall capacity by 7% to 22% (depending on use levels), decreased travel times by 1 to 3 minutes, with increasing traffic volumes up to 7% during congestion periods (Mirshahi et al. 2007).
- Efficiency: Thirteen case studies in Texas of minor geometric improvements showed benefit-to-cost ratios from 400:1 to 9:1 (*Transportation Research Record: Journal of the Transportation Research Board, No. 1925*).

Access Management: Treatments and Impacts

Access Management: Driveway Location, Raised Medians, Channelization, Frontage Road

- Safety
  - Research undertaken by the Kentucky Transportation Center estimated that access management could reduce the total statewide annual crash rate by more than 20% (House 2008).
  - An access management research project conducted by the Iowa DOT in seven communities showed that after implementation of a series of access management techniques, total accidents were reduced by approximately 39%, and rear-end and left-turn accidents were reduced by 41% and 42%, respectively (FHWA, U.S. Department of Transportation, and Institute of Transportation Engineers 2004).
  - A study on NY-27 in New York State indicated that access management had the potential to reduce the number of accidents by 53%, 77%, and 48%, respectively, for NY-27 at Unqua Road and the westerly Sunrise Mall driveway, the Philips Plaza driveways, and Old Sunrise Highway (Gluck et al. 2004).
- Mobility
  - Application of access management in Huairou County, China, increased the average travel speed by 16.3% and reduced the travel delay by 25.8 seconds (Jin and Yang 2009).
  - A research project undertaken by the Kentucky Transportation Center estimated that access management could result in a reduction of delay on the statewide surface street system of 46 million hours per year with the largest delay saving on Urban Class I and II roadways (House 2008).
- Efficiency: TTI's 2009 Urban Mobility report identified access management programs in 90 U.S. cities as reducing delay by a total of 61 million hours (Schrank and Lomax 2009).
- Energy and environment: A study by the Ohio–Kentucky–Indiana Regional Council of Governments concluded that 40% of all fuel consumption in highway transportation was attributable to vehicles stopped and idling at traffic signals (Fwa 2006).
- Customer satisfaction: A study of the effects of access management conducted in 1996 indicated that close to 80% of businesses reported no customer complaints about access to their businesses after project completion. More than 90% of motorists surveyed had a favorable opinion of improvements made to roadways that involve access management. The vast majority of motorists thought that the improved roadways were safer and that traffic flow had improved (Texas Department of Transportation 2004).

Signal Timing, ITS: Treatments and Impacts

Transportation Management Center

- Safety
  - A traffic management system in Espanola, New Mexico, on NM-68 provided a decrease in total crashes of 27.5% and a reduction in vehicle delay of 87.5% (RITA, U.S. Department of Transportation 2013).
  - The Camera Deployment and Intelligent Transportation Systems Integration project in Monroe County, New York, reduced incident validation times by 50% to 80%, saving between 5 and 12 minutes per incident (Maccubbin et al. 2008).
  - A 1994 evaluation showed that the COMPASS Downsview TMC, built and operated by the Ministry of Transport, Ontario, has resulted in a reduction in average duration of incidents from 86 minutes to 30 minutes, and the system prevented about 200 accidents per year (RITA, U.S. Department of Transportation 2013).

  - The Wisconsin DOT's freeway traffic management system resulted in a decrease in crashes of 14.8% (RITA, U.S. Department of Transportation 2013).
  - A study of the INFORM system on Long Island, New York, found a 15% accident reduction and a 9% increase in speed (RITA, U.S. Department of Transportation 2013).
- Mobility
  - A freeway management system in South Africa estimated up to a 48% reduction in travel times and up to 25% of additional throughput. These remarkable results were due to the combined implementation of CCTV systems, DMSs, in-vehicle monitoring, and toll collection (Vanderschuren 2009).
  - The Michigan Intelligent Transportation System Center reduced delays from incidents by about 40% and increased the speed by 8% (RITA, U.S. Department of Transportation 2013).
  - The Wisconsin DOT's freeway traffic management system reduced the travel time by 9%, 12%, and 16% on three separate roadway segments. Peak-period average speed in the mornings increased 3%, while volume increased 22%. Net savings of 1,454 driver-hours per peak-hour were calculated as a result of ramp metering alone (RITA, U.S. Department of Transportation 2013).
  - An estimate of average freeway incident time savings as a result of the Houston, Texas, TranStar system is 5 minutes, and a savings of 30 minutes is possible for major freeway incidents. Total annual delay savings is estimated at 573,095 vehicle hours (RITA, U.S. Department of Transportation 2013).
  - Because of Navigator in Atlanta, Georgia, the delay between the report of a crash and dispatch of emergency services has been cut in half, and accidents are cleared from the roadway 38% faster (RITA, U.S. Department of Transportation 2013).
- Efficiency
  - An evaluation of the effect of Wisconsin DOT's highway TMC in the Milwaukee metropolitan area on highway operations revealed a 5:1 benefit-to-cost ratio, excluding cost savings from crashes (Kraft 1988).
  - A statewide traffic operations center (TOC)-based freeway management program in Maryland yielded an overall benefit-to-cost ratio of 7:1 (Kraft 1988).
  - The total annual delay savings at Houston TranStar, a multiagency TMC in Houston Texas, is estimated at 573,095 vehicle hours, resulting in about $8.4 million in savings per year (FHWA and Federal Transit Agency 1999).
- Energy and environment: The Michigan Intelligent Transportation System Center led to an annual reduction of 41.3 million gallons of fuel used—a reduction of 122,000 tons of carbon monoxide, 1,400 tons of hydrocarbon, and 1,200 tons of nitrogen oxides (FHWA and Federal Transit Agency 1999).

Signal Retiming and Optimization

- Safety
  - Signal retiming in Lexington, Kentucky, reduced stop-and-go traffic delays by about 40% and accidents by 31% (Sunkari 2004).
  - In New York, 122 standard four-leg intersections on Long Island were studied for signal retiming. Eight percent fewer reportable crashes were recorded during the 36 months relative to the control sites. Crashes involving pedestrians and bicyclists dropped 37% relative to the control group of intersections. The researchers found a 12% reduction in injury crashes. The experimental sites were 9% less likely than the controls to report multiple-vehicle injury crashes (Insurance Institute for Highway Safety 2001).
- Mobility
  - The Texas traffic-light synchronization program reduced delay by 23% by updating equipment for traffic-signal control and optimizing signal timing on a previously coordinated arterial. Travel time was lowered by 14% (RITA, U.S. Department of Transportation 2013).
  - Programs for traffic-signal retiming resulted in travel time and delay reductions of 5% to 20%, and fuel savings of 10% to 15% across the nation (Maccubbin et al. 2008).
  - Traffic-signal retiming at 11 intersections on US-1 in St. Augustine, Florida, reduced delay by 36% and travel time by 10% (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - Burlington, Ontario, Canada had travel time lowered by 7% after retiming 62 intersections (ITS Joint Program Office, U.S. Department of Transportation 2009).
- Efficiency
  - Benefit-to-cost ratios for traffic-signal optimization ranged from 17:1 to 175:1 (RITA, U.S. Department of Transportation 2013).
  - On San Jose Boulevard in Jacksonville, Florida, retiming traffic signals at a 25-intersection section reduced average arterial delay by 35%, arterial stops by 39%, and arterial travel time by 7%, resulting in estimated annual fuel savings of 65,000 gallons and overall annual cost savings of $2.5 million (2001) (Sunkari 2004).
  - On US-1 in St. Augustine, Florida, retiming traffic signals at an 11-intersection arterial reduced average arterial delay by 36%, arterial stops by 49%, and arterial travel time by 10%, resulting in estimated annual fuel savings of 26,000 gallons and overall annual cost savings of $1.1 million (2001) (Sunkari 2004).
- Energy and environment: Signal-retiming projects were found to reduce fuel consumption by 2% to 9% in several U.S. and Canadian cities (RITA, U.S. Department of Transportation 2013).

Traffic-Signal Preemption at Grade Crossings

- Safety
  - Automated enforcement systems have reduced highway–rail crossing violations by 78% to 92% along two corridors in Los Angeles, California (RITA, U.S. Department of Transportation 2013).
  - In Baltimore, Maryland, a "second train coming" warning system decreased the frequency of the most common risky behavior at crossings (i.e., drivers who crossed the tracks after the protection gates began to ascend from the first train but before the protection gates could be redeployed for the second train) by 26% (RITA, U.S. Department of Transportation 2013).
- Mobility
  - In San Antonio, Texas, a modeling study found that if traffic congestion were to increase by 25%, posting nearby railroad crossing closing delays on freeway DMSs would reduce total network delay by up to 6.7% (RITA, U.S. Department of Transportation 2013).
  - The integration of a simulation model with optimization techniques showed that delays at grade crossings can be reduced by up to 8% (Zhang 2000).

Traffic Adaptive Signal Control, Advanced Signal Systems

- Safety: Deployments of adaptive signal control systems—in Scottsdale, Arizona; Oxnard, California; San Francisco, California; Howard County, Maryland; New York, New York; Fairfax, Virginia; and Minnesota—resulted in crash reductions ranging from 24% to 70% (RITA, U.S. Department of Transportation 2000).
- Mobility
  - Adaptive signal control systems have been shown to reduce peak-period travel times by 6% to 53% according to field studies in several cities (RITA, U.S. Department of Transportation 2013).
  - Adaptive signal control integrated with freeway ramp meters in Glasgow, Scotland, increased vehicle throughput by 20% on arterials and by 6% on freeways (Maccubbin et al. 2008).
  - In Los Angeles, California; Broward County, Florida; and Newark, New Jersey, travel time decreased by 13% to 25% (ITS Joint Program Office, U.S. Department of Transportation 2013).
  - Application of ACS-Lite (FHWA adaptive control software) in Gahanna, Ohio; Houston, Texas; and Bradenton, Florida, resulted in travel time reductions of up to 11% as a result of signal-timing optimization. Delay reduction was estimated to be up to 35% (Shelby et al. 2008).
  - Adaptive signal systems implementation in San Antonio, Houston, and Atlanta has shown total savings in travel time ranging from 95,000 to 2 million hours (Cambridge Systematics, Inc. 2002).
  - The implementation of the SCOOT (adaptive control technique) system in Glasgow and Coventry in the United Kingdom reduced average delay at traffic signals by approximately 12% (Klein 2001).
  - The automated traffic surveillance and control system (ATSAC) in Los Angeles reported in 1994 an 18% reduction in travel time and a 44% reduction in delay (Klein 2001).
  - The Sydney coordinated adaptive traffic system (SCATS) deployment in Park City, Utah, reduced travel times for the a.m. weekday period by an average of 7.6% and 3.9% for the p.m. weekday period. Weekend travel times were reduced by 1.9%. Travel time stopped delay was also reduced during "SCATS On" by approximately 0.5 minute on the weekend and up to 1 full minute during the weekday, or 13% and 20%, respectively (Martin and Stevanovic 2008).
- Efficiency
  - The traffic-light synchronization program in Texas shows a benefit-to-cost ratio of 62:1, with reductions of 24.6% in delay, 9.1% in fuel consumption, and 14.2% in stops (RITA, U.S. Department of Transportation 2013).
  - A 2005 Oakland Metropolitan Transportation Commission analysis of its traffic-signal coordination program yielded a benefit-to-cost ratio of 39:1 (Maccubbin et al. 2008).
  - Application of ACS-Lite in Gahanna, Ohio; Houston, Texas; and Bradenton, Florida, resulted in fuel savings of up to 7% (Shelby et al. 2008).
- Energy and environment
  - An adaptive signal control system in Toronto, Ontario, Canada, reduced vehicle emissions by 3% to 6% and lowered fuel consumption by 4% to 7% (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - ATSAC in Los Angeles reported in 1994 a 13% reduction in fuel consumption and 13% reduction in pollutant emissions (Klein 2001).

Advanced Transportation Automation Systems, Signal Priority, and AVL

- Safety: Kansas City Area Transit Authority (KCATA) dispatchers estimate that response times to bus operator calls for assistance have been reduced from 7 to 15 minutes to 3 to 4 minutes with the automated vehicle location (AVL) system (Bang 1998).

- Mobility
    - In Toronto, Ontario, Canada, transit signal priority reduced transit delay by 30% to 40% and travel time by 2% to 6% (ITS Joint Program Office, U.S. Department of Transportation 2009).
    - Experience in 13 U.S. cities and abroad shows 1.5% to 15% improvement in bus travel time due to transit signal priority (ITS Joint Program Office, U.S. Department of Transportation 2009).
    - In Denver, Colorado, transit AVL decreased early and late arrivals by 12% and 21%, respectively (RITA, U.S. Department of Transportation 2013).
    - In 1998, in Portland, Oregon, an AVL system with computer-aided dispatching (CAD) improved on-time bus performance by 9%, reduced headway variability between buses by 5%, and decreased run time by 3% (RITA, U.S. Department of Transportation 2013).
    - Data from transit systems in Portland, Oregon; Milwaukee, Wisconsin; and Baltimore, Maryland, show that AVL-CAD systems have improved schedule adherence by 9% to 23% (ITS Joint Program Office, U.S. Department of Transportation 2009).
    - The on-time performance (from 1 minute early to 3 minutes late) of KCATA improved from 78% to 95% after AVL installation (Bang 1998).
    - The San Pablo Corridor (California) transit signal priority (TSP) system reduced the total intersection delay by 16% (104 seconds), total running time was reduced by 5% (118 seconds), and therefore, bus average traveling speed was increased by 5% (Zhou 2008).
    - Field operational tests of the ATSP system at the seven intersections along California State Route 82, El Camino Real, showed that the average intersection delay for testing bus runs was reduced by 50% (Li and Zhou 2008).
- Efficiency
    - In Scandinavia, vehicles equipped with a GPS-based tracking system and onboard monitoring systems were able to reduce wasted mileage and emissions in southern and central Sweden and increase freight movement by 15% (RITA, U.S. Department of Transportation 2013).
    - A Kansas DOT survey of transportation agencies found that AVL applications for highway maintenance can have benefit-to-cost ratios ranging from 2.6:1 to 24:1 (Maccubbin et al. 2008).
    - The Winston-Salem Transit Authority in North Carolina reports that the AVL-CAD paratransit system has decreased operating expenses by 8.5% per vehicle mile and by 2.4% per passenger trip (Bang 1998).
    - KCATA achieved savings of $400,000/per year in supervisor labor costs because the AVL system made it more acceptable to allow short-term reductions in the size of the field supervision force resulting from absences or temporary reassignment of supervisors (Bang 1998).
    - Sweetwater County, Wyoming, almost doubled ridership without increasing dispatching staff by implementing AVL and CAD. Operating expenses decreased 50% per passenger-mile (Federal Transit Administration, U.S. Department of Transportation 2007).
- Energy and environment
    - Simulation of a transit signal priority system in Helsinki, Finland, indicated that fuel consumption decreased by 3.6%, nitrogen oxides were reduced by 4.9%, carbon monoxide decreased by 1.8%, hydrocarbons declined by 1.2%, and particulate matter decreased by 1.0% (ITS Joint Program Office, U.S. Department of Transportation 2009).
    - A transit signal priority system in Southampton, England, reduced bus fuel consumption by 13%, lowered bus emissions by 13% to 25%, increased fuel consumption for other vehicles by 6%, and increased the emissions of other vehicles up to 9% (ITS Joint Program Office, U.S. Department of Transportation 2009).
    - A study estimating the impact of implementing transit signal priority on a 3.95-mile section of Columbia Pike in Arlington, Virginia, indicated that during the a.m. peak period, transit signal priority could decrease fuel consumption between 1.8% (express buses scenario) and 2.8% (cross-street buses scenario) and decrease nitrogen emissions by 1.7% (RITA, U.S. Department of Transportation 2002).
- Customer satisfaction
    - More than 85% of "Smart Traveler" kiosk users in Los Angeles indicated that they would continue to use the kiosks to obtain travel information (Bang 1998).
    - The Rochester–Genesee Regional Transportation Authority in New York has implemented an automated transit information system that answers 70% of information request calls. Information request calls have increased by 80% (Bang 1998).
    - Since the implementation of an AVL-CAD system, the Winston-Salem Transit Authority reports that paratransit ridership has risen by 17.5% and its client base has increased by 100% (Bang 1998).

Traffic Demand Metering: Treatments and Impacts

Ramp Metering, Ramp Closure

- Safety
    - Crash frequency increased by 26% after the ramp-metering system on Minneapolis–St. Paul, Minnesota,

  freeways was deactivated (RITA, U.S. Department of Transportation 2013).
  - A survey of traffic management centers in eight cities found that ramp metering reduced the accident rate by 24% to 50% (Maccubbin et al. 2008).
- Mobility
  - A ramp-metering study in Salt Lake Valley showed that with an 8-second metering cycle, mainline peak-period delay decreased by 36%, or 54 seconds per vehicle (RITA, U.S. Department of Transportation 2013).
  - Freeway volume declined 9% and peak-period throughput decreased 14% after ramp meters were experimentally turned off in the Twin Cities, Minnesota (Maccubbin et al. 2008).
  - A study of the integrated freeway ramp metering and adaptive signal control on adjacent routes in Glasgow, Scotland, found a 20% increase in vehicle throughput on the arterials and a 6% increase on freeways (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - A ramp closure at Gardiner Expressway in Toronto, Ontario, Canada, led to daily travel time savings of 225 vehicle hours per day (*Transportation Research Record: Journal of the Transportation Research Board, No. 2047*).
  - A simulation study on I-4 segment in Orlando, Florida, revealed a reduction of up to 21% in travel time when VSL is used together with ramp-metering systems (Abdel-Aty and Dhindsa 2007).
  - Five pilot projects were tested on the A40 motorway in Germany; results showed that congestion decreased more than 50% during peak periods, and traffic incidents at the ramps decreased 40% (Mirshahi et al. 2007).
  - Ramp metering in the Netherlands has helped regulate the flow on highways, led to measured speed increases, and allowed capacity increases of up to 5% (FHWA, U.S. Department of Transportation 2006).
  - Ramp metering at the Oakland–Bay Bridge toll facility in San Francisco, California, resulted in an overall average travel time decrease of 16.5% and a site-specific travel time savings averaging from 2.5 to 3.5 minutes per vehicle (Clark 2007).
  - A study regarding the use of ramp meters in North America found that the mainline peak-period flows increased 2% to 14.3% because of on-ramp metering (Clark 2007).
- Efficiency
  - The benefit-to-cost ratio of the Minneapolis–St. Paul ramp-metering system was found to be 15:1 (RITA, U.S. Department of Transportation 2013).
  - The Minneapolis–St. Paul shutdown study found that freeway volumes were 10% higher with ramp meters than they were during the shutdown (RITA, U.S. Department of Transportation 2013).
  - A study in Glasgow, Scotland, found freeway volumes increased 5% with ramp metering (ITS Joint Program Office, U.S. Department of Transportation 2009).
- Energy and environment: Ramp metering saved 2% to 55% of the fuel expended at each ramp in a simulation study in Minneapolis–St. Paul (RITA, U.S. Department of Transportation 2013).
- Customer satisfaction
  - Most drivers believed that traffic conditions worsened when the Minneapolis–St. Paul ramp-metering system was shut down, and 80% supported reactivation (RITA, U.S. Department of Transportation 2013).
  - Fifty-nine percent of survey respondents in Glasgow, Scotland, found ramp metering to be a helpful strategy (ITS Joint Program Office, U.S. Department of Transportation 2009).

Variable Speed Limits: Treatment and Impacts

Variable Speed Limits

- Safety
  - VSLs in England supplemented with automated speed enforcement have reduced rear-end crashes on approaches to freeway queues by 25% to 30% (Maccubbin et al. 2008).
  - A multiyear evaluation of VSL impact on traffic safety indicated a reduction in accident numbers by as much as 20% to 30% after VSL installation (*Transportation Research Record: Journal of the Transportation Research Board, No. 2065*).
  - VSLs (also called speed harmonization in Europe) on the A5 motorway in Germany were attributed with a 3% reduction in crashes with light property damages, 27% reduction in crashes with heavy material damage, and a 30% reduction in personal-injury crashes (Mirshahi et al. 2007).
  - In the Netherlands, VSLs have reduced collisions by about 16% (Mirshahi et al. 2007).
- Mobility
  - A road-weather information system with VSL signs in Finland was projected to decrease the average vehicle speed by 0.4% to 1.4% and reduce the annual crash rate by 8% to 25% (RITA, U.S. Department of Transportation 2013).
  - The use of VSLs with distributed traffic-signal controllers was shown to reduce bottlenecks by 20% (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - The analysis of a European motorway equipped with VSLs and controlled algorithms thresholds showed

that critical occupancy is shifted to higher levels, which enabled higher flows (*Transportation Research Record: Journal of the Transportation Research Board, No. 2047*).
  - A simulation study on I-4 segment in Orlando, Florida, revealed a reduction of up to 21% in travel time when VSLs were used together with ramp-metering systems (Abdel-Aty and Dhindsa 2007).
  - A simulation study on I-66 and I-95 in Northern Virginia showed that VSLs together with hard shoulder use resulted in travel time savings of up to 7 minutes per vehicle (Mazzenga and Demetsky 2009).
  - In the Netherlands, VSL implementation has increased throughput 3% to 5% and reduced the cost of work zone traffic control (Mirshahi et al. 2007).
  - A study in Germany found that VSLs could increase the total capacity of a freeway by 10%.
- Efficiency: A VSL system in Copenhagen, Denmark, reduced mean vehicle speeds by up to 5 km/h and contributed to smoother traffic flow (Maccubbin et al. 2008).
- Energy and environment
  - A simulation study on I-66 and I-95 in Northern Virginia showed that VSLs together with hard shoulder use resulted in fuel savings of up to 4.5 miles per gallon (Mazzenga and Demetsky 2009).
  - Researchers studied air quality along a section of the Amsterdam ring road, on which the speed limit was lowered from 100 km/h to 80 km/h, and found that levels of some pollutants were reduced by up to 15% (Speed Limits Can Reduce Air Pollution 2009).
  - The American Trucking Association indicated that bringing speed limits for trucks down to 65 mph would, at a minimum, save 2.8 billion gallons of diesel fuel and reduce CO_2 emissions by 31.5 million tons in a decade. Limiting car speeds to 65 mph would, at a minimum, reduce gasoline consumption by 8.7 billion gallons and CO_2 emissions by 84.7 million tons over the same 10-year period (American Trucking Association 2009).
  - A study of the I-35 corridor in Austin, Texas, showed that by reducing the speed limit from 65 mph to 55 mph, the average daily total NO_x emission in a 24-hour period can be reduced by approximately 17% (Harb et al. 2009).
- Customer satisfaction: A survey of motorists in Copenhagen, Denmark, found that 80% of respondents had favorable impressions of VSLs and traveler information posted on DMSs near a work zone (Maccubbin et al. 2008).

Congestion Pricing: Treatments and Impacts

Electronic Toll Collection

- Safety: The addition of open road tolling (ORT) to an existing electronic toll collection (ETC) mainline toll plaza in Florida decreased crashes by an estimated 22% to 26% (RITA, U.S. Department of Transportation 2013).
- Mobility
  - The addition of ORT to an existing ETC mainline toll plaza in Florida decreased delay by 50% for manual cash customers and by 55% for automatic coin machine customers and increased speed by 57% in the express lanes (RITA, U.S. Department of Transportation 2013).
  - On the New Jersey Turnpike, E-ZPass participation and variable tolling were projected to decrease peak-period traffic congestion at urban interchanges by 15% to 20% and have minimal impacts on nonturnpike diversion routes (Maccubbin et al. 2008).
  - Simulation studies on the New Jersey Turnpike showed that if a 10% discount is applied to off-peak electronic tolls, an 8.5% delay reduction can be observed (*Transportation Research Record: Journal of the Transportation Research Board, No. 2047*).
- Efficiency
  - New Jersey Turnpike's E-ZPass provided 1.2 million gallons annual fuel savings across 27 tolling locations (ITS Joint Program Office, U.S. Department of Transportation 2009).
  - On the Tappan Zee Bridge toll plaza in New York City, a manual toll lane can accommodate 400 to 450 vehicles per hour, while an electronic lane peaks at 1,000 vehicles per hour (*Transportation Research Record: Journal of the Transportation Research Board, No. 2086*).
  - On the Oklahoma Turnpike, the cost to operate an ETC lane is approximately 91% less than the cost to staff a traditional toll lane (Maccubbin et al. 2008).
  - A benefit-cost analysis performed for an ETC in Taiwan revealed a benefit-to-cost ratio of 3.23:1 in terms of user benefits (Chu et al. 2009).
- Energy and environment: An evaluation of ETC systems at three major toll plazas outside Baltimore, Maryland, indicated that these systems reduced environmentally harmful emissions by 16% to 63% (RITA, U.S. Department of Transportation 2013).
- Customer satisfaction
  - Survey data from approximately 500 businesses in London indicated that 69% of respondents felt that congestion charging had no impact on their business, 22% reported positive impacts on their business, and 9% reported an overall negative impact (RITA, U.S. Department of Transportation 2013).
  - Public support in California for variable tolling on SR-91 was initially low, but after 18 months of operations, nearly 75% of the commuting public expressed approval of virtually all aspects of the express-lanes program (Maccubbin et al. 2008).

Cordon Pricing (Areawide)

- Mobility
    - During the first few months of the congestion charging program in London, automobile traffic declined by about 20% in the charge zone (a reduction of about 20,000 vehicles per day). Overall, peak-period congestion delay inside the charging zone decreased by about 30% approximately 1 year after the system was implemented. Average traffic speed during charging days (including time stopped at intersections) increased 37%, from 8 mph (13 km/h) before the charge and up to 11 mph (17 km/h) after pricing was introduced (RITA, U.S. Department of Transportation 2013).
    - After 3 years of operation, an access control zone in the historic core of Rome revealed a decrease by 15% to 20% in traffic, an increase on average speeds by 4%, and an increase in public transportation use by 5% (FHWA, U.S. Department of Transportation 2006).
    - In Stockholm, Sweden, a cordon pricing scheme is being implemented, and estimated impacts include a 10% to 15% reduction in traffic into the city center during peak periods and a 7% increase in public transportation use (FHWA, U.S. Department of Transportation 2006).
- Efficiency
    - Congestion pricing in London decreased inner-city traffic by about 20% and generates more than £97 million each year for transit improvements (RITA, U.S. Department of Transportation 2013).
    - Cordon charging in London increased bus ridership by 14% and subway ridership by about 1%. Taxi travel costs declined by 20% to 40% as a result of the reduced delays (RITA, U.S. Department of Transportation 2013).
    - Congestion-mitigating benefits of cordon charging in London enabled taxi drivers to cover more miles per hour, service more riders, and decrease operating costs per passenger-mile (Maccubbin et al. 2008).
- Energy and environment: Congestion charging in London led to reductions in emissions of 8% in oxides of nitrogen, 7% in airborne particulate matter, and 16% in carbon dioxide compared with data from 2002 and 2003 before the introduction of congestion charging (Maccubbin et al. 2008).
- Customer satisfaction: In May 2003, members of the London First business group—approximately 500 businesses—were surveyed. The results indicated that 69% of respondents believed that congestion charging had no impact on their businesses, 22% reported positive impacts, and 9% reported an overall negative impact. Many industries supported the charge because its direct costs were offset by savings and benefits such as faster delivery times (RITA, U.S. Department of Transportation 2013).

Lane Treatments: Treatments and Impacts

Managed Lanes: High-Occupancy Vehicles Lanes, High-Occupancy Toll Lanes, Truck-Only Lanes, Truck-Only Toll Lanes, Bypass Ramp

- Safety: A study by the Texas Transportation Institute (TTI) suggested that HOV lanes increased the number of auto accidents, either in the HOV lane or in adjacent regular lanes. In Dallas, Texas, accidents involving injury have increased by 56% in HOV zones since they were built in the 1990s (Jim Handdler and Associates 2009).
- Mobility
    - A study showed that the implementation of the Super HOT concept (freeway pricing strategy and managed lanes system) in the Los Angeles, California, and Atlanta, Georgia, areas would reduce peak-period congestion delay by up to 33 hours and 28 hours per traveler annually, respectively, for these two cities (*Transportation Research Record: Journal of the Transportation Research Board, No. 2065*).
    - A study on Houston, Texas, HOV lanes showed that the average daily directional peak-period savings ranged from around \$8,300 to more than \$50,000 per corridor. The Katy Freeway HOV lane produced the most savings in both the a.m. and p.m. peak periods, with approximately \$81,000 per day in savings. The Southwest Freeway HOV lane had the least amount of savings during both the a.m. and p.m. peak-periods, averaging around \$18,000 per day. The research estimates that the HOV lane savings for the four freeways combined exceeds \$149,000 per day, resulting in almost \$38 million per year in travel time savings (Fenno et al. 2005).
    - HOV lanes on the M606-M62 HOV gate in the United Kingdom has provided approximately a 16% reduction in travel times (Mirshahi et al. 2007).
- Efficiency: A study shows that the implementation of the Super HOT concept (freeway pricing strategy) in the Los Angeles and Atlanta areas would provide annual savings for each traveler of up to 83 gallons and 70 gallons of fuel, respectively, for these two cities (*Transportation Research Record: Journal of the Transportation Research Board, No. 2065*).

Changeable Lane Assignments: Reversible, Variable

- Safety: It was estimated that variable speed limit signs and lane-control signals installed on the autobahn in Germany would generate cost savings as a result of crash reductions that would be equal to the cost of the system within 2 to 3 years of deployment (RITA, U.S. Department of Transportation 2013).

- Mobility
  - An assessment made on the basis of a before-and-after study indicated that the changeable lane assignments on the A3-A86 motorway east of Paris saved daily travel time by 1,204 hours (Desnouailles et al. 2009).
  - Creation of an emergency-vehicle and public-transport lane on the A48 in Grenoble, France, reduced travel time for buses during the morning peak period by 16% (Desnouailles et al. 2009).

Multimodal Travel: Treatment and Impacts

Integrated Multimodal Corridors

- Mobility
  - Implementation of the integrated multimodal corridor (IMC) (I-888) in Oakland, California, is expected to reduce freeway congestion by at least 10%. Moreover, overall freeway travel time reliability will be improved by the same amount (RITA, U.S. Department of Transportation 2013).
  - As a result of the implementation of the Lund Link (an IMC in Lund, Sweden) in 2003, public transportation ridership has increased by 20% in the corridor, and about 120 new parking spaces have been avoided (FHWA, U.S. Department of Transportation 2006).

Travel Reduction: Treatments and Impacts

Travel Alternatives: Reduction in Trips and Diversion to Other Times (Ride-Share Programs, Telecommuting, Home Office, Videoconferences)

- Mobility
  - People who participated in casual carpooling in the San Francisco area gained the benefit of a 10- to 20-minute time savings while avoiding a $1 toll by using the HOV toll-bypass lane (Victoria Transport Policy Institute 2008).
  - A 1993 study found that the average one-way commute for those who work inside standard statistical metropolitan areas (SSMAs) is 22.8 minutes, while the average round-trip urban commute is 45 minutes. The study predicts more than 800 million hours in savings of commuter time annually due to lessened congestion and a reduction of 696 million vehicle hours in congestion due to telecommuting (Goodwin and Hardiman 1997).
- Efficiency
  - Employees telecommuting 2 days a week can save companies 15% to 25% in higher productivity, as well as decrease turnover, reduce space requirements, and decrease sick-time use by 2 days, resulting in a total savings per employee of an estimated $12,000 annually (*Telecommuting/Telework Programs* 2001).
  - The telecommuting program in the city of Los Angeles resulted in a $6,100 annual cost benefit to the city per telecommuter (U.S. Department of Transportation 1997a).
  - Located in Atlanta, Georgia Power implemented a pilot telecommuting program in 1992. This pilot program saved approximately $100,000 in leased office space (U.S. Department of Transportation 1997a).
  - Move Media, in West Hollywood, was estimated to have saved approximately $30,000 per year in reduced overhead expenses through its telecommuting efforts (U.S. Department of Transportation 1997a).
- Energy and environment
  - Vanpooling in the Puget Sound region, Washington, had significant environmental benefits, including annual reductions in tailpipe emissions of 370 tons and annual reductions in greenhouse gases of 63,475 tons in 1999 alone (Victoria Transport Policy Institute 2003).
  - A study done by the Metropolitan Washington Council of Governments of four measures to reduce transportation emissions found that its Telework Resource Center (a program that assisted businesses in implementing telecommuting) was estimated to reduce NO$_x$ emissions by 0.9 tons per day and volatile organic compounds (VOCs) by 0.5 tons per day (Lanarc Consultants n.d.).
  - A survey of an AT&T Telework Program indicated that in 2000 the program saved 5.1 million gallons of gas and also resulted in a reduction of 50,000 tons of CO_2 emissions (Teleworking and Teleconferencing 2009).
  - A 1993 U.S. DOT study estimated that 5.2% of the workforce telecommuting 3 to 4 days a week would save 1.1% of national fuel consumption (Teleworking and Teleconferencing 2009).
- Customer satisfaction
  - BC Tel/Telus, has had a ride-sharing program in place since the 1970s, and more than one-third of its employees participate in registered carpools. According to a survey in 2000, 98% of participants said they were very or quite satisfied with the carpooling program (Lanarc Consultants n.d.).
  - BC Hydro and Power Authority's telecommuting project piloted telecommuting from October 1993 to June 1994. At the end of the pilot, 100% of the telecommuters wanted to continue to telecommute, while 95% of managers wanted their employees to continue, with 5% being neutral (Lanarc Consultants n.d.).

APPENDIX G

Cost Information of Travel Time Reliability Strategies

Tables G.1 through G.18 provide information on capital and operational costs for Categories 2 through 5 of the categories of treatments for improving travel time reliability. These categories are information collection and dissemination, vehicle technologies, incident and special event management, and infrastructure improvements and demand optimization.

Category 2: Information Collection and Dissemination

Table G.1. Surveillance and Detection

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Remote verification (closed-circuit television [CCTV])	Medium	6	14	1.2	1.8	Monroe County, New York, deployed five CCTV cameras at high-priority intersections at a cost of $279,338.
Driver qualification	Low	NA	NA	NA	NA	Cost paid by vehicle buyer.
Automated enforcement	High if done by agencies, low if done by contractors	6	22	1.2	4.3	Cost initially borne by private contractors. If system is successful in reducing violations, revenue stream dries up, and agencies may have to pay for systems.

Note: The General Cost Information is informed by the RITA, U.S. Department of Transportation 2009, Maccubbin et al. 2008, and Hadi and Sinha 2005. Overall cost range applies to the application of a treatment in roadway segment or corridor. For example, several dynamic message signs can be installed along an important route. Unit capital cost and unit operation cost values were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., transportation management centers, integrated multimodal corridors, etc.). NA = not available.

Table G.2. Probe Vehicles and Point Detection

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Global Positioning System, video detection, microwave radar, Bluetooth MAC (mobile access code) Readers	Low	15	20	1.5	2	Colorado Springs, Colorado, spent about $5.6 million to replace in-pavement loops with video detection at 420 intersections. At a cost of $65,000, Washington State Department of Transportation (DOT) added a traffic camera system to fight congestion at two of the busiest intersections in the Puget Sound area.

Note: See Table G.1 for note.

Table G.3. Pretrip Information

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
National Traffic and Road Closure Information	Low–medium	NA	NA	NA	NA	
Planned special events management	Low–medium	NA	NA	NA	NA	

Note: See Table G.1 for note.

Table G.4. Real-Time Information

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Pretrip information by 511, websites, subscription alerts, highway advisory radio (HAR)	Variable	100 (for 511); 16 (for HAR)	1,000 (for 511); 32 (for HAR)	10 (for 511); 0.6 (for HAR)	100 (for 511); 1 (for HAR)	511 total cost (design, implement, and operate) averaged $1.8 million–$2.5 million (six State and Tampa, Southeast Florida, and Central Florida). 511 in Alaska (develop and implement) cost $1.2 million. Advanced traveler information system in Pennsylvania cost $8.2 million. The HAR system deployed at Blewett/Stevens pass in Washington State included a portable HAR unit ($30,000) and two fixed HAR stations ($15,000 each).
Road weather information systems	Low–medium	25	25	0.4	2.5	Washington State DOT installed a system in the mountainous region of Spokane to collect and communicate weather and road conditions, border crossing, and other information. The total cost was $446,807. Automated wind warning systems in Oregon cost approximately $90,000 each, and annual operations and maintenance costs range between $3,000 and $3,500. Ohio DOT added 86 weather stations to its existing road weather information system for approximately $3.7 million.
Freight shipper congestion information, commercial vehicle operations	Low	121	261	10	20	

Note: See Table G.1 for note.

Table G.5. Roadside Messages

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Travel time message signs for travelers (dynamic message signs [DMSs] and variable message signs)	High	38	94	2	5	In Orange County, California, the cost of software for posting travel times on DMSs was $50,000.

Note: See Table G.1 for note.

Category 3: Vehicle Technologies

Table G.6. Vehicle Infrastructure Integration

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Vehicle–infrastructure integration	Low–high	9.6	20.3	1	2	

Note: See Table G.1 for note.

Table G.7. Driver Assistance Products

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Electronic stability control, obstacle detection systems, lane-departure warning systems, road-departure warning systems	Low	5	10	0.15	0.26	Cost paid by vehicle buyer.

Note: See Table G.1 for note.

Category 4: Incident and Special Event Management

Table G.8. Pre-Event

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Service patrols	High	NA	NA	810	990	Operating a freeway service patrol program cost $2.4 million for 2005 in Southeast Michigan. Colorado DOT launched a service patrol program along I-70; 2005 operating costs were $1.5 million.

Note: See Table G.1 for note.

Table G.9. Postevent

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
On-scene incident management (incident responder relationship, high-visibility garments, clear buffer zones, incident screens)	High	2,400	3,450	515	341	The integrated freeway and incident management system covering 28.9 miles in San Antonio, Texas, was deployed for approximately $26.6 million. The cost to equip a police vehicle in Dane County, Wisconsin, for coordinated interagency incident response was $8,000 to $10,000.
Work zone management	Variable (depends if infrastructure is added or not)	150	500	15	50	The Arkansas State Highway and Transportation Department leased an automated work zone information system in West Memphis for $495,000. The intelligent transportation systems (ITS) work zone system cost $1.5 million in Albuquerque, New Mexico, and $2.4 million in Lansing, Michigan. Illinois DOT implemented work zone ITS on the I-64 add-lane construction project at a cost of $435,000. Based on a study of 17 states, it was found that the majority of work zone ITS cost between $150,000 and $500,000.

Note: See Table G.1 for note.

Category 5: Infrastructure Improvements and Demand Optimization

Table G.10. Geometric Design Treatments

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Bottleneck removal (weaving, alignment)	Medium–high	NA	NA	NA	NA	
Geometric improvements (interchange, ramps, intersections, narrow lanes, temporary shoulder use)	Medium	NA	NA	NA	NA	

Note: See Table G.1 for note.

Table G.11. Access Management

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000,000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Access management (driveway location, raised medians, channelization, frontage road)	Low	NA	NA	NA	NA	

Note: See Table G.1 for note.

Table G.12. Signal Timing, Intelligent Transportation Systems

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Transportation management center (TMC)	High	2,400	3,450	515	341	A new traffic management system in Espanola, New Mexico, cost $862,279. TMC physical components in Lake County, Illinois, cost $1.8 million.
Signal retiming and optimization	Low	2	5	0.16	0.31	The cost to retime a traffic signal ranged from $2,500 to $3,100 per intersection per update from six separate studies. The average cost to retime signals in the Metropolitan Transportation Commission (California) program was $2,400 per intersection. The cost of retiming 16 signals at the Mall of Millenia (Florida) was about $3,100 per intersection.
Traffic-signal preemption at grade crossings	Medium	115	130	4.25	4.85	
Traffic adaptive signal control, advanced signal systems	Medium–high	120	150	15	20	
Advanced transportation automation systems, signal priority, and automated vehicle location	Low–medium	10	14	0.34	0.46	

Note: See Table G.1 for note.

Table G.13. Traffic Demand Metering

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Ramp metering, ramp closure	Low–medium	19	31	0.94	2.2	A freeway ramp-metering system in Denver, Colorado, cost $50,000. Minnesota DOT estimated ramp-metering operations for FY 2000 cost $210,000.

Note: See Table G.1 for note.

Table G.14. Variable Speed Limits

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Variable speed limits	Low–medium	3.7	5	0.3	0.5	A variable speed limit system consisting of multiple intelligent transportation system components and covering 40 miles over the Snoqualmie Pass in Washington State was designed and implemented for $5 million.

Note: See Table G.1 for note.

Table G.15. Congestion Pricing

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Electronic toll collection (ETC)	High	17	31	0.47	0.94	The cost to implement ETC with managed lanes on a 26-mile section of I-5 was estimated at $1.7 million in San Diego County, California. A limited-access tolled expressway featuring express ETC lanes and open road tolling in Florida cost $237 million.
Cordon pricing (areawide)	Low–medium	NA	NA	NA	NA	Annual operations and maintenance costs of congestion pricing in London were estimated at £92 million.

Note: See Table G.1 for note.

Table G.16. Lane Treatments

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Managed lanes: high-occupancy vehicle (HOV), high-occupancy toll (HOT), truck-only toll	Medium–high	NA	NA	NA	NA	The cost to convert two reversible HOV lanes on an 8-mile stretch of I-15 in San Diego, California, to HOT lanes was $1.85 million. Cost estimates of operational concepts for converting HOV lanes to managed lanes on I-75/I-575 in Georgia ranged from $20.9 million to $23.7 million.
Changeable lane assignments (reversible, variable)	Medium–high	34	62	3.25	6	

Note: See Table G.1 for note.

Table G.17. Multimodal Travel

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Integrated multimodal corridors	High	2,400	3,450	515	341	

Note: See Table G.1 for note.

Table G.18. Travel Reduction

Treatment and Impact	Overall Cost Range (low = <$200,000, medium = >$200,000 but <$1 million, high = >$1 million)	Unit Capital Cost ($000)		Unit Operation Cost ($000/year)		General Cost Information
		Low	High	Low	High	
Travel alternatives (ride-share programs, telecommuting, home office, videoconferences)	Low	NA	NA	NA	NA	

Note: See Table G.1 for note.

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