SHRP 2 Reliability Project L11

Evaluating Alternative Operations Strategies to Improve Travel Time Reliability

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SHRP 2
STRATEGIC HIGHWAY RESEARCH PROGRAM
Accelerating solutions for highway safety, renewal, reliability, and capacity

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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FINAL REPORT

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ABSTRACT

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. The basic causes of unreliable travel times are an imbalance between demand and capacity and the congestion that results from too much demand for a given level of capacity. Once congestion forms, travel times become more variable (less reliable) and thus less predictable. Moreover, congested facilities do not have the resilience to accommodate unexpected travel interruptions, leading to flow breakdowns and serious degradation of reliability.

The types of solutions that can be brought to bear on the demand/capacity imbalance depend on whether congestion can be anticipated or whether congestion results from unexpected events. Where volume routinely approaches and/or exceeds capacity (recurring congestion), demand management and capacity increases are likely to be effective in improving reliability. In locations where unexpected disruptions cause the majority of congestion (non-recurring congestion), techniques that detect disruptions and facilitate rapid recovery from those events are more likely to be effective.

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 due 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.

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 (multi-modal) 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 needs to be provided to travelers so that they can make informed choices about their best travel option, given their own values of time and reliability.

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 regarding 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 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, then the travel time is considered unreliable because it is difficult to generate consistent and accurate estimates of travel time. If there is little or no variation in the travel time for the same trip, then the travel time is considered reliable.

Travel time reliability is important because when travel times are variable or unreliable, it is more difficult for travelers and shippers to plan their travel, often forcing them to pay a price of allowing extra time to protect themselves against the uncertainty of arrival times. This may lead to ineffective or even counter-productive 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 results from too much demand for a given level of capacity. Once congestion forms, travel times become more variable (less reliable) and thus less predictable. Moreover, congested facilities do not have the resilience to accommodate unexpected travel interruptions, leading to flow breakdowns and serious degradation of reliability.

Travel times vary from one day to the next because traffic-influencing conditions differ from day to day. There are seven sources of congestion that influence travel-time reliability. They are as follows:

1. Fluctuations in normal traffic
2. Physical bottlenecks
3. Special events
4. Traffic incidents
5. Weather
6. Traffic-control devices
7. Work zones

These seven 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 given roadway or set of roadways (bottlenecks, incidents, bad weather, work zones, and traffic controls).

There are two categories of actions we can use to respond to these factors. The first category, aimed at influencing 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:

- expansions or additions to highway facilities
- the 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, bad weather, work zones)
- the 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 be brought to bear on the demand/capacity imbalance depend on whether congestion can be anticipated or results from unexpected events. Where volume routinely approaches and/or exceeds capacity (recurring congestion), demand management and capacity increases are likely to be effective in improving reliability. In locations where unexpected disruptions cause the majority of congestion, techniques that detect disruptions and facilitate rapid recovery from those events are more likely to be effective. Even in situations where unexpected disruptions cause the majority of congestion, however, demand management and/or capacity increase strategies will also warrant consideration since their effect is to create a capacity margin that helps assure the system's resilience in effectively responding to unexpected events.

IMPROVED TRAVEL-TIME RELIABILITY: WHAT'S 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 scarce highway capacity to road users 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 and which has been the basis for allocating scarce roadway capacity.
- Charge each road user the full costs for using the roadway network.
- Set up 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 have 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 total available (useful) capacity
- Ready availability of accurate information describing available travel options, the expected travel times for those options, and the prices to be paid for each of those options, so that travelers and shippers can make informed choices when they plan trips, just prior to the execution of those trips, and during the execution of those trips
- 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 the funds generated from user fees to the agencies that supply the multi-modal, 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 would require a more holistic view of funding, managing, and operating that transportation system than now occurs in the United States. Consumers (individual travelers and shippers/carriers) would be given travel options, as well as information about those travel options, would be charged separately and explicitly for each of those options, and the cost associated with each option would reflect the costs of providing those transportation services. Consumers would 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 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, for some trips, would choose high-cost, faster, more reliable travel options (e.g., overnight air express shipping, or SOV commuting via HOT lanes). Other consumers would 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 expected results would be that:

- Travel consumers have choices
- Travel consumers 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 goes toward providing and improving that combination of transportation services.

Improved transportation system reliability does not mean that all travel would 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.

NEXT STEPS FOR MIGRATING TOWARD A MORE "RELIABLE" FUTURE

The most important changes necessary to produce significant improvements in travel reliability are (1) to bring market forces to bear on both travel decisions (which results from better and more ubiquitous information available to all travelers) and (2) to provide additional supply in a way that is balanced against demand. As noted at the beginning of this summary, a more reliable roadway system will only occur on a sustainable long-term basis 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 our 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, 1) roadway agencies are constantly faced with situations in which demand exceeds capacity; 2) the resources to remedy that situation are not being generated and deployed to meet those demands; and 3) travelers have insufficient information and incentive to change their behavior to travel at less congested times or via other 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 becomes part of the travel decision. In addition, there is better resource allocation when the funding generated by that travel is spent in the corridors where it is generated to support needed increases in supply (travel capacity) .These ideas constitute a major philosophical shift from how we currently operate our roadway system.

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.

Regardless, 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 (incidents, weather, etc.) 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
- an increase in revenue targeted at capacity enhancements where demand is high.

In order to implement these improvements, three steps are identified:

- Steps toward Balancing Demand and Capacity
- Steps to Strengthen Interagency and Intermodal Relationships
- Technical/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. 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 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 inter-agency cooperation below.)

Of particular significance is determining the base price-performance level that is acceptable. A congestion-free HOT lane price is acceptable, since low cost/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.

So long as congestion does exist, some non-trivial level of travel time un-reliability 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, versus how much money are we willing to pay in order to help manage the limited roadway capacity that we have?

The answers to these basic questions will undoubtedly be different in congested urban areas and 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 their leaders begin to understand the merits of road pricing, equity will become addressable through a variety of paths, including 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 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 which 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 take advantage of them 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 agency-specific goals.
- Strengthen relationships with neighboring jurisdictions, especially where improved integration of facilities benefits both agencies (e.g., shared traffic operations centers, multi-agency incident response teams, and corridor management teams).
- Create and provide easily-accessed, standardized transportation system performance data to those that 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 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 usage-based and a value-based revenue generation structure.

TECHNICAL/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 USDOTs 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 SHRP2 - C05 Project.)
- 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
- better balance between travel demand and available capacity through better demand management.

The USDOT Vehicle Infrastructure Integration (VII) program has considerable potential to contribute to many of these areas. But, the simplest technical aspects of the Vehicle Infrastructure Integration (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, that can provide data that is 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 1) the actual causes of unreliable travel time *in the areas specific to the agency and its partners* and 2) 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 commodity business to technology innovation service business will have an impact of technological innovations. Infrastructure intervention will be intrinsically related to **vehicle automation** on the roadway network. Mesh and wireless networks will facilitate vehicle-roadway communications, improving traffic flow and reducing travel time variability. The vehicle-roadway system will operate as a mobile communications and information delivery center to users. Operation and maintenance of roadway agency communication devices will have to be well-planned and structured to meet user (consumer's) satisfaction. Innovative technologies will also impact how **data sharing and agency cooperation** is handled. The transmission of huge amounts of data such as video, audio and large databases will happen in matters of seconds. This will improve interagency cooperation, especially 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 restore traffic operations.

In addition to vehicle technology innovations, the **integration of other technological innovations beyond transportation** innovations will enhance travel-time reliability. For example, health conditions of travelers will be monitored by vehicles in the future. Breakdown points/specific locations which may be a threat to health (e.g., heart attacks) can be mapped and linked to 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 that are listed below.

<u>Automation/Infrastructure Strategies</u>

- Real time control of transit arrivals, connections and pre trip
- Real time road pricing
- Reliability and quality control with pricing
- Vehicle Infrastructure Integration (VII) implementation
- Instant automated incident detection and assessment
- Robotic deployment of visual screens
- Vehicle automation
- Automated, reliable DUI detection and intervention
- 3D video, 3D Telepresence, haptic interfaces
- Automation in truck operations
- Resilient infrastructure
- Wearable Computers with Augmented Reality

<u>Information Technology/Data Sharing</u>

- 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., GPS tracking of trucks and containers)
- Data sharing

- Predictive models for real-time systems operation

Integration/Cooperation

- Customized, real time routing
- Multimodal routing, schedules, trip planning
- Real time information on parking availability, roadway conditions, routing, rerouting
- Rapid incident clearance
- Latest onboard technology
- BRT and signal pre-emption
- 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 (AACN) in all vehicles
- Next Generation 9-1-1 fully implemented
- 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
- 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” where workers that live nearby will go to work, regardless of their employer location. Government may also support people living within a certain distance of their place of employment. That will cause the miles traveled between jobs and housing to be reduced dramatically, having a positive impact on travel-time reliability.

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 (multi-modal) 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 for them, 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. The results of those performance reviews then would be fed back into the management decisions that determine which actions are taken under specific roadway conditions. That is, agencies would actively use the information that runs the management systems to continually assess the performance of that system 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 information allow travelers to choose more reliable trips.

1. INTRODUCTION

The SHRP2 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 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 both freight and person transport in urban and rural areas.** The intent of this project is to provide a short-term perspective regarding system operations and travel-time reliability, and to produce a long-term view with innovative ideas that can be implemented in the future.

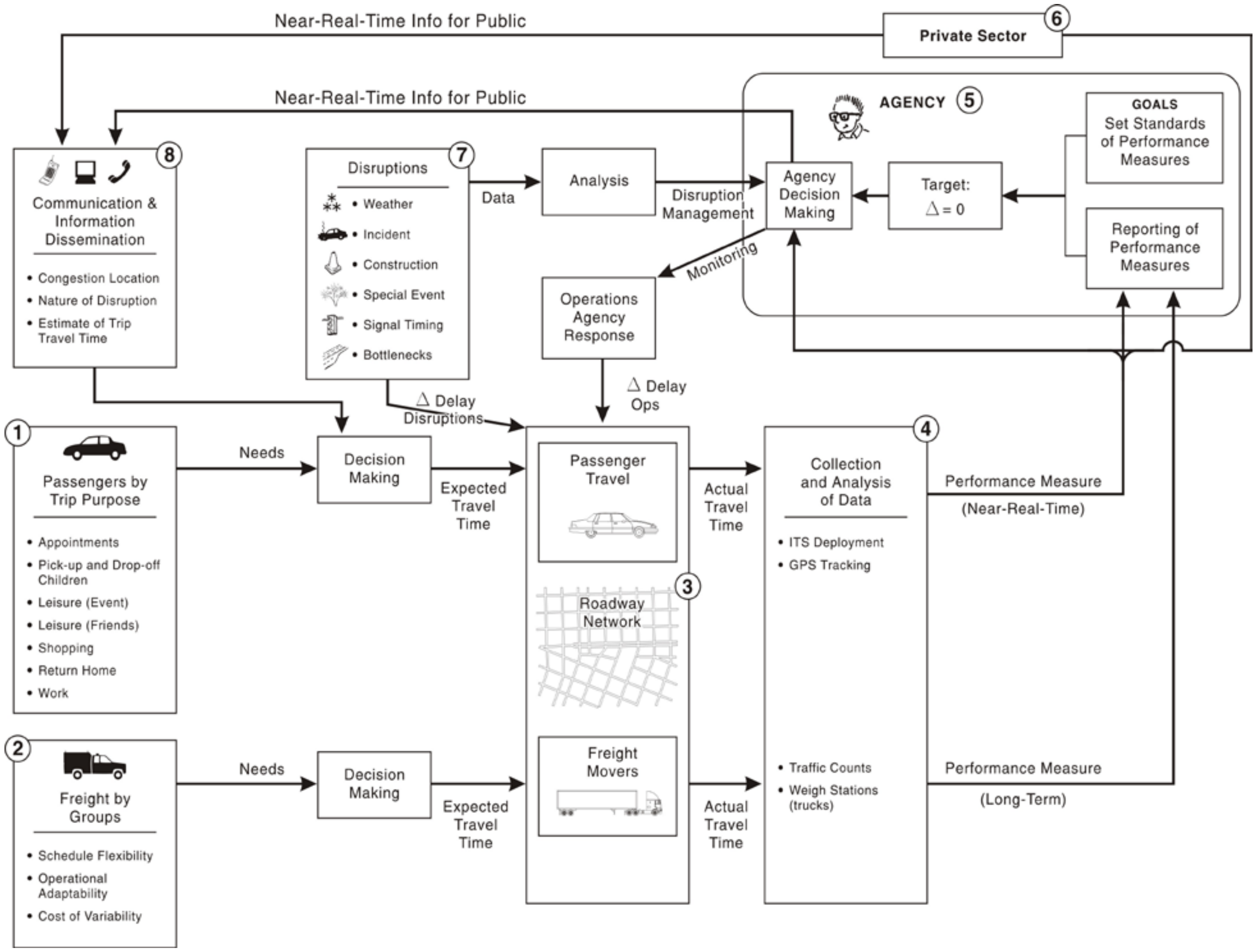
TRAVEL-TIME RELIABILITY

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 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, then the travel time is considered unreliable. If there is little or no variability, then the travel time is considered 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, given information on travel-time reliability. In addition, it illustrates the agency decision-making process given various disruptions and its 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 - (1) passenger travelers and (2) freight movers - have transportation needs. According to these needs, these users make decisions on their trips and estimate an "expected travel time." While both user types undertake their trips on the roadway network (3), the expected travel time is affected by delays from disruptions and from agency operational strategies. The actual travel time is collected through ITS device or traffic counts. The roadway performance data (4) are analyzed and translated to performance measures. The long-term performance measures are reported regularly and compared to the agency goals (5). The near-real-time performance measures are a direct input for the real-time agency decision-making. The disruptions (7) directly affect the roadway network (3) performance. Because the target of agencies (5) is to reach their goals, agency response and monitoring of the roadway network (3) 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 (8) from the agency (5) or from the private sector (6) to passenger travelers (1) and freight movers (2) to assist them in their travel decision-making.

Figure 1.1 Travel-time Reliability Interactions among Roadway Users, the Agency, and the Roadway Network



TRAVEL-TIME RELIABILITY AND CONGESTION

Travel time varies from one day to the other because the traffic-influencing conditions differ from day to day. The original F-SHRP Reliability Research Plan identified seven sources which not only contribute to total congestion but often also result in unreliable travel times. While in general, higher congestion leads to higher unreliability in travel times there may be instances where a facility is reliably congested and hence travel time, although high, can be predicted with a high degree of certainty. The results of SHRP2 L03 [(1)] indicate that the background traffic volume is the overriding factor affecting reliability. Therefore, strategies and treatments that mitigate congestion should be helpful in reducing the variability in travel time. A brief summary of the seven sources of congestion and their contribution to congestion (taken from the SHRP2 L03 study) follows.

1. **Physical Bottlenecks (42%)**: Bottlenecks are sources of congestion that occur on short segments of roadway that exhibit lower capacity than upstream segments of roadway, essentially resulting in unreliable travel. Bottlenecks commonly form either at changes in roadway geometry (e.g., lane drops), or due to crashes, or where 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 impact travel conditions, causing 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 others.
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 (1) their socio-economic characteristics (in the case of passenger travel) or operational characteristics (in the case of freight) and (2) their context of travel. In the case of passenger travelers, the socio-economic characteristics include attributes such as income, whereas the travel context may be defined using 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 such as international border crossings and long-haul versus local travel.

Passenger Travelers

The classification of passenger travelers based on their socio-economic characteristics requires the 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 based on the context of travel requires the consideration of the following attributes:

- Travel Purpose (such as work, child-escort, appointments, shopping, return home, and leisure);
- Trip Frequency (daily or occasional);
- Flexibility (constrained or flexible);

- Mode (such as single-occupant auto, multi-occupant auto, transit, and walk/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 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 travel-time-reliability problem of 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, they 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.

Table 1.1 Classification of Passenger Travelers by Trip Purpose

Broad Classification by Trip Purpose	Detailed Classification by Trip Purpose	Example
Daily, Constrained Trips	Work	-
	Pick-up and Drop-off Children	-
Daily, Unconstrained Trips	Shopping	Grocery, etc.
	Return-home	-
Occasional, Constrained Trips	Appointments	Medical, personal services, etc.
	Leisure	Movies, Sports Events, etc.
Occasional, Unconstrained Trips	Leisure	Visit Friends, etc.

Freight Movers

Freight movers can generally be classified as shippers or carriers. A shipper is an entity or business (like Wal-Mart) 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 the 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 1.2 Classification of Freight Movers by Quality of Freight Operations

Classification by Quality of Freight Operations	Specific Levels Considered Example
Nature of Scheduling	Truck arrival is scheduled tightly (less than one hour window)
	Truck arrival is scheduled loosely (1-4 hour window)
	Truck arrival is 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	Non-perishable or low value goods
	Perishable or high value goods
Travel-time Risk	Short range (many deliveries in one day)
	Medium range (2-3 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 (less 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 but ability to shift off peak
	Trip occurs during peak period and limited ability to shift
	Trip occurs off peak

The different combinations of the criteria listed above in Table 1.2 were generalized 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 narrow windows

(2) Level of Operational Adaptability

- Complete: Carrier can change route, has many deliveries, has 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 due to 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 freight mover classifications were defined, which is much more manageable and usable, and are shown in Table 1.3.

Table 1.3 Classification of Freight Movers by Characteristics

Group Number	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. For example grocery store deliveries by large company.
2	Flexible	None	High	Carrier that pays drivers by the hour.
3	Inflexible	Complete	High	Carrier required meeting tight time windows for delivery, for example delivery companies like Fed-Ex, or residential moving company.
4	Inflexible	None	High	Carrier that moves air freight, or fresh seafood and must deliver in tight time window.
5	Flexible	Complete	Low	Carrier moves natural resources.
6	Flexible	None	Low	Carrier has no delivery time windows.
7	Inflexible	Complete	Low	Oversize/overweight specialty movers.
8	Inflexible	None	Low	Drayage trucking company.

TRAVEL-TIME RELIABILITY REQUIREMENTS

For each of the user categories developed above, there are corresponding requirements in terms of travel-time reliability. In order 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

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

<u>Daily, Constrained Trips</u>: The traveler "sees" 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.

<u>Daily, Unconstrained Trips</u>: The traveler "sees" 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.

<u>Occasional, Constrained Trips</u>: The traveler does not "see" the day-to-day variability as 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.

<u>Occasional, Unconstrained Trips</u>: The traveler does not "see" the day-to-day variability as 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 travel-time expectations are based on a combination of personal experience and information from on-line mapping utilities (such as MapQuest) and GPS devices. Further, if the trip is undertaken in a familiar area, travelers do factor in congestion while estimating travel time. For some participants, reliability was simply not encountering congestion. These people did not like "being stopped when they are supposed to be travelling." One participant indicated (in the context of freeway travel) that "if you are taking more than two minutes per mile (30 mph), you should probably be looking for an alternate route" suggesting that lower than anticipated speeds 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:

- Narrower windows are not required, in part, because they are currently unattainable. Carriers are not willing to promise delivery windows they know they cannot generally make; and
- For carriers that make many deliveries in one day, a series of longer than average travel times compound, making 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 the 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/overweight restrictions and the 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 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 JIT 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, like FedEx. Solutions typically involve adding cost to the carrier in increased wait times.

TRAVEL-TIME RELIABILITY IMPORTANCE

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, then it could disrupt their 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 the 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 the different trip purposes (currently and in the future) can be inferred as shown in Table 1.4 below. This table also presents a summary of the reported actions and consequences from the focus group interviews.

Table 1.4 Summary of Actions and Consequences of Unreliability for Passenger Travelers

Trip Purpose	Importance of Reliability	Actions to Deal with Unreliability	Consequences of Unreliability
Appointments (medical, personal services, etc.)	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/late fee. Wait for next available opening – affects travel for rest of day. Several days before next another 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 keeping child waiting. School / day-care may charge fee for late pick-up or even call police if consistent late.
Leisure (Movies, Sports Events, etc.)	Medium-Low	Schedule during off-peak periods.	Get stressed – not desirable as the trip is for "leisure". Miss event if it is a one-time-only event like sports. Forfeit money paid for tickets. More difficulty in finding parking.
Leisure (Visit Friends, etc.)	Low	Call and reschedule or meet somewhere else. Shorten planned visit in order to meet the start time for the next scheduled event.	Feeling of 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 time spent shopping, and possibly limit the number of items shopped for.	None (as long as the 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 the return-home trip. Choose travel time for the trip *to* the activity so that the travel *from* the activity to home is reliable.	Tired and stressed (especially if kids are travelling). Children needing attention at home. Pets needing attention at home. Ice cream bought at the grocery store can melt!
Work	High	Allow more time than ideal for travel (especially if the work schedule is fixed). Prepare for the day in advance & wake up early. Affects the residential-location choice.	Loss in pay and other types of penalties. Poor reflection. Particular cause of concern in the current economic times.

Freight Movers

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

Table 1.5 Summary of Actions of Unreliability for Freight Movers

Group Number	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	Carrier could spread particularly congested deliveries across vehicles so deliveries do not compound throughout the day.
4	Inflexible	None	Large	Carrier has limited choices so will need to increase price for services.
5	Flexible	Complete	Low	Cost of variability is low, so changes should only be undertaken if cost-effective.
6	Flexible	None	Low	Cost of variability is low, so changes should only be undertaken if cost-effective.
7	Inflexible	Complete	Low	Cost of variability is low, so changes should only be undertaken if cost-effective.
8	Inflexible	None	Low	Cost of variability is low, so changes should only be undertaken if cost-effective.

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 one 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
        - Infrastructure upon 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 a rural environment.
        - Urban
        - Rural.
- Weather Conditions
    - This describes the typical weather patterns in a region, which will affect the exposure to variability in travel times.
        - Frequent weather disruptions

- Infrequent weather disruptions.

Carriers with greater exposure will exercise a stronger response to variability due to their increased frequency of disruption. However, these are not characteristics of the carrier, rather 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 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 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.

While 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 directly be compared 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 above mentioned performance measures, 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, since it can represent a ratio for one or more trips it is not necessarily a travel-time reliability measure. A good practice for computing reliability performance is to base them on measurements taken over an extended period of time. The SHRP2-L03 [(1)] project recommends that six months of data be collected for urban freeways where winter weather is not a problem. Where winter weather causes problems on a significant number of days, more data ought to be collected for empirical studies of reliability.

REFERENCES

(1) Margiotta, R. SHRP2-L03: *Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies*. TRB, National Research Council, Washington, D.C., 2009. URL: http://trb.org/TRBNet/ProjectDisplay.asp Project ID=2179, Accessed Sept. 23, 2008

2. EFFECTIVENESS OF AGENCIES

The purpose of this section is to describe the current effectiveness of transportation agencies (state, local, toll authorities, and MPOs 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 based on a comprehensive literature review. Lastly, the effectiveness of agencies by transportation management infrastructure is analyzed.

EXISTING AGENCY MEASURES

In the RRD 312[(1)] study, interviews were conducted with ten 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 (1) Data Collection, (2) Operations Application, and (3) Planning Application.

Considerable interest has been expressed at the national level in the use and reporting of more reliability performance measures by these 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 SAFETEA-LU, 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 that are being obtained from a variety of programs. Information obtained through Research and Innovative Technology Administration's (RITA's) ITS Deployment Program [(2)] shows the types of transportation management infrastructure in use in each of the 50 states and 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. They are based on road segments rather than overall trip variability, as the components of specific trips are not known to outside parties. There will therefore necessarily be differences in the views taken of a given level of 'reliability' measured by external data and that of individuals valuing 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 only occurred recently and is still not widespread.

<u>Output Measures</u>

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" are:

- Number of VMS signs in place
- Number of calls to a 511 system
- Number of events incident management systems responded to last month
- 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. Where roadway agencies 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
- 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, vehicles volumes, 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 not often 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 data necessary to report on freight-delivery reliability. While 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 GPS 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 (New Jersey, Minnesota, and Texas) have stressed the need to have measures that are directly applicable within their organization's institutional framework. In other words, the measures should be able to inform alternative approaches regarding how a state fosters freight mobility.

ISSUES AFFECTING THE EFFECTIVENESS OF AGENCIES

States that are actively looking to report more travel-time reliability performance measures 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) 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 ten 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 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/procedures that remove disruptions quickly and/or supply additional, short-term capacity increases to compensate for capacity lost due to 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 shipment) views 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 more effectively together 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 than that of the traveler/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 the infrastructure that they have. 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 their 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, then 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/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 mitigate the change in conditions 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 rather 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/Techniques

Once an event/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:

- Understand the nature of the event/disruption;
- Understand what actions/resources are required to deal with that event/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/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:

- Agencies to access and share resources;
- Functional, multi-agency protocols for working together;
- Interagency working arrangements that are region-wide, 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/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 SHRP2 L03[(3)] and SHRP2 L06[(4)] projects focus on existing processes/techniques used by transportation agencies with respect to incorporating reliability, and were also used as input to this effort.

Knowledge of Available Tools' Effectiveness

Since the resources necessary to massively overbuild the transportation system are and will continue to be lacking, 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 which can quantify the on-going 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 the underlying management support systems that describe:

- The status and performance of the transportation system;
- The causes of unreliable travel times;
- When and where these events/disruptions take place;
- The size of the impacts these events/disruptions have on travel times;
- The effectiveness of each action taken in response to these events/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 between peers to help evaluate and improve an agency's procedures. Including reliability measures and efficiency is a new trend.

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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 have 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:

- Existing Travel Performance and Disruption Data
- Potential Performance Measures for Agency Use
- Developing Performance Measures and Setting Goals

EXISTING TRAVEL PERFORMANCE AND DISRUPTION DATA

An understanding of how reliability of roadway operations affects stakeholders allows 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 the following subsections:

- Summary of Data Availability
- Roadway Performance Data
- Disruption Data

Summary of Data Availability

Because of the cost of collecting data and the relatively low priority of this 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 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 fewer still 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 GPS information from cell phones into 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

Section 2 of the Phase 2 Draft Report for the SHRP2 L03 project [(1)] 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 only describe 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 five years as a variety of new data-collection technologies become available and are adopted by transportation agencies. Examples of recent data technology include:

- 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 Corporation'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. USDOT is sponsoring efforts through the American Transportation Research Institute (ATRI) 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, travel-time and speed data could potentially be collected on most major freeway systems at a moderate cost, if they 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, while 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, though the blue-tooth 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 center-line roadway miles and modest number of instrumented vehicles using those roadways at any given time of day that does not allow the estimation of travel times within statistically reliable boundaries. The large number of center-line miles means that infrastructure-based technologies, such as Bluetooth or ALPR 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, means that an insufficient number of instrumented vehicles may be present to provide statistically valid travel-time and delay information when vehicle probe-based data collection approaches are used.

Four additional factors complicate the collection of travel-time reliability data on urban arterials. The first is the difficulty of accounting for mid-block vehicle stops (e.g., short shopping trips and/or pick-up 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 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 only available well after the fact. The systems that collect these data rely heavily on manual equipment placement and pick up. 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 the 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 is 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 simply 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. While 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 non-recurring 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 because of 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 on freeways in congested urban areas with significant operational improvement programs than they are for rural areas, smaller urban areas, and arterials.

<u>Traffic Incidents</u>

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 and/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. 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 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/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 major traffic congestion, information is generally available that describes the nature of the changes in traffic demand that these events generate. 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 measureable influence on expected travel-time performance, as demand volume decreases during school holidays and increases during the first few days of school terms. Where travel-demand increases, as a result of these events, just enough to exceed roadway capacity, “unexpected” congestion occurs. The difficulty is in understanding which “special events” are large enough to generate measurable increases in demand during periods when those increases are likely to cause congestion. Few data exist and considerable work would be needed to collect and make available the datasets necessary to develop or apply that information.

Traffic-Control Devices/Signal Timing

Signals and other traffic-control devices also disrupt traffic flow. These disruptions, unlike the disruptions described above, are 1) intentional, and 2) 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 those movements. The delay caused by stopping one traffic movement to allow another traffic movement to safely occur 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 in order to improve their performance. The most common of these changes is to allow signal-timing plans to change based on 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 based on 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 they do not have is a record of exactly what phase length was actually operated over the course of a day/week/month/year. That is, 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 really 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 as they occur based on factors not routinely recorded by roadway agencies (e.g., the weather conditions and visibility between a roadway and a distant mountain). The SHRP2 L03 project [(1)] also includes information about the sources and procedures for disruption data.

POTENTIAL PERFORMANCE MEASURES FOR AGENCY USE

Based on 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 in order to improve their ability to manage their lives and businesses.

Within each of these three 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 only describes 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., HOT 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, considering 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 along a particular facility. The following five measures are aimed at characterizing roadway performance:

- The mean travel time along defined segments of the roadway system at specified times of day, days of the week, and times of year;
- The 80^{th}percentile travel time of defined segments of the roadway system at specified times of day, days of the week, and times of year;
- The 95^{th}-percentile travel time of defined segments of the roadway system at specified times of day, days of the week, and times of year;
- The percentage of time and/or trips that each of those defined segments of the roadway system operate at lower than a reporting standard adopted by the roadway agency; and
- The traffic volume on defined segments of the roadway system at specified time of day, day of the week, and time of year.

For reporting purposes, the 95^{th} 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 80^{th} 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, 80^{th}percentile, and 95^{th} percentile) are tracked to describe the variability experienced on the roadway segment under study. The need for three statistics rather than one relate to the fact that 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 (prior to some deadline) is extremely important, and therefore a traveler might plan with the 95^{th} 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 where 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 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 SHRP2 L03(1) project 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. This 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, in heavily congested roadways, even this slower vehicle speed standard may result in a large number of "failures" due to the high demand in comparison to the available capacity. This results in the agency appearing to fail no matter what possible actions they can take within their 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 percent, 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 the broad passenger traveler needs.

Table 3.1 Example Performance Measures for Person Travel

Trip Purpose	Importance of Reliability	Performance Measure
Appointments (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 évents, 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 percentile or 80th Percentile
Work	High	95th percentile Travel Time

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

Table 3.2 Example Performance Measures for Freight Travel

Group Number	Level of Schedule Flexibility	Level of Operational Adaptability	Cost of Variability	Performance Measures
1	Flexible	Complete	Large	Mean and 80^{th} Percentile Travel Time
2	Flexible	None	Large	Mean and 80^{th} Percentile Travel Time
3	Inflexible	Complete	Large	Mean and 80^{th} Percentile Travel Time
4	Inflexible	None	Large	Mean and 95^{th} Percentile Travel Time
5	Flexible	Complete	Low	Mean and 80^{th} Percentile Travel Time
6	Flexible	None	Low	Mean and 80^{th} Percentile Travel Time
7	Inflexible	Complete	Low	Mean and 80^{th} Percentile Travel Time
8	Inflexible	None	Low	Mean and 95^{th} Percentile Travel Time

Note that the suggested ed "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 them within the context of the external factors that affect roadway performance. For example, a small increase in mean and 95^{th} 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.

<u>Travel Difference in Passenger Travelers and Freight Movers</u>

As discussed in previous sections, when considering roadway performance, it is important to note that "freight mover performance" is likely to be different than "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, Freight Data from Intelligent Transportation System Devices, noted that even before congestion 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 make point-to-point travel times different because the routes used for those trips may be different. In addition, the pick-up 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 than 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	Performance related to	Performance Measure	Performance Measure depends mainly on
Roadway Users: Passenger 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 center line miles for which real time travel information is available, and the accuracy of that data Percentage of roadway mile 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, 95th Percentile Travel Times for defined roadway segments Percentages of time and/or trips 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" (~45mph) 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 center line miles for which real time travel information is available, and the accuracy of that data Percentage of roadway mile 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:

- 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 SHRP2 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, projects SHRP2-L01 [(2)] SHRP2-L02 [(3)] and SHRP2-L13 [(4)] 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:

<u>Traffic Incidents</u>

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/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 a given incident imparts. 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 the National Cooperative Highway Research Program and NTOC [(5)] have published comprehensive guidance on the selection and use of these measures. NCHRP 20-07 – Task 215: Statewide Incident Reporting Systems [(6)] and the NCHRP 20-07 – Task 202: Guide to Benchmarking Operational Performance Measures [(7)] are two reports that 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:

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

<u>Weather</u>

The key weather variables define the following:

- The existence and intensity (amount) of precipitation
- The existence and intensity (amount) of snow fall
- The existence of winds strong enough to disrupt traffic flow
- The existence of visibility restrictions
- The 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 increment possible, but not less than hourly. Data as geographically as precise as possible is most useful. That is, weather data from a local airport are good, but the weather occurring on a roadway five miles away from the airport can be considerably different, especially with regard to the timing and amount of precipitation that falls. Therefore, the more geographically precise the collected weather data can be, the better it is.

Work Zones/Construction

The key construction variables that affect reliability are as follows:

- Location of the construction event
- Time and duration of lane/shoulder closures by extent of closure
- Time, duration, and nature of lane modifications/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. There will be 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 (weather, changes in construction plans, etc.), these data have limitations but 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)
- Duration of the event.

Special events impact the performance of roadways in two ways: 1) they significantly increase traffic volumes prior to and after the event and 2) they change the origin/destination travel pattern of trips using roadways associated with those events. As a result, they 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 be difficult to identify and collect data on. Similarly, attendance at smaller venues may have significant impacts near the venue itself, but go unnoticed on 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/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 includes the following:

- The location of all traffic-control mechanisms
- The time that specific control plans or actions take effect
- Descriptions of all signal-timing phases (as planned, and if possible, where executed)
- 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 changes to those plans.

<u>Bottlenecks</u>

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 in the future. 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 of 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.

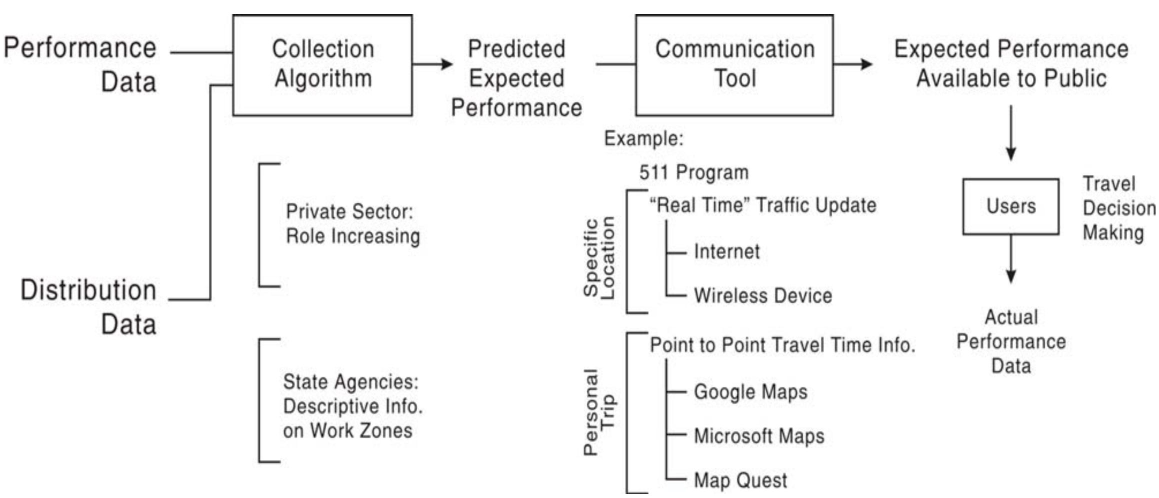
In response to stakeholder input, the following performance measures describe the types of information that are most useful:

- The percentage of freeway center-line miles for which real-time traveler information is available;
- The percentage of arterial center-line miles for which real-time traveler information is available;

- The percentage of freeway center-line 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 vs. predicted);
- The percentage of arterial center-line 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 vs. predicted);
- The 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;
- The percentage of statewide rural roadway miles for which real-time traffic-disruption data (incidents, accidents, work zone closures, weather-related slowdowns) are available; and
- The 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/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 as 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.

Figure 3.1 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 the transportation agencies, stakeholders, and decision makers. The act of developing performance measures and setting goals logically follow from needs of stakeholders identified earlier in this report and take 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. To do that, it is important to clearly define and evaluate the intended outcome. After all, performance measures are developed to assist in the achievement of specific outcomes: 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 where "truly good" performance cannot be obtained because of circumstances beyond the control of the agency.

<u>Engineering Optimal Goal</u>

At first blush, the first of these performance-goal categories would seem the obvious choice for engineers. For example, we 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, the North Carolina Department of Transportation (NCDOT) "2009-2010 Executive Organizational Performance Measures and Targets" [(8)] report 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, NCDOT decided that they could not expect to control growth and VMT, but they could potentially lower the expected increase. WSDOT 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 publically failing to achieve its goals or even to make substantial progress toward achieving those goals. For a public agency that can be easily attacked in the news media, adopting a performance goal that makes it 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 back off quantitative goals illustrate the challenges of goal setting. A recent one, which is probably also the best known, involved the Minnesota Department of Transportation (MnDOT). MnDOT deployed a large number of ramp meters in the Twin Cities area and operated them in a manner that gave priority to freeway traffic flow in order to meet freeway performance goals. However, this operations strategy resulted in long ramp queues which generated motorist complaints. Then public officials began questioning this operations policy. The result was a widely publicized shut-off 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 to adjacent streets. A legally mandated maximum approach queue setting of four minutes was a performance standard imposed on the operating agency by elected officials.(9)

In 1990, the California Air Resource Board (CRB) implemented regulations that required that two percent 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 ten percent of vehicles for sale. In 1996 and 2001, CRB had to change these regulations due to the difficulty in implementation and the slow development of appropriate technology.(10)

“Stretch” Goal

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 these 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, producing more dramatic reductions in the number of fatal accidents. These agreed upon, but acknowledged to be unreachable, goals comprise the second category of performance goals, are called “stretch goals.” These goals serve very useful purposes, primarily as rallying points around which resources and programs can be based. 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

The 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 when agencies do 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 the 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 like 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 the changes in travel demand that those changes will impose on the transportation system. For example, there is no way to know if there is a large family reunion 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, which 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 HOV lane or high occupancy toll (HOT) lane performance and where 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 agencies interviewed for this project is that they do not have the necessary data to establish a baseline. As a result, they are reluctant to set goals without knowing whether they can possibly meet those goals. 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 the third strategy listed above. As data become available to define the current baseline conditions, they set "goals" to improve on those conditions. In terms of travel-time reliability, this means setting goals to decrease the current mean travel times, 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, all while 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 center-line 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/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." Where publically acceptable, 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 percent of the time during peak periods) where 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.

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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 was paid to research documents and other literature related to these topics:

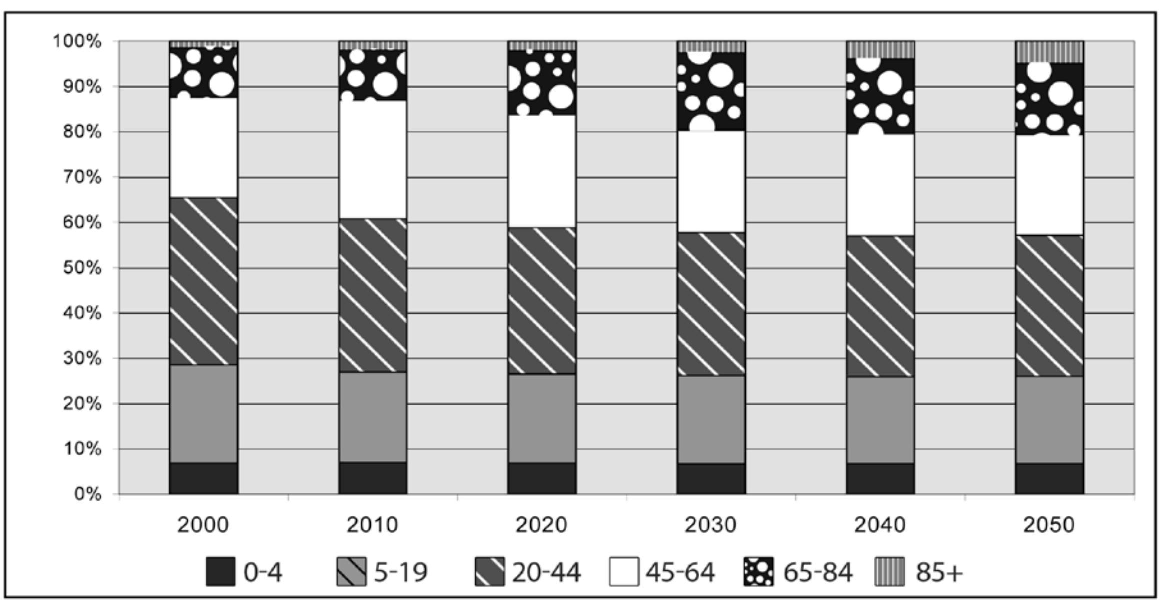
1. Demographics, Land Use, and Urbanization
2. Environment and Climate Change
3. Energy Costs and Availability
4. Technological Innovation
5. Freight
6. Finance, Road Pricing, and Privatization

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 our 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—more than a 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 U.S. will receive the largest population increase of any country in the world, primarily due to immigration. As the Baby Boomers continue to enter retirement, the U.S. faces one of the most-dramatic demographic shifts in its history. The baby boom ran 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. Thus the U.S. is, on average, growing older because of the baby boomers as shown in Figure 4.1.

Figure 4.1 US Demographic Changes



Source: US Census Bureau

United States Department of Transportation (USDOT) 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:

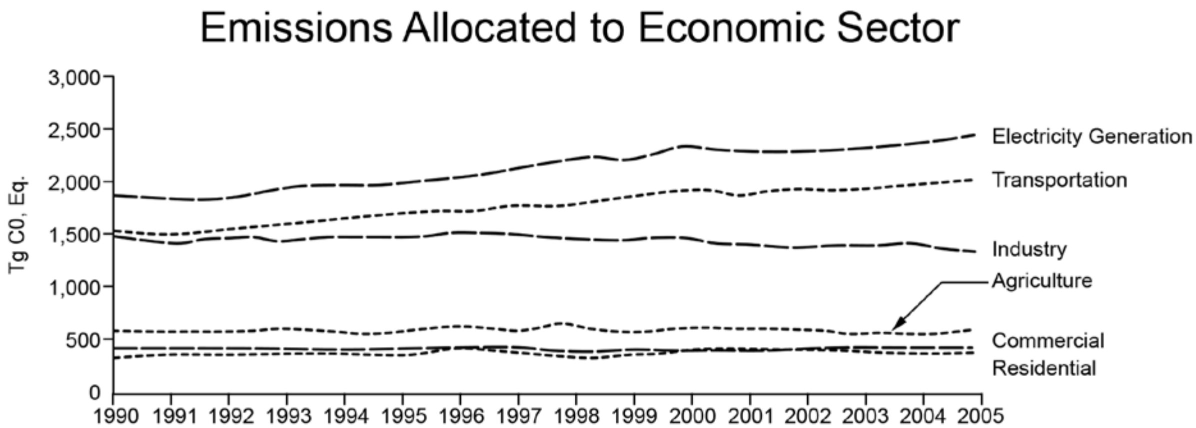
- Suburban seniors aging in place
- Increasing performance capabilities of seniors—and thus more elderly drivers
- Increasing percentage of non-English speaking population
- Flattening of the growth in household income
- Increasing motor-vehicle ownership
- Increasing level of education
- Increasing re-gentrification and densification of central cities; continued growth at the low-density edge of cities
- Increasing number of multi-worker families
- Increasing prevalence of internet usage and telecommuting
- Increasing transit usage
- Decreasing average vehicle size
- 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*." 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. The growth in GHG emissions is linked to the increase in VMT for the following vehicle categories, Figure 4.2:

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

Figure 4.2 CO2 Emissions Allocated to Economic Sector



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

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, 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, 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 percent. Adverse weather not only degrades traffic flow and increases travel times, but also degrade transportation safety. Aside from these direct weather effects, climate change will lead to other trends that affect travel-time reliability. Policymakers may begin to implement hard-line measures to reduce greenhouse gas emissions. These measures could include adoption of zero-VMT growth policies, heavy taxation of oil, and increased 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

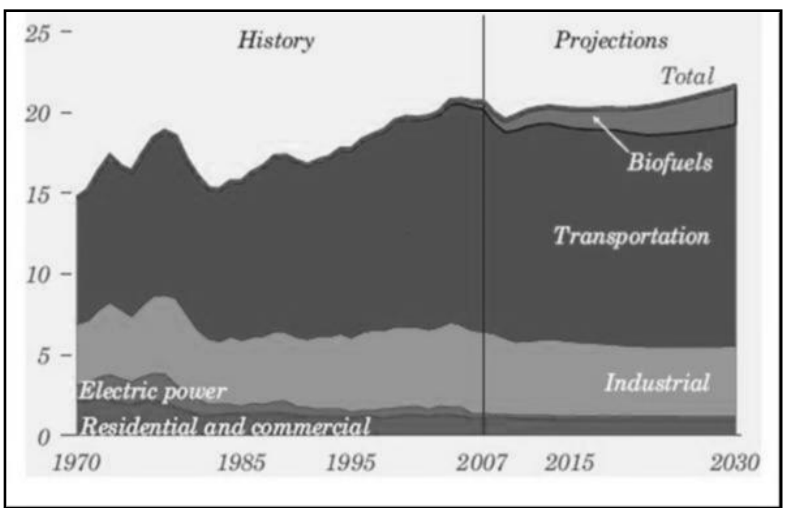
The Annual Energy Outlook 2009 (AEO2009), prepared by the Energy Information Administration (EIA), presents long-term projections of energy supply, demand, and prices through 2030, based on results from EIAs National Energy Modeling System (NEMS). The projections in AEO2009 look beyond current economic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

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

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.

As shown in Figure 4.3, total U.S. demand for liquid fuels is anticipated to grow by only 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 (CAFE) standards, and requirements for the increased use of renewable fuels.

Figure 4.3 Total Liquid Fuels Demand by Sector (million barrels per day)



Source: Energy Information Administration: Annual Energy Outlook 2009

Some of the key projections in the Annual Energy Outlook include:

- 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 LDV sales in 2007 to 40% in 2030. Sales of plug-in hybrid electric vehicles (PHEVs) 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 (FFVs) 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, a rate of 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:

- In-vehicle ITS
- Traffic-Signal Optimization/Retiming
- Traveler Information Systems
- Traffic-Incident Management
- Safety Service Patrols
- Surveillance and Detection
- Road Weather Information Systems
- Electronic Toll Systems/Open Road Tolling
- Ramp-Metering Systems
- Electronic Border Crossing Systems
- High Occupancy Toll Facilities
- Work-Zone Management Systems

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

- Sharp decrease in cost of advanced wireless condition and performance sensors.
- Increased pressure for efficiency of freight logistics, coming from increasing fuel prices and/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 IC engine, new fuels, or radically different energy systems (e.g., hydrogen fuel cells).
- Increases in capabilities and decreases in costs of broadband communications technologies that support work/shop/learn 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 AASHTO, it is expected that there will be a 90% increase in tons moved domestically by 2035, resulting in approximately 25% of the traffic on the National Highway Systems (NHS) to be trucks with 8% of 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 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 practice such as just-in-time delivery as well issues such as constrained rail infrastructure capacity which may move goods from rail to the trucks. The limited capacities of already congestion port and road infrastructure in urban area 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, particular for intercity routes since they 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 and with the 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 the Rand Corporation include:

- 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 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 (IT) 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 there will continue to be a gap between available funds and infrastructure investment needs. As a result, it is likely there will be increasing levels of congestion and unreliable travel during peak periods. Pavement and structure deterioration are likely to continue throughout the roadway system, especially on lightly built streets and roads. A frequently suggested option is 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, it is likely there will 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 one of the many different types of public-private partnerships (PPP).

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 TIFIA credit and private activity bond (PAB) programs, and re-capitalization of State Infrastructure Banks (SIBs).

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5. ALTERNATIVE FUTURES

USING ALTERNATIVE FUTURES TO IDENTIFY TRENDS

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

a. A range of cumulative impacts on the operation of the transportation system and the demands placed upon it;
b. The frequency of non-recurring congestion;
c. The priorities likely to be placed on mitigating such congestion;
d. The technologies that may exacerbate the problem or facilitate effective responses to it; and
e. The broader social, environmental, and contexts within which the future transportation system is managed.

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

- Alternative Future 1: The Optimistic Scenario
- Alternative Future 2: The Mediocre Scenario
- Alternative Future 3: The Pessimistic Scenario

Global climate change, economy, and energy were considered to be the defining variables within each alternative scenario. The first alternative (the optimistic scenario) features minimal change in severe weather events, strong economic growth (including rapid technology innovation), and stable energy prices. The second alternative features typical (historical) weather-related events, moderate economic growth and advancement in technology, and some increases in energy prices. The third alternative 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 assure 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 the climate change, 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 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 within the U.S. The demand for reliable transportation will increase because of 1) increased travel demand as a result of strong economic, population, and employment growth, and 2) 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: The Optimistic Scenario.

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 GDP will increase at 3 to 4% annually over the next twenty years. A new “clean” energy industry will result in population and employment growth coupled with a drop in unemployment to below-normal levels (4-5%). These demographic trends will lead to increased travel demand, measured in vehicle miles of travel increasing at 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 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, putting 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 which facilitate telecommuting and ecommerce.

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. This 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 utilize this comprehensive information on the transportation system to adapt their travel choice 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 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 LDV sales in 2020. Hybrids (including standard hybrids and plug-in hybrids) will account for 65% of all new LDV sales, while micro hybrids, 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 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, etc. 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, 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

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

<u>Freight Trends</u>

- 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 onto rail, water, and (to a lesser extent) air.

<u>Financing Trends</u>

- Due to the switch to alternative or highly fuel-efficient vehicles, this future will see extensive application of vehicle-use charges based on location, vehicle miles traveled, and time of day. This 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 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 the Sources of Congestion

The expected travel behavior and the impact the scenario drivers that are 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 due to increased VMT will be offset by safety gains through technological advancements related to: o Congestion o Run-off the Road Crashes o Weather Management o Incident Management
Weather	• Stable impact of weather on congestion • Technological advancements
Work Zones/ Construction	• Comprehensive, accurate data related to construction management activities will provide pre-trip 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 less disruptions and congestion to road users • Automated enforcement of speeds through work zones improves safety
Fluctuations in Demand/ Special Events	• Comprehensive, accurate data related to special event activities will provide pre-trip information
Traffic-control Devices/ 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/transfer centers

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 (1) a stronger economy and increased employment, (2) pressure for efficiency coming from climate change and energy constraints and regulations, and (3) 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: The Mediocre Scenario.

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 will affect transportation infrastructure, bringing about more unexpected failures and service interruptions. Interruptions in electric power will be more common (until transmission infrastructure is renewed and protected). This will impact 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 twenty years. Employment will grow and the unemployment rate will return to normal levels (5-7%). Through mostly immigration, the population will increase at about 0.9% annually. Together, these demographic trends will lead to increased travel demand, measured in vehicle miles of travel. Vehicle miles of travel 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 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 ecommerce. 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, providing 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 micro hybrids, 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 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 good 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 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.
- Public-private partnerships 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 of the scenario drivers that are described for the Mediocre Scenario could have the impacts on transportation-system reliability are shown in Table 5.2.

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: o Congestion o Run-off the Road Crashes o Weather Management o Incident Management
Weather	• Increase frequency of rare events such as tornados, heavy rain and snow storms, flooding, etc., will cause service interruptions and decrease travel-time reliability • Technological advancements will allow for better system integration and weather management
Work Zones/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 closure 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/ 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/ Signal Timing	• Available technologies will be deployed to interconnect TCDs and make them more adaptable/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 decision by system owners, operators, and users to make the 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

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 due to, 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/goals focused on 1) reducing fuel consumption, 2) decreasing greenhouse gas emissions, and 3) supporting economic growth. With the high value of travel cost, delays become a much stronger economic constraint and thus strategies aimed at reducing delays and travel variability 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.

Scenario Drivers

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

Climate

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

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
More Intense Weather Events	• Damage to assets • Increased frequency of road traffic disruption, including interruption of emergency routes

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 nine to eleven. The expected increase in average temperature by 2030 is one degree Celsius over current temperatures. Sea level rise is not likely to show significant change over the next twenty 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 twenty 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 gross domestic product (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 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, resulting in a stagnant housing market and continuing decline in international trade. Key industries, such as manufacturing and energy, will lose economic strength. 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 due to unrest in source countries as well as targeted foreign attacks against pipelines and other parts of the distribution system. Even with this 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, where transportation costs will become 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 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 will be done primarily 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 car pooling services will be readily available to permit travelers to determine their desired objective (routes that minimize cost, routes that minimize GHG emissions, etc.).
- In-vehicle hazard identification technologies will be 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 greenhouse gas emission and to prepare for climate adaptation challenges (such as aggressive policies on fuel consumption, targeted CO_2 reductions, etc.). 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, etc. 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 provide for more-efficient freight movement.

Freight Trends

- The demand for freight and freight movements will grow modestly. Infrastructure capacity limitation will impact 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, increasing the use of trucks and contributing to roadway congestion.

<u>Finance</u>

- The national government may take steps to use technology to enhance revenue collection (VMT tax, etc.). With economic stimulus a national and/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 vehicle miles traveled, use of higher efficiency vehicles, and mode shifts) there may be increased interest in public private partnerships.

Effects on the Sources of Congestion

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

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: o Congestion related crashes decrease o Run-off the road crashes increase because of extreme weather
Weather	• Increase frequency of rare events, such as tornados, heavy rain and snow storms, flooding, etc., will cause service interruptions and decrease travel-time reliability
Work Zones/Construction	• Work zones will become more common because of the following: o Infrastructure failures and infrastructure maintenance and renewal activities due to adverse weather o 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/ 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/ 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

SUMMARY OF ALTERNATIVE FUTURES

The possible range of future outcomes for the three scenarios is summarized in Table 5.5. These three different scenarios help to define the possible range of impacts. This summary spans the set of reasonable predictions that are taken from on 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 the may unfold in the future to help DOTs, MPOs, and members of the transportation industry ensure that our infrastructure, both physical and institutional, is prepared to address the transportation needs during the next twenty years**.**

In response to the scenario drivers and responding trends that are shown on Table 3.2, 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 that are described at the bottom of Table 5.5 present the range of future outcomes that may occur.

Table 5.5 Alternative Futures Summary

	Alternative 1 Optimistic Scenario	Alternative 2 Mediocre Scenario	Alternative 3 Pessimistic Scenario
Scenario Drivers			
Environment & 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 & 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 & revitalization	Slow population growth Dense development to minimize transportation costs
Technology	Considerable increase in energy & transportation technologies Increase expectations for reliability	Increase in energy & transportation technologies Deterioration of transportation infrastructure will decrease reliability	Increase in energy and transportation technology Increase in cost of travel
Policy & Institutional	GHG emission targets will be met	GHG emission targets will not be met	GHG emission targets will not be 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. Manufacturing shifts to US, 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 impacts	Significant impacts
Work Zones/ Construction	Improved through ITS Better system integration	Work zones more common, ITS able to minimize delays & improve safety	Work zones more common because of infrastructure failing
Fluctuations in Demand/Special Events	Information dissemination spreads peak demand through accurate, real-time data	Information dissemination spreads peak demand	Lower demand reduces fluctuations in demand
Traffic-control Devices/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 disable traffic devises more frequently Higher energy costs effect operations of signal systems
Bottlenecks	Increase due to demand	Remain consistent	Decrease due to weak demand

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.

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 2. In order to identify the strategies and treatments that are most likely to have the greatest impact, a literature review focused on previous and current work of other SHRP 2 Reliability and Capacity projects including L03, L06, L07, and C05 was conducted. In addition to SHRP2 projects, information from the FHWA, state DOTs, universities, and other countries were reviewed to ensure a broad assessment of strategies and treatments. Innovative technologies that may impact travel-time reliability in the future were also reviewed and presented at the end of this chapter.

SOURCES OF CONGESTION/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. They are briefly summarized as follows. (1)

1. **Physical Bottlenecks:** Bottlenecks are sources of congestion that occur on short segments of roadway that exhibit lower capacity than 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).
2. **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.
3. **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 impact travel conditions, causing delays and congestion.
4. **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.
5. **Traffic Control Device:** 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:** Variation in day-to-day demand leads to some days with higher traffic volumes than others.
7. **Special Events:** 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.

The FHWA website (2) provides national estimates of the amount of delay caused by each of the sources of congestion noted above. SHRP 2 Project L03 (3) further quantifies these estimates by using real-time traffic data from Atlanta and Seattle. The fundamental objective of project L03 was to develop predictive relationships between highway improvements and travel-time reliability. An overall finding from the LO3 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 SHRP2 LO3 study:

- Traditional capacity projects significantly improve reliability, not only 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 SHRP2 - LO3 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 occur (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 occur due to 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 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 i8mprove travel-time reliability (e.g., GPS technology to measure the variation in travel times). The application of one or more treatments composes a strategy.

These strategies and treatments were identified through a literature review of other SHRP2 projects listed as follows:

- SHRP 2 L03: Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies [3]
- SHRP 2 L06: Institutional Architectures to Advance Operational Strategies [4]
- SHRP 2 L07: Evaluation of Cost-Effectiveness of Highway Design Features [5], and
- SHRP 2 C05: Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs [6, 7]

Additionally, FHWA publications and international research documents were also reviewed. These sources are listed in the References portion at the end of this chapter.

Classification of Strategies

Based on their general focus area, the strategies are grouped into six major categories as follows:

- Agency Management, Organization, and Resource Allocation
- Information Collection and Dissemination
- Vehicle Technologies
- Incident and Special Event Management

- Infrastructure Improvements and Demand Optimization
- Technology Innovations

Table 6.1 provides an outline of the organization of strategies (sorted among the first five categories) that could improve travel-time reliability. The sixth category – Technological Innovations – is discussed at the end of this chapter.

Table 6.1 Organization of Strategies

Category	Strategy
Agency Management, Organization, and Resource Allocation	Systems Operations and Management (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)
	Pre-trip Information
	Real-time Information
	Roadside Messages
Vehicle Technologies	Vehicle Infrastructure Integration
	Driver Assistance Products
Incident and Special Event Management	Pre-event Strategies
	Post-event Strategies
Infrastructure Improvements and Demand Optimization	Geometric Design Treatments
	Access Management
	Signal Timing/ ITS
	Traffic Demand Metering
	Variable Speed Limits
	Congestion Pricing
	Lane Treatments
	Multimodal Travel
	Travel Reduction

Each category in Table 6.1 is further subdivided into strategies and treatments. This chapter provides detailed information regarding 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). 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 the agency management strategies. General cost information highlighting some example applications in the U.S. is also presented in the Appendix G.

Agency Management, Organization, and Resource Allocation

It is important for public agencies to re-assess 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 non-capital, non-capacity measures that are at the core of 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.

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. They 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 the well-known examples), best practice is confined to only a few congested metropolitan areas. Even in those metropolitan 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 organized to handle infrastructure improvements as the bulk of their work. With a SO&M structure in place, implementing and managing the various strategies and treatments discussed below is much more do-able. 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 [(4)]:

- Systems Operations and Management Awareness
- Systems Operations and Management Structure
- Systems Operations and Management as High Priority Budget Item
- Identify Opportunities for public-private partnerships

The purpose of these strategies is to support transportation agency management towards 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 [(8, 9)] 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 which allow trucker to more-flexibly respond to business needs.

Table 6.2 provides a summary of the key strategies for the 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 use of resources, driven by good information and the ability to decide and act, are all parts 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 (speed, flow, incidents, etc.) 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. They 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 the examples presented in this section. The possible impact on reliability, strengths/weaknesses/opportunities/threats, 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 the public and private information systems are achieved. Information technologies are available today and are rapidly expanding because there is market demand for them. Travelers and transportation managers can access better information regarding current and predicted transportation system performance. This gives travelers travel options and the ability to choose among them. This will result in better system performance.

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

Strategy	Treatments	Possible Impact on Reliability	Barriers to Institutional Change
1.1.Systems Operations and Management Structure Awareness	Undertake educational program, re: SO&M as customer service	Provides a platform from where 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/ethic		Fuzzy legislative authority
1.2.Establish SO&M Structure	Establish top-level SO&M executive structure	A dedicated structure will allow for an interrelated sequence of planning, systems engineering, resource allocation, procurement, project development and implementation, procedural coordination, etc.	Absence of experiences SO&M manager(s)
	Establish appropriate organizational structure		Staffing level constraints
	Identify core capacities		Shortfall/turnover in qualified staff
	Determine, allocate responsibility, accountability and incentives		Staffing level constraints

Table 6.2 - Key Agency Management, Organization, and Resources Allocation Strategies - Continued

Strategy	Treatments	Possible Impact on Reliability	Barriers to Institutional Change
1.3.Establish SO&M as High Priority Budget Item	Develop program-level budget estimate	A dedicated budget will ensure that Agencies have the funds available to implement the various strategies and treatments available to improve travel time reliability.	State funding ineligible 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		State funding ineligible for SO&M
	Develop methodology for trade offs		No performance outcome measures
1.4.Identify Opportunities for public-private partnerships	Agree on operational roles and procedures with PSAs	Bringing together the functional and/or geographic priorities of various agencies will allow for cooperated efforts to effectively apply strategies and treatments, with key roles played by several parties.	Conflicting partner priorities
	Identify opportunities for joint operations activities with local government/MPOs		Conflicting partner priorities
	Develop procedures that accommodate partners' goals and maximize mobility (minimum disruption) MOUs		Conflicting partner priorities
	Rationalize staff versus outsourcing activities, responsibilities and oversight		Conflicting partner priorities

Table 6.3 Key Information Collection and Dissemination Strategies

Strategy	Treatments	SWOT				Technology	Status	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats	Low, Medium, High	Current, Emerging, New	
2.1.Surveillance and Detection	Remote Verification (CCTV)	Improves mobility due to 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, Public acceptance	Can be self sustaining	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, Public acceptance	Implemented by private contractors.	Public acceptance	Medium	Current and Emerging	Traffic Incidents Bottlenecks
2.2. Probe Vehicles and Point Detection	GPS, Video Detection, Microwave Radar, Transponders, Bluetooth MAC Readers	Improve travel time estimation by capturing real time information	Needs further testing and research	Good portion of roadway networks can be covered due to decreasing costs of technology		High	New	Traffic Control Devices

Table 6.3 Key Information Collection and Dissemination Strategies – Continued

Strategy	Treatments	SWOT				Technology	Status	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats	Low, Medium, High	Current, Emerging, New	
2.3.Pre-trip Information	National Traffic and Road Closure Information	Improve 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	Improve reliability and mobility	Lack of coordination between event and transportation agencies		Diversity (size, location, purpose)	Medium	Current	Special Events
2.4.Real-time Information	Pre-trip information by 511, web sites, subscription alerts, 511, real-time navigation systems	Improve 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 (RWIS)	Improve reliability and mobility	Variability in traffic conditions not quickly reflected by the system	Implementation on remote areas where weather information is critical to drivers	Other technologies (vehicle integrated)	Low-Medium	Current	Weather
	Freight Shipper Congestion Information/Commercial Vehicle Operations (CVO)/Border Technology Systems/Smart Freight/Weigh in Motion	Improve reliability and mobility	Cost, driver acceptance , multiple agency cooperation required	Implementation on 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
2.5.Roadside Messages	Travel Time Message Signs for Travelers (DMS)/Queue Warning Systems	Improve 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

Vehicle Technologies

Another set of strategies involves in-vehicle driver assistance systems. Vehicle Infrastructure Integration (VII) (previously referred to as Vehicle-Infrastructure Integration, VII) is a research program focused on enabling wireless communications among motor vehicles and between motor vehicles and roadside infrastructures. Researchers, auto 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, Vehicle Infrastructure Integration (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 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.

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 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 (post event). Similarly, strategies that address special events relate 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 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.

Table 6.4 Key Vehicle Technologies Strategies

Strategy	Treatments	SWOT				Technology	Status	Application to Sources of Congestion
		Strengths	Weakness	Opportunities	Threats	Low, Medium, High	Current, Emerging, New	
3.1.Vehicle Infrastructure Integration	Vehicle Infrastructure Integration (VII)	Improve 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. OD estimations)	Driver Privacy	High	New	Traffic Control Devices Traffic Incidents Weather Fluctuation in Normal Traffic
3.2.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	Desired by customers, Implemented by auto manufacturers		High	New	Traffic Incidents

Table 6.5 Key Incident and Special Event Management Strategies

Strategy	Treatments	SWOT				Technology	Status	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats	Low, Medium, High	Current, Emerging, New	
4.1.Pre-Event	Service Patrols	Improve mobility and Safety	Cost	Faster response to incidents in remote areas	Priority budget item	Low	Current and Emerging	Traffic Incidents Work Zones
4.2.Post-Event	On-Scene Incident Management (Incident Responder Relationship, High visibility garments, Clear Buffer zones, Incident Screens)	Improve 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	Improve mobility and Safety	Medium Cost	As work zones tend to increase nationwide, work zone management seems to be fundamental.	If infrastructure needs to be added, costs will increase significantly	Medium	Current and Emerging	Work Zones

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 occur (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 occur (due to the ability of the roadway to "absorb" these events).

This set of strategies focuses on improvements applied to the roadway environment and 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 (ITS), traffic-demand metering, and the application of variable speed limits. Strategies related to agency intervention or guidance include travel pricing and Travel Demand Management (TDM) measures, which focuses on reducing vehicular travel and promoting alternative travel modes - all measures that are inclined to improve non-recurring congestion.

Some of the strategies that fall into this category are also considered part of the emerging concept called Active Traffic Management (ATM). The 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.*"

The Advanced Traffic Management 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 active traffic management 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. [(10)]

Table 6.6 summarizes 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.

Economic principles suggest that to improve travel-time reliability, travel demand and capacity will be balance. So, removing bottlenecks eliminates capacity constraints and managing demand smooths out surges in traffic. To accomplish these two objectives, the mission of transportation agencies may have to become 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 under any scenario to effectively address reliability problems.

Table 6.6 Key Infrastructure Improvements and Demand Optimization Strategies

Strategy	Treatments	SWOT				Technology	Status	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats	Low, Medium, High	Current, Emerging, New	
5.1.Geometric Design Treatments	Bottleneck Removal (Weaving, Alignment)	Reduce congestion	Cost		Difficulty of post-construction	N/A	Current	Physical Bottlenecks
	Geometric Improvements (Interchange, Ramp, Intersections, Narrow Lanes, Temporary Shoulder Use)	Improve mobility	Difficulty of post-construction	Sustainability		Low	Current	Physical Bottlenecks Traffic Incidents
5.2.Access Management	Access Management (Driveway location, Raised medians, channelization, frontage road)	Improve mobility and safety	Cost	Incorporated into regional planning/land use programs	Difficult to implement in post development stage	Low	Current	Traffic Incidents
5.3.Signal Timing/ ITS	Transportation Management Center (TMC)	More efficient coordination and operation of various transportation systems	Cost	Technology development and deployment may reduce installation costs		Medium	Current and Emerging	All but Bottlenecks
	Signal Retiming/ Optimization	Improved mobility/ reduced fuel consumption	Cost - Corridor Implementation	Overall network – wide optimization		Low	Current	Traffic Control Devices
	Traffic Signal Preemption at Grade Crossings	Reduce delay and improve safety	Highway/ railroad interagency cooperation	Better traffic management strategy due to the interconnection highway and rail signal systems	Increasing highway and rail traffic volumes	Medium	Emerging	Traffic Control Devices

Table 6.6 Key Infrastructure Improvements and Demand Optimization Strategies (Continued)

Strategy	Treatments	SWOT				Technology	Status	Application to Sources of Congestion
		Strengths	**Weaknesses**	**Opportunities**	**Threats**	**Low, Medium, High**	**Current, Emerging, New**	
5.3.Signal Timing/ ITS	Traffic Adaptive Signal Control/ Advanced Signal Systems	Improve 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)	Improve Transit, Freight, CVO Mobility	Cost	Application to multimodal corridors and will help reduce auto utilization with reliable transit services, Improvement to freight operations may reduce cost of fuel consumption and gas emissions.	Lack of support and funding	High	Emerging	Traffic Control Devices
5.4.Traffic Demand Metering	Ramp Metering, Ramp Closure	Improve mobility and safety	Impact on arterials (relocate congestion)	Application on freeways that have reached their saturation point.	Public acceptance	Medium	Emerging	All but Weather & Work Zones
5.5.Variable Speed Limits (VSL)	Variable Speed Limits	Improve mobility and traffic flow	It is a new concept to drivers in U.S. It needs research and advertising	Low cost application. Integration with other ITS technologies	Public acceptance	Low	Emerging	Physical Bottlenecks

Table 6.6 Key Infrastructure Improvements and Demand Optimization Strategies (Continued)

Strategy	Treatments	SWOT				Technology	Status	Application to Sources of Congestion
		Strengths	Weaknesses	Opportunities	Threats	Low, Medium, High	Current, Emerging, New	
5.6.Congestion Pricing	Electronic Toll Collection	Increased capacity and reduced delays	Cost	Replace old Open Toll Roads	Driver's non compliance, resistance to paying the tolls, concerns about equity	High	Emerging	Physical Bottlenecks
	Cordon Pricing (Area wide)	Preserve Capacity and Improve mobility	Public acceptance	Deployment in areas where there is no room for constructing new lanes/roads	ROW	Low	Emerging	Physical Bottlenecks Fluctuation in Normal Traffic Special Events
5.7.Lane Treatments	Managed Lanes: High-Occupancy Vehicles (HOV) lanes, High-occupancy Toll (HOT) lanes, truck only lanes, Truck-only Toll (TOT) lanes, HOV By-Pass Ramp	Optimize capacity and reduce congestion	Public acceptance	It can be viewed as a new source of funding	ROW	Low	Current and Emerging	Physical Bottlenecks Fluctuation in Normal Traffic Traffic Incidents
	Changeable Lane Assignments (Reversible, Variable)	Optimize capacity and reduce congestion	Cost	Deployment in areas where there is no room for constructing new lanes/roads	Interagency cooperation and driver awareness required	Low	Emerging	Traffic Control Devices
5.8.Multimodal Travel	Integrated Multimodal Corridors (IMC)	Reduce congestion and Improve mobility	Cost	Application to large urban corridors	Difficult to implement	High	Emerging	Fluctuation in Normal Traffic Special Conditions Physical Bottlenecks
5.9.Travel Reduction	Travel Alternatives - Reduction in Trips/Diversion to other times (Ride Share Programs, Telecommuting, Home office, video conferences)	Reduce congestion and Improve mobility	Public acceptance Require technology and agency buy-in			Low	Current and Emerging	Fluctuation in Normal Traffic Special Conditions Physical Bottlenecks

STRATEGIES EFFECTIVENESS AND AREAS OF APPLICATION

The references listed in Appendix F note the literature reviewed in order 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/treatments listed in this section were ranked based on the following general levels of delay reduction:

1. Delay Reduction of up to 50%
2. Delay Reduction of up to 20%
3. Delay Reduction of up to 10%
4. Other Improvements such as safety, capacity, etc.
5. Unknown benefits to date

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

As shown in Table 6.7 , the treatments with the greatest delay-reduction potential include: National Traffic and Road Closure Information, Service Patrols, On-Scene Incident and Work Zone Management, Transportation Management Centers, 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 inter-agency cooperation. For example, National Traffic and Road Closure Information may have to obtain data from weather-related agencies in order to make it available to the roadway users. In the same fashion, TMCs may have to be interconnected with emergency responders and law-enforcement authorities in order to quickly address any roadway disruptions. Additionally, the intent of these treatments is to cover 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 pre-trip planning purposes through the FHWA National Traffic and Road Closure information website (http://www.fhwa.dot.gov/trafficinfo), which also contains links to a collection of 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 non-recurring congestion conditions (e.g., road closures).

Table 6.7 Level 1 Strategies (Delay Reduction of up to 50%)

Category	Strategy	Treatments	Application to Sources of Congestion	Key Quantitative Benefits	Overall Cost Range*	Effective ness-Cost Rank
2.Information Collection and Dissemination	**2.3.Pre-trip Information**	National Traffic and Road Closure Information	Weather, Work Zones	Reduces delays (early and late arrivals) by 50%	**Low-Medium**	**1-B**
4. Incident and Special Event Management	**4.1.Pre-event**	Service Patrols	Traffic Incidents	Can reduce incident response by 19% to 77% and incident clearance time by 8 min.	**High**	**1-E**
	4.2.Post-event	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 percent	**Low**	**1-A**
		Work Zone Management	Work Zones	Reduces work zone related delays by 50% to 55%	**Variable (depends if infrastructure is added or not)**	**1-D**
5. Infrastructure Improvements and Demand Optimization	**5.3.Signal Timing/ ITS**	Transportation Management Center (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 6-53%.	**Medium-High**	**1-C**
	5.6. 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**

Notes: Overall Cost Range* :Low - <200K
Medium - >200K but < 1 million
High - >1 million

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along an important route.

Service Patrols
Service Patrols are commonly applied in urban/suburban settings to detect, respond to, and clear incidents. They are also 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 non-tolled), but are also applied to arterials by some regions. They are primarily applied to address a non-recurring congestion need in order to safely and efficiently get traffic flow back to normal conditions.

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 be provided regionally, across multiple communities. The treatment is also typically applied in a non-recurring congestion environment in response to a traffic incident 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 also be applied within all area types (urban, suburban, and rural) and facility types and operations (i.e., tolled and non-tolled). Work-zone management is a treatment used for reducing source for non-recurring 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 (TMC)
Transportation Management Centers are a treatment that 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. Since TMCs rely on the availability of field ITS devices to relay information back to a centralized location, the application of this treatment is confined to roadways with these devices, which are more commonly freeways and arterials. In addition, it is applied in both recurring and non-recurring congestion situations, given that the infrastructure to view both exists at all times with this treatment type.

Traffic Adaptive Signal Control/Advanced Signal Systems
This treatment is one 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 non-recurring congestion management needs.

Electronic Toll Collection (ETC)
ETC treatments have a limited application area that includes tolled freeway facilities. The high installation costs of this treatment are another limiting factor. Thus, they are usually confined to facilities in larger urban areas that serve regional travel needs. ETCs are 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 ETCs may become more widespread.

Table 6.8 shows the second most-effective group of strategies and treatments found in the literature review. Accordingly, the supporting references are also shown in Table 6.8. The treatments included in this group include: CCTV, Pre-trip information Road Weather Information Systems, Dynamic Message Signs, Geometric Design Treatments, Signal Retiming, AVL, Ramp Metering, Congestion Pricing, and Managed Lanes. Interestingly, these treatments have lower costs when compared to the Level 1 treatments A common characteristic of these treatments is that they address local congestion sources and their benefits may not been seen in other parts of the roadway network. The context in which each of the treatments associated with Table 6.8 could be applied was also considered as described below.

Remote Verification (CCTV)
This treatment 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., CBDs), 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 non-recurring congestion and can be used to monitor the status of either (typically via a TMC).

Pre-trip information by 511, web sites, subscription alerts, radio
This treatment type provides pre-trip 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 which is 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, rural) and facility type. The treatment provides valuable information during both recurring and non-recurring congestion conditions that can be used by motorists when planning a trip.

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

Dynamic Message Signs (DMS)
DMS plays an important role on travel-time reliability since it is one of the main sources of travel-time reliability information for en-route roadway users. Permanently-mounted Dynamic Message Signs 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 they can also be found in suburban and rural areas. Additionally, they are used to disseminate information where both recurring and non-recurring congestion conditions exist.

Table 6.8 Level 2 Strategies (Delay Reduction of up to 20%)

Category	Strategy	Treatments	Application to Sources of Congestion	Key Quantitative Benefits	Overall Cost Range*	Effectiveness-Cost Rank
2.Information Collection and Dissemination	**2.1.Surveillance and Detection**	Remote Verification (CCTV)	Traffic Control Devices, Special Events, Weather, Traffic Incidents	5% reduction in travel times in non-recurring congestion and overall 18% reduction in travel times.	**Medium**	**2-C**
	2.4.Real-time Information	Pre-trip information by 511, web sites, subscription alerts, radio	Traffic Control Devices, Special Events, Weather, Work Zones, Traffic Incidents	Potential reduction in travel time from 5% to 20%.	**Variabl e**	**2-E**
		Road Weather Information Systems (RWIS)	Weather	Reduces delays by up to 12%.	**Low-Medium**	**2-B**
	2.5.Roadside Messages	Travel Time Message Signs for Travelers (DMS & VMS)	All	improve trip time reliability with delay reductions ranging from 1 to 22 percent.	**High**	**2-F**
5. Infrastructure Improvements and Demand Optimization	**5.1.Geometric Design Treatments**	Bottleneck Removal (Weaving, Alignment)	Physical Bottlenecks	Reduces travel time by 5% to 15%.	**Medium -High**	**2-D**
	5.3.Signal Timing/ ITS	Signal Retiming/ Optimization	Traffic Control Devices	Traffic signal retiming programs resulted in travel time and delay reductions of 5 to 20 percent.	**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**
	5.4.Traffic Demand Metering	Ramp Metering, Ramp Closure	All	A study regarding the use of ramp meters in North America found that the mainline peak period flows increased 2% to 14% due to on-ramp metering.	**Low-Medium**	**2-B**
	5.6. Congestion Pricing	Cordon Pricing (Area wide)	Physical Bottlenecks, Fluctuation in Normal Traffic, Special Events	Congestion pricing in London decreased inner city traffic by about 20%.	**Low-Medium**	**2-B**

	5.7.Lane Treatments	Managed Lanes: High-Occupancy Vehicles (HOV) lanes, High-occupancy Toll (HOT) lanes, Truck-only Toll (TOT) lanes	Physical Bottlenecks, Fluctuation in Normal Traffic, Traffic Incidents	Provides reduction in travel times up to 16%.	**Medium -High**	**2-D**

Overall Cost Range* :Low - <200K
Medium - >200K but < 1 million
High - >1 million

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

Geometric Design Treatments
These 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 on a facility in need of higher safety performance - where crashes have been known to create non-recurring congestion conditions. The improvement of horizontal and/or vertical alignments is most-often applied in the case of older facilities of all types and settings.

Signal Retiming/ 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 of the setting types. Typically, this treatment is applied to address recurring congestion issues, but it has the flexibility to also be applied in non-recurring 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 (AVL)
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. In the cases of Signal Priority and AVL, these treatments 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 including transit, fire, and emergency response vehicles.

Ramp Metering, 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 in 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 the closing of a ramp.

Congestion Pricing (Area wide)

Congestion Pricing is a treatment with limited applications. Internationally, it has only been applied in large urban areas such as Singapore, London, and Stockholm. 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 unfeasible infrastructure expansions in large metropolitan areas.

Managed Lanes: High-Occupancy Vehicles (HOV) Lanes, High-Occupancy Toll (HOT) Lanes, and Truck-Only Toll (TOT) 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. They are also used on some arterial roadways. Managed lanes can be operated either as tolled or non-tolled facilities. They are most commonly found in urban areas. In urban areas, they 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. As highlighted by the supporting references, this group has the potential to reduce delays by up to 20%. The treatments that comprise 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 in which each of the treatments could be applied is described in the section below.

Planned Special Events Management

This treatment is applied in urban, suburban, or rural locations where special events cause non-recurring congestion and unexpected delays to 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. Due to 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/Commercial Vehicle Operations (CVO)

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 VMS, 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 is a treatment applied within a vehicle rather than on a particular facility type. Nevertheless, the number of automobiles with these safety capabilities will become more common.

Traffic Signal Preemption at Grade Crossings

This treatment is 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 inter-agency communications will increase the deployment of this treatment. Focus is often most desirable at locations with high daily volumes and a high number of crashes involving vehicles and trains.

Table 6.9 Level 3 Strategies (Delay Reduction of up to 10%)

Category	Strategy	Treatments	Application to Sources of Congestion	Key Quantitative Benefits	Overall Cost Range*	Effectiveness-Cost Rank
2.Information Collection and Dissemination	**2.3.Pre-trip Information**	Planned Special Events Management	Special Events	Reduced delay due to special events.	**Low-Medium**	**3-B**
	2.4.Real-time Information	Freight Shipper Congestion Information/ Commercial Vehicle Operations (CVO)	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**
3.Vehicle Technologies	**3.2.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% and reduces travel times by 4% to 10%.	**Low**	**3-A**
5. Infrastructure Improvements and Demand Optimization	**5.3.Signal Timing/ ITS**	Traffic Signal Preemption at Grade Crossings	Traffic Control Devices	Simulation models showed that delays at grade crossings can be reduced by up to 8%.	**Medium**	**3-C**

Overall Cost Range*:Low - <200K
Medium - >200K but < 1 million
High - >1 million

Table 6.10 shows the treatments identified in Level 4, where the quantified improvements are mainly related to increased safety and capacity, as indicated by the supporting literature review. 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 if they are implemented together. The European experience has shown that when 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 in 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. They 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 for this treatment.

Geometric Design Improvements
Geometric 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.[4, 5]

Variable Speed Limits (VSL)
This treatment is applied to freeway facilities to vary the facility 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.

Table 6.10 Level 4 Strategies (Other Improvements – Safety, Throughput)

Category	Strategy	Treatments	Application to Sources of Congestion	Key Quantitative Benefits	Overall Cost Range*	Effectiveness-Cost Rank
2.Information Collection and Dissemination	**2.1.Surveillance and Detection**	Driver Qualification	Traffic Incidents	Reduce non-recurring 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 done by contractors)**	**4-D**
	2.2.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**
5. Infrastructure Improvements and Demand Optimization	**5.1.Geometric Design Treatments**	Geometric Improvements (Interchange, Ramp, Intersections, Narrow Lanes, Temporary Shoulder Use)	Physical Bottlenecks, Traffic Incidents	Geometric improvements revealed increased overall capacity by 7% to 22%.	**Medium**	**4-C**
	5.5.Variable Speed Limits	Variable Speed Limits (VSL)	Physical Bottlenecks, Special Events	Increases throughput by 3% to 5%.	**Low-Medium**	**4-B**

Overall Cost Range*:Low - <200K
Medium - >200K but < 1 million
High - >1 million

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, Access Management, Changeable Lane Assignments, Integrated Multimodal Corridors, and Travel Alternatives. One of the reasons why information regarding 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 of the treatments associated with Table 6.11 could be applied was also considered as described in the section below.

Vehicle Infrastructure Integration (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, on-board computer processing, advanced vehicle-sensors, GPS navigation, smart infrastructure, and others, to provide the ability for vehicles to identify threats and hazards on the roadway and communicate this information over wireless networks to give drivers alerts and warnings. 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)
This treatment 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, and bridges/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 the freeway with gate controls on both ends. Temporary shoulders are another form of this treatment that is applied on freeways to reduce congestion levels.

On arterial facilities, a movable barrier can be applied to physically separate opposing directions of traffic flow 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 using variable lane-use control signs that change the assignment of turning movements to accommodate variations in traffic flow.

Integrated Multimodal Corridors (IMC)
This treatment 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 (Rideshare Programs, Telecommuting, Home Office, Video conferencing)
Of the travel alternatives treatment types, rideshare 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.

Table 6.11 Level 5 Strategies (Unknown Benefits)

Category	Strategy	Treatments	Application to Sources of Congestion	Key Quantitative Benefits	Overall Cost Range*	Effectiveness Rank
3.Vehicle Technologies	**3.1.Vehicle Infrastructure Integration**	Vehicle Infrastructure Integration (VII)	Traffic Control Devices, Traffic Incidents, Weather, Fluctuation in Normal Traffic	Unknown benefit towards reducing congestion.	**Low-High**	**5-B**
5. Infrastructure Improvements and Demand Optimization	**5.2 Access Management**	Access Management (Driveway location, Raised medians, channelization, frontage road)	Physical Bottlenecks, Traffic Incidents	Unknown benefit towards reducing congestion.	**Low**	**5-A**
	5.7.Lane Treatments	Changeable Lane Assignments (Reversible, Variable)	Traffic Control Devices	Unknown benefit towards reducing congestion.	**Medium-High**	**5-C**
	5.8.Multimodal Travel	Integrated Multimodal Corridors (IMC)	Fluctuation in Normal Traffic, Special Conditions, Physical Bottlenecks	Unknown benefit towards reducing congestion.	**High**	**5-D**
	5.9.Travel Reduction	Travel Alternatives (Ride Share Programs, Telecommuting, Home office, video conferences)	Fluctuation in Normal Traffic, Special Conditions, Physical Bottlenecks	Unknown benefit towards reducing congestion.	**Low**	**5-A**

Overall Cost Range*: Low - <200K
Medium - >200K but < 1 million
High - >1 million

TECHNOLOGICAL INNOVATIONS IN THE FUTURE

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 multi-modal integration will change the behavior of commuters in the next 20 years. As these mobile applications are being developed and integrated with traffic data, we will see more information related to:

- Carpool/Car Sharing Programs
- Transit Information
- Safety Applications (e.g., automated accident notification)
- Emergency Ride Programs
- Parking Information

- Dynamic Routing integrated with ridership programs
- Multi-modal travel options with cost and time info

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 in the morning, 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 usage 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.

An 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 decrease 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 regarding 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 its application widespread is the Smart Cards and radio frequency identification (RFID) tags. The market penetration for this technology will be a reality, and privacy issues will be overcome. With that, 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, the "telecommuting collaborative technologies" will finally turn telecommuting into a practice part of major business activities. Video-conferencing systems allied with the Next Generation of 100 GBs networks and high-speed wireless networks (WIMAX) will provide superior video- and data-stream quality, regardless of where employers are (at home; flying; in another city; etc.).

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

Automated cars and highway systems are other concepts that have been around for decades but have never taken off. With the advances in research of Vehicle Infrastructure Integration (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 is to fully develop the capabilities of Vehicle Infrastructure Integration (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, the share smart car concept makes carpooling and conventional transit more effective, by solving the "last mile” problem.

Regarding 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 the top of gas taxes will lead to a shift from fossil-based vehicles. Hydrogen fuel will also appear as an environmentally friendly alternative to fossil-based fuels, especially in Europe and Asia. In North America, bio-diesel 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 job locations and related activities. With the full deployment of telecommuting capabilities, suburban areas will see more “business centers” where workers that live nearby will go to work, regardless of their employer location. Government will also support people living within a certain distance of their place of employment. With that, miles traveled between jobs and housing will reduce dramatically, having a positive impact to travel-time reliability.

The least-sustainable suburban communities will be redesigned into work-leisure areas where “community-gathering” spaces will be created nearby residential neighborhoods. Walkable social activities will transform once old cheap land in the suburbs.[11] The actionable future needs to combine multimodal transit, telecommuting, ridesharing, 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 via 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 where you’re going 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 we will pay for car safety. It is not hard to envision a gradual evolution as computers stealthily take on more and more of the driving chores. [12, 13]

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

Home → transit/bike → Grocery Shopping → Smart/City/Zip…whatever Car → Home

In the future, every roadway user will be a decision maker, with the power of deciding where, how and when to make every single 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:

- Automation/infrastructure
- Information technology/data sharing
- Integration/cooperation

Automation/Infrastructure

Imagine automated cars capable of pick up elderly and disabled people in residential areas and taking them to nearby supermarkets, doctor's appointments, and wherever else they might like to go. This will be possible due to 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, since the cars come to you. In a way it 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. (17)

Not far away from this concept, the revolutionary in-wheel traction and steering system of the CityCar from the Massachusetts Institute of Technology (MIT), a stackable, all-electric, two-passenger vehicle could radically alter personal urban transportation. Basically, CityCars work as shopping carts, stacking on at each other. It is intended to have an efficient shared used. Another innovation is that it spins on its own axis, avoiding u-turns and conflicting turning movements. In the same fashion, the development of rechargeable motorcycles and bicycles equipped with communication devices capable to provide all sorts of information to riders will complement the automated car view.

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 mesh/wireless networks. The idea of the vehicle as a mobile information center will be widespread with the addition of increasing electronic intermediation of vehicle control.(19)

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

Table 6.12 Automation/Infrastructure Strategies

Strategy	Description/Application	Modes Affected	Impact on Reliability
Real time control of transit arrivals, connections and pre trip	Advanced transit operation strategies.	Transit	Medium
Real time road pricing	Broadly applied, broadly accepted.	Passenger Vehicles/Freight	Medium
Reliability and quality control with pricing	It permits reservation systems, guaranteed arrival times at a price.	Passenger Vehicles/Freight	High
Vehicle Infrastructure Integration (VII) implementations	It will make crashes on limited access roadways rare. Greatly affects reliability.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	High
Instant automated incident detection and assessment	Information to first responders and rerouting algorithms.	Passenger Vehicles	Medium
Robotic deployment of Visual screens	Eliminate gapers' blocks.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	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, Freight	Medium
3D video, 3D telepresence and haptic (touch based) interfaces	Telecommuting becomes a real option due to advanced communication technologies, and general acceptance of this family friendly, environmentally soft work style.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	High
Automation in truck operations	Exclusive, tolled, automated lanes. Reduces crashes and driver fatigue. Increases reliability.	Freight	High
Resilient infrastructure	Will work 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, Bike, Peds)	Medium

Information Technology/Data Sharing

Futuristic predictions say that by 2030, video calling will be pervasive, generating 400 exabytes of data - the equivalent of 20 million Libraries of Congress. The phone, web, email, photos, and music will explode to generate 50 exabytes of data. With that, 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.[19, 20 and 21] Such overwhelming data availability will challenge agencies capability of handling and making good use of such amount of data. Information sharing across agencies is a key factor to overcome this issue, 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 an improved data quality and amount, electronic data collection (particularly in recording the incident start and stop times) will have significantly improved overall data usefulness. These communications enhancement will ultimately provide a more accurate measure of the benefit of implemented tactics to the traveling public and the media.[22]

Paired with this, 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 for the public. Cost information dissemination will be also 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 audio that is useful to first responders will become common, reducing traffic incident clearance times.[23]

Another change that will be seen related to information technology is the increased use of social networks related to carpooling/bikes/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.

Table 6.13 Information Technology/Data Sharing Strategies

Strategy	Description/Application	Modes Affected	Impact on Reliability
Comprehensive real time information	Real time information will be available to all modes in an integrated fashion. Peds, Bikes and Vehicles will have relevant information and options on how to proceed with their trips.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	High
Video coverage of networks	See the picture of the road ahead in your car, on your phone, in the TMC.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	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	The barriers will be overcome through creative confidentiality agreements, technologies and algorithms.	N/A	Medium
Predictive models for real-time systems operation	Forecasting models will support real time systems operations and prevent possible breakdowns on the network	N/A	Medium

Integration/Cooperation

It is known that more fuel efficient cars, more public transportation, more ridesharing, 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.[24] 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 Department of Transportation (WSDOT) 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, WSDOT 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. [25]

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 car-sharing and bike-sharing. 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. It will better demonstrate, through performance metrics and evaluation, the return on investment.[19] We will see the continued evolution and integration of previously separate information and safety systems. The establishment of more strategic approaches and the good use of performance measurements will be critical for evaluating the efficiency of integrated strategies.

Field tests have been conducted to integrate the Utah Highway Patrol (UHP), the Utah Department of Transportation (UDOT), Salt Lake City Fire and Police Departments, the Utah Transit Authority (UTA), and the Valley Emergency Communications Center (VECC) information systems to enable the real-time exchange of incident data. These tests have revealed the importance of involving agency IT staff early in the development of the integrated system and the importance of developing close working relationships among the agencies involved in this effort. [22]

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 way that public transportation will move people and goods in long urbanized commutes while shared vehicles will help people to reach their final destination. Modes at different levels such as subways, buses and airplanes will have synchronized and integrated departure/arrival times - optimizing network usage.

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 which may be a threat to health (e.g., heart attacks) can be mapped and linked to congestion patterns. A better understanding of the correlation of traffic and human factors will be achieved. [26]

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

Table 6.14 Integration/Cooperation Strategies

Strategy	Description/Application	Modes Affected	Impact on Reliability
Customized, real time routing	Tuned to your preferences and driven by real time congestion and reliability data, with predictive capability. What will conditions be when you get there?	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 3PLs.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	Medium
Real time information on parking availability, roadway conditions, routing, rerouting	Time spent on parking will be significantly reduced. Drivers will know where to find parking available 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, Bike, Peds)	High
Latest onboard technology	Fleet turnover inertia overcome with software upgrades rather than new vehicle purchases	Passenger Vehicles, Freight, Transit	Medium
BRT and signal pre-emption	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 due to 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
Combined sensors/ computer/ wireless link)	Multiple information fusion methods combine data from multiple sensors & databases. Data fusion nodes communicate on an ad hoc wireless network.	N/A	Medium
Advanced Automated Crash Notification Systems (AACN) in all vehicles	Crash notification within one minute for all crashes. Network of sensors in infrastructure to detect imminent or actual events or hazards	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	High
Next Generation 9-1-1 fully implemented	Full AACN telemetry data in actionable form pushed into NG 911 system. Image from inside vehicle automatically received at PSAP after crash.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	High
Hybrid Wireless Mesh Networks	Mesh networks will facilitate the communication of (VII) and improve mobile interconnection. Vehicle-to-Vehicle and Vehicle-to-Infrastructure networks will be a reality.	All (Passenger Vehicles, Freight, Transit, Bike, Peds)	High

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7. A CONCEPT OF OPERATIONS

CONCEPT OF OPERATIONS DEFINITION

According to the USDOT, a concept of operations 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 the roles and responsibilities of the stakeholders, a typical concept of operations is intended to be a high-level document. In fact, the depth of information of a concept of operations will likely rely heavily upon the quantity and variety of systems and likely scenarios within a region. To that end, many regional 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 concept of operations, the significance of their roles and responsibilities is readily apparent and gaps or challenges in regional operations identified and prepared for. The resulting documentation can be a series of statements an agency or group of entities may wish to adopt that are binding, simply stated facts, or establish a goal or direction.

TRAVEL-TIME RELIABILITY CONCEPT OF OPERATIONS PURPOSE

The intent of this Concept of Operations document is to define the roles and responsibilities of participating agencies play in applying strategies and treatments that can 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 those strategies most relevant to their region and be able to measure the performance of each strategy. The purpose of this Concept of Operations document is to:

- Establish a baseline set of existing conditions that describes the strategies that are employed today; and
- Describe the 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 future scenarios that span the range of future 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 non-recurring 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, etc.). The following five reliability measures were found to be most relevant to the user categories and are most widely used by transportation agencies:

- **Planning Time (95^{th} Percentile Travel Time).** This is the length of a particular trip in minutes that a traveler can use in planning to assure arrival as scheduled (required) 95% of the time. It is calculated by computing the 95^{th} percentile travel time for a specific trip measured over a given time period (i.e., six months or one year). This measure estimates how large delay will be during the heaviest traffic days.
- **Buffer Index.** This is the difference between the 95^{th} 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.
- **Planning-Time Index.** This is the 95^{th} 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 95^{th} percentile measure).
- **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 travel-time reliability. Nevertheless, it is an important measure because it can be directly compared to the planning time index.
- **Percent On-time Arrival**. This is the percent of trips that are completed within a given target schedule. It is best suited for tracking the performance of scheduled trips (such as buses and light rail).

As suggested by the SHRP2 - L03 project Draft Final Report, 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 assure 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 regarding how to adjust their trip plans to deal with unreliability. It is desirable if agencies focus on reporting and evaluating the Planning-Time Index since 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 us to express 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.

Figure 7.1Appendix 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.

USDOT

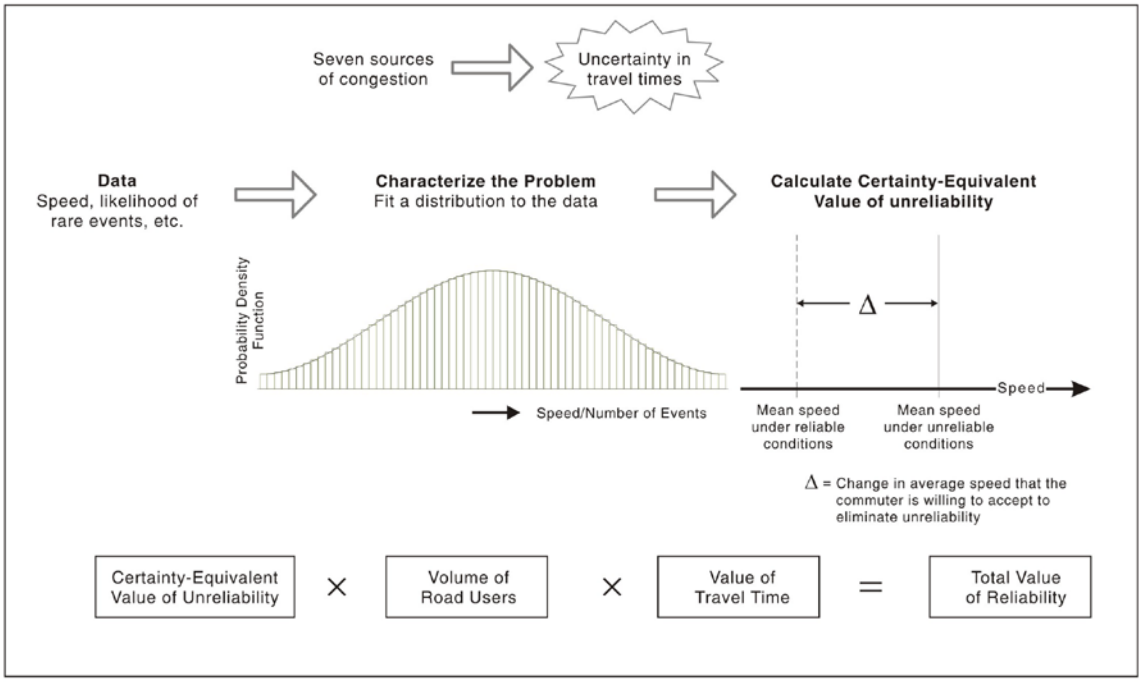
- Reliability policies have been established to promote the importance of reliability as a key performance measure and promote its implementation by agencies.
- Limited performance-measures data are being collected.
- Funding for reliability research and improvements has been provided.

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 this data.
- Some truck lanes at ports of entry and weigh-station bypass lanes are provided.
- Traveler information is provided using various delivery methods.

- Limited ramp metering, variable speed limits, hard shoulder running, and truck lanes have been deployed.
- VMS, HAR, 511, and traffic enforcement applications are increasing.

Figure 7.1 - Concept for Valuing Travel-Time Reliability



Local Transportation Agencies

- Traffic signal timing and signal optimization strategies are deployed.
- Traveler information systems are being deployed.

Private Data Information Providers

- Traffic and weather conditions are available from web-sites, radio traffic reports, and twitter.
- Travel-time data is available from private firms.

Emergency Responders

- Some of the major highway corridors have incident response coverage which is coordinated among jurisdictions.
- Some ITS applications are in place.
- Service Patrol Programs such as Road Rangers are implemented.

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.

Vehicle Manufacturers

- Luxury car models have in-vehicle safety systems like 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 USDOT and State DOTs to develop Vehicle Infrastructure Integration (VII), an initiative to provide vehicle-to-vehicle communications and to improve safety and mobility. Vehicle Infrastructure Integration (VII) is currently being tested in California and Michigan.

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/or in-vehicle information systems.
- Telecommuting is increasingly common but still only accounts for a tiny fraction of the urban travel market.

FUTURE SCENARIOS OVERVIEW – A CON OPS PERSPECTIVE

The key characteristics that describe future conditions are described below. For the future baseline, optimistic, mediocre, and pessimistic conditions, technologies, organizational activities, and key responsibilities are described.

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 of these technologies can be operated as an active traffic management system.

The deployment of currently available traveler information systems such as DMS, 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 of 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, which 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.

The **automobile manufactures** will play a role by providing a broader range of car models (more than just luxury models). They 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 the current and potential trends to identify (1) a range of factors affecting the operation of the transportation system and demands for it, (2) the frequency of non-recurring congestion, (3) the priorities likely to be placed on mitigating such congestion, (4) the technologies that may exacerbate the problem or facilitate effective responses to it, and (5) the broader social, environmental, and 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 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 U.S. The demand for reliable transportation will increase because of (1) increased travel demand as a result of strong economic, population, and employment growth and (2) 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 multi-jurisdictional 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 the policies and procedures in place and the data 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 via 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 technologies, some automated highway systems will be deployed for trucks, transit and autos.

Since there will be adequate **transportation funding**, intercity transport alternatives such as high-speed rail and automated lanes will be available for trips under 300 miles, thereby reducing 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, non-recurring congestion. Driver assistance systems will be good enough 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 TMC during the process. Due to the reduction in incidents because of driver assistance systems, incident response will be more focused on disaster response, including evacuation planning. Intermodal transfer of goods will be seamless due to 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 intermediate 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 (1) a stronger economy and increased employment, (2) pressure for efficiency coming from climate change and energy constraints and regulations, and (3) emerging technologies making more-reliable transportation systems feasible. This demand will draw new technologies into the marketplace and promote their deployment. Since the economy in this scenario will be less robust, the level of tolling will be less and the amount of funding for transportation improvements will be less. Increasing energy prices and moderate population growth will mean that there will not be as much pressure to accommodate car usage as there is in the optimistic scenario. However, congestion will still need to be managed.

In terms of **transportation funding**, a gas tax is still 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 due to 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 where 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 due to 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 still 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 in this scenario than will occur in the optimistic scenario. Non-recurring 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 by-pass at freeway speeds or a facilitated inspection. Logistics efficiency and JIT will be relevant but will not be a primary driver of freight mobility. Security and infrastructure health monitoring will be limited to major facilities. Some hazmat vehicles will be tracked. The location for some global trading patterns will shift as more manufacturing moves back to North America due to rising energy prices. Also, more containers from Asian ports will go directly to east coast and Gulf ports via 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 due to, 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 (1) reducing fuel consumption, (2) decreasing greenhouse gas emissions, and (3) 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. Since the economy in this scenario will not be very robust, the amount of funding for transportation improvements relative to the needs will be greatly restricted. Steep increases in energy prices, the increasing effects of climate change, and low population growth will mean that car usage will be limited and agencies 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 only be available to pay for new facilities. Tolls will be removed when a facility is paid for. A relatively large gas tax increase will occur, but this increase will still 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 of speed, red light running, ramp meters, and toll evasion. Automated Highway Systems will not be fully implemented, requiring some motorists' awareness 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 due to 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 non-recurring 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). It 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, since crash rates will be high and disasters will be frequent. Some weigh stations and ports of entry will have inspection technology that allows for by-pass at freeway speeds. Logistics efficiency and JIT will not be emphasized because many companies will be in a survival mode and because 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 ASSIGNMENT

In order 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.

Table 7.1 Impact of Alternative Futures on the Sources of Congestion

Sources of Congestion	Impact based on Future Scenario		
	Optimistic Scenario	Mediocre Scenario	Pessimistic Scenario
Traffic Incidents	**High**	Medium	Low
Weather	Low	Medium	**High**
Work Zones	Low	Medium	**High**
Fluctuations in Normal Traffic/Special Events	Medium	**High**	Low
Traffic Control Devices	Medium	**High**	Low
Physical Bottlenecks	**High**	Medium	Low

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/special events are expected to be increasingly frequent sources of congestion due to 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 tornados, snow storms, 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 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 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, since all of the 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, Transportation Management Center (TMC) was assigned to the baseline scenario, since 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 that 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 the strategy usage 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 due to the higher number of disruptions related to recurrent weather events in the pessimistic scenario, the expansion of this treatment will be critical to 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 and to all future scenarios due to 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 Vehicle Infrastructure Integration (VII). Under the Fluctuations in Normal Traffic/Special Events source of congestion, VII is only identified for the optimistic scenario. Since it is a set of technologies that is still being tested, its application was not assigned to the baseline scenario. Due to 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 roadmap 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 ROADMAP

This roadmap 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 responded to in order to overcome congestion and travel-time reliability threats generated in all three alternative future scenarios.

Improved Travel-Time Reliability: What's Needed?

The most significant benefits in improving travel-time reliability would 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 would become available in the next 20 years. These changes, solutions, and actions would 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 would 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 to travel-time reliability unless more significant structural changes occur in balancing travel demand and transportation supply (capacity) as shown in Figure 7.2.

Figure 7.2 - Implemented Reliability Performance

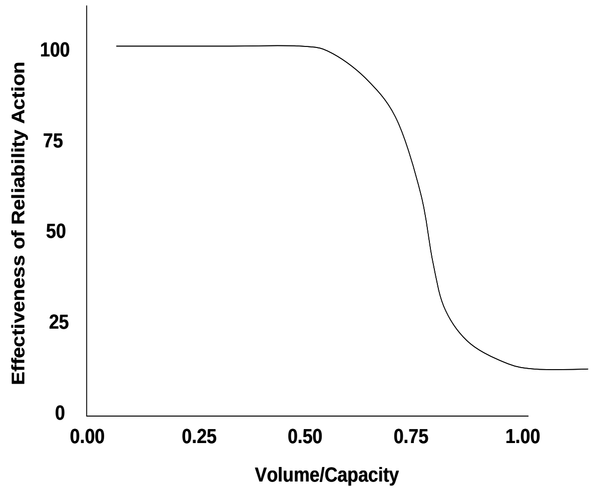


Table 7.2 Key Treatments to Respond to Baseline and Future Scenarios

Source of Congestion	Baseline System & ConOps	Optimistic Scenario System & ConOps	Mediocre Scenario System & ConOps	Pessimistic Scenario System & ConOps
Traffic Incidents	Remote Verification Service Patrols TMC	Remote Verification Driver Qualification Automated Enforcement Pre-trip 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 & Road Closure Pre-trip information RWIS TTMS VII TMC
Work Zones	National Traffic and Road Closure Information WZM	VII Work Zone Management	TTMS WZM	National Traffic and Road Closure Pre-trip information TTMS WZM TMC
Fluctuations in Normal Traffic/ Special Events	Remote Verification PSEM Pre-trip information	PSEM Pre-trip information TTMS VII TMC ATA VSL Managed Lanes	Remote Verification PSEM Pre-trip 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 or Closure Variable Speed Limits Electronic Toll Collection Managed Lanes	Ramp Metering, Ramp Closure Variable Speed Limits Electronic Toll Collection Managed Lanes

ATA - Advanced Transportation Automation
CVO - Commercial Vehicle Operations
PSEM - Planned Special Events Management
RWIS - Road Weather Information Systems
SRO- Signal Retiming & Optimization
TMC - Transportation Management Center
TTMS – Travel Time Message Signs (including variability)
VII- Vehicle Infrastructure Integration
WZM- Work Zone Management

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 easily available describing available travel options, the expected travel times for those options, and the prices to be paid for each of those options, so that travelers and shippers can make informed choices when they plan trips, just prior to the execution of those trips, and during the execution of those trips
- travelers would be required to pay more directly for the transportation services they receive, and set 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
- agencies that deliver those services would be held more directly accountable for the quality of those services
- the funds generated from user fees would be returned to the agencies that supply the multi-modal, 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 transportation system than now occurs in the United States. It will require that consumers (individual travelers and shippers/carriers) be given travel options, as well as information about those travel options, be charged separately and explicitly for each of those options, and that the cost associated with each option reflect the costs of providing those transportation 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 those travel options.

In this system, some consumers, for some trips, will choose high cost, faster, more reliable travel options (e.g., overnight air express shipping, or SOV commuting via HOT 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 that:

- Travel consumers have choices
- Travel consumers 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 concept of operations, 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, since 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, traffic signal light outages, bridge expansion, joint deterioration, potholes, and more serious structural failures could be major contributors to reduced system reliability in the future. Infrastructure monitoring systems are likely to be a critical part of any attempt to assure 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. Since many highway systems of the future are likely to be greatly dependent on pricing systems for revenue, congestion management, and data collection, it will be 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 non-performers to lower status jobs as is done in the case of non-performing 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 look at a wider of range options, such as truck-only lanes, micro-cars, 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 also focus on the movement of information from A to B. Providing the information needed by commuters to make informed decisions on telecommuting 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, it 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 even handed in providing service and advice. Thus, it would never be an information carrier, like 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 may 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, people 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 where 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 it is for the automobile. Thus, improvements to one mode can bring benefits to the other. Where 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:

- 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
- 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. While 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 received 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 in 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 this open, collaborative environment where 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 Departments of Transportation include Maryland DOTs Coordinated Highways Action Response Team (CHART) program, Florida DOTs Rapid Incident Scene Clearance (RISC program), Georgia DOTs Towing and Recovery Incentive Program (TRIP), Washington State DOTs 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 TSMO 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 roadmap is that transportation funding during the next 20 years will be adequate to deploy the infrastructure to implement the concept of operations developed here. Agency approaches to generating these transportation funds are discussed below.

Revenue contributed to the National Highway Trust Fund is not growing as fast as the needs for it are growing. 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 based on the vehicle damage (weight), the number of occupants, the type of facility used, and the number of miles traveled. 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 and/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/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 that:

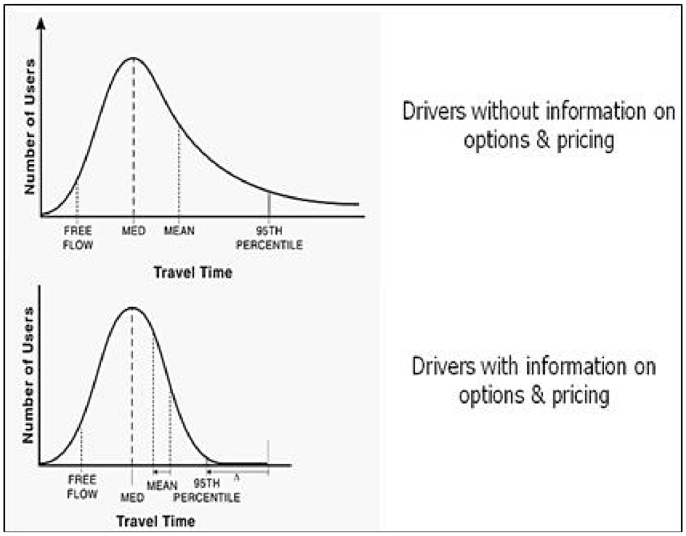
- pricing is an effective strategy for managing demand
- the equity consequences can in some cases be remediated by the targeted deployment of funds collected (including discounts or subsidies) providing better transit services or other benefits that may or may not relate to transportation
- the data collected by location-based pricing schemes is 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 is shown in Figure 7.3 below.

One should bear in mind that pricing is not the only means of allocating scare 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 of making travel time reliability more visible as a cost and an operational consideration, is that in the absence of pricing it becomes apparent the implicit or "shadow" price road users really pay includes both the cost of travel time and unreliability they experience to use a route. So in reality both 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 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 since the time resources each person has is the same,

Another option for bringing supply and demand into balance on highly congested roads are 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. Depending upon the approach, various degrees of economic efficiency and equity can be achieved.

Figure 7.3 Value and Effect of Pricing Information



Technology

As noted before, the key for managing the transportation system for reliability and, therefore, making the concept of operations 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. The communications system is necessary to exchange that data and to communicate 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 this challenge 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 since they can supply a wealth of real-time probe vehicle data, for:

- Pricing/Congestion Management
- Traveler information
- 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
- Head and fog light status
- Airbag deployment
- Transmission status (in a specific gear or in park).

Communications

While 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 (DSRC) that support connected vehicle and vehicle-to-infrastructure applications.3G wireless is widely available and 4G deployment is starting. Wi-Fi 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:

- Traffic Management Centers, traffic signal systems, and freeway management systems
- Vehicles and roadsides
- Vehicles and vehicles
- First responders and trauma centers
- Traffic management and law enforcement personnel
- Telecommuters and workplaces
- 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 an OnStar™ like monitoring center, possibly run by auto makers. 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 this data could also move between vehicles so they 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 were putting their windshield wipers on. This could trigger a warning message in the receiving vehicle indicating ice on the roadway, congestion ahead, or rain ahead, respectively.

HOW THE FUTURE TRANSPORTATION SYSTEM COULD WORK

Imagine four different travelers:

- Anne: a business person working in the northern suburbs of a major city, needing to travel to an afternoon meeting in the southwest portion of the city.
- Fred: also lives north of the city. He works the late shift as a janitor. He needs to be at work by 5:00 PM and comes home at 1:00 AM. He drives to work despite his limited income because the bus service is infrequent when he comes home at 1:00 AM.
- Armand: also lives north of town. He is on his normal 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: 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 PM or face a late fee of $300 for every ten 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 PM on the Western Loop. An older model car (one without the new, automated tire pressure warning gauges) blew a tire and swerved into the car next to it. Because the traffic volumes are at 85 percent 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 are needed for the occupants of the older model vehicle.

Because of the size of the crash and the high volume/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 (TMC) knows immediately that a crash has occurred.

Agency Responses to the Crash on the Western Loop

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 enters the basic parameters of the crash - describing the event into 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 the 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 the size/scope of the crash

- adjusting lane control and dynamic message signs (DMS) upstream of the crash site, as well as adjusting traffic controls and DMS 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
- changing pricing values on the HOT lane that is part of the Western Loop (the base roadway pricing for the general purpose lanes remain the same).

Regional and private sector traveler information systems receive the crash notification, including the details about that crash (location, number of lanes closed, the number of vehicles involved, and the fact that EMS has been called). They 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:

- 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, Vehicle Infrastructure Integration (VII)-based on-board systems that provide voice notification of changes in roadway conditions to all Vehicle Infrastructure Integration (VII) vehicles approaching the scene and to all vehicles that have planned itineraries that will use either the Western Loop freeway or one of the roads forecast to carry re-routed traffic
- mobile device text and audio messages (including links to more detailed information accessible via Smart Phone or in-vehicle navigation systems)
- 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 forecast traffic conditions from the active traffic management system. These data are entered automatically into their 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 traffic signal control plans to account for the 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 coaches
- sending out "late bus" and "off-route" bus notifications via multiple communications protocols concerning all bus routes/trips affected by the crash (this includes "be aware of possible delays" notifications on routes for trips that <u>might</u> be affected later in the day)

- updating real-time arrival information for affected routes based on real-time position information and forecast roadway performance information.

Traveler Responses to the Crash on the Western Loop

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 the "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 smart phone'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 SOV-based travel options (a "fastest available" general purpose lane freeway option, a HOT lane option, and a city street option), each of which is accompanied by periodically updated expected travel times and out-of-pocket costs. In the bottom right corner of the screen, she 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, which 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 adjusts her schedule to adapt to the new time she must depart to assure that she arrives on time for her meeting.

Fred is thinking about getting ready for work and accessing the web on-line at his neighborhood library. He checks the regional operations website and sees the alert about the Western Loop (his route to work). He doesn't have the 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/departure information he needs to take the bus to work. A link on the transit page takes him to a late-night dial-a-ride service reservation page, which allows him to schedule a pick-up at 1:15 AM that will take him to a transit center located two miles from his work place just in time to catch a bus that will get him 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 on-line 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 his radio in his kitchen. (Yes, FM radio is still alive and well in 2030.) 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 DOTs website describing 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 using the traffic forecasting algorithm 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 is an expensive failure to 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. While 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 via his head's up display. The driver calls Giovanni using his voice activated phone in his van and gets the OK to take the HOT lane. Not only does it save Giovanni the late delivery fine, it means that he won't have to pay the driver overtime.

Funding the Agency Response

While our four travelers are revising their travel decisions—all different choices but all <u>choices</u> and all 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, allowing them to move injured patients off-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 Vehicle Infrastructure Integration (VII). But, no mechanical system is failure proof. In addition, there are still some older, non- Vehicle Infrastructure Integration (VII) vehicles on the road.

Corridor revenues have funded the Active Traffic Management system. When combined with the in-vehicle Vehicle Infrastructure Integration (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 do 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 still like (and prefer) to drive their cars. The differences are that it is easy to find fast, convenient, and safe alternatives when driving is not a good option. And travelers 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 1) to bring market forces to bear on both travel decisions (which results from better and more ubiquitous information available to all travelers) and 2) to provide additional supply in a way that is balanced against demand.

As noted earlier in this chapter a more reliable roadway system will only occur on a sustainable long-term basis 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 our 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, 1) roadway agencies are constantly faced with situations in which demand exceeds capacity; 2) the resources to remedy that situation are not being generated and deployed to meet those demands; and 3) travelers have insufficient information and incentive to change their behavior to travel at less congested times or via other modes.

Allocating scarce highway capacity based 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 (incidents, weather, etc.) 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

- an increase in revenue targeted at capacity enhancements where demand is high.

In order to implement these improvements, three steps are offered for consideration:

- Steps toward Balancing Demand and Capacity
- Steps to Strengthen Interagency and Intermodal Relationships
- Technical/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 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 inter-agency cooperation below.)

Of particular significance is determining the base price-performance level that is acceptable. A congestion-free HOT lane price is acceptable, since low cost/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.

So long as congestion does exist, some non-trivial level of travel time un-reliability 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, versus how much money are we willing to pay in order to help manage the limited roadway capacity that we have?

The answers to these basic questions will undoubtedly be different in congested urban areas and 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 their leaders begin to understand the merits of road pricing, equity will become addressable through a variety of paths, including 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 which 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 the 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 agency-specific goals.
- Strengthen relationships with neighboring jurisdictions, especially where improved integration of facilities benefits both agencies (e.g., shared traffic operations centers, multi-agency incident response teams, and corridor management teams).
- Create and provide easily-accessed, standardized transportation system performance data to those that 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 usage-based and a value-based revenue generation structure.

Technical/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 USDOTs 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 SHRP2 - C05 Project.)
- 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
- better balance between travel demand and available capacity through better demand management.

The USDOT Vehicle Infrastructure Integration (VII) program has considerable potential to contribute to many of these areas. But, the simplest technical aspects of the Vehicle Infrastructure Integration (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, that can provide data that is 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 (1) the actual causes of unreliable travel time *in the areas specific to the agency and its partners* and (2) 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 where new technologies are emerging. Table 7.3 shows how different the future (2030) can be when compared to today if the implementation roadmap and steps presented in this chapter are followed by agencies and involved stakeholders.

Table 7.3 Summary of the Future

Focus Area	Existing/Near Term	Future/2030
Communication	Communication mostly via pre-trip information such as: • Traffic reports (511) • Weather & road condition detection information mostly used for maintenance • Demand for information growing	Communication expansion through widespread real-time traveler information Large scale information collection & 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 info systems used in traffic management strategies
Traffic Management	Isolated traffic management actions (lacks technical & institutional integration): • Roadside messages - DMS/VMS • 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 (network-wide) • 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 (pre-fabrication, quick repair materials, self-repair materials, embedded sensor that give early warning of infrastructure failures) Work zone management (real time traffic control, performance incentives) Pricing/congestion management Route/mode choice based on system optimization rather than solely user convenience, which can be done with pricing and will yield better overall solution Active Traffic Management with multi-agency 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/driver inspection • Automated vehicle inspection • Weigh-in-Motion • Land use info
Performance Measures	Very limited	Performance driven decision-making at the corridor and system level

Table 7.3 Summary of the Future (Continued)

Focus Area	Existing/Near Term	Future/2030
Fuel Technologies	Mostly gasoline	Mostly clean fuel technologies that reduce environmental impact
Vehicle Features	Stability control & airbags Automated cruise control & side collision / blind spot warnings in luxury vehicles only	Vehicle Infrastructure Integration (Vehicle Infrastructure Integration (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/micro cars that may possibly allow greater throughput & 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 reacts to congestion	More choices than today – modes, departure times, fee-based quality of service options User understands travel options and associated costs
Information	Need for information growing Use of information through cell phones & internet limited Navigation limited to route-guidance	More, and more reliable, pre-trip information based on real-time measurements as well as forecasts of system performance In-Vehicle navigation & congestion information
Telecommuting & Rideshare	Some telecommuting Increased rideshare programs	Technology innovations fully support telecommuting Well-established rideshare programs
Travel Pricing	User accepts 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 multi-modal choices Focus on supplementing travel

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 be multi-dimensional 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 upon only one or two of these elements at a time.

The remainder of this section provides an overview of the organizational, business practices 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 recently been completed within SHRP2 Project L06 (Institutional Architectures to Advance Operational Strategies) that can become a blueprint for effecting the organizational changes necessary for the broad-based and comprehensive implementation of operational strategies to improve system reliability. Quoting from the L06 project work:

> *The research across state DOTs has resulted in the development of an "Operations Capability Maturity Model" (CMM). 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 towards "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 US and internationally as a means of improving the products and services as 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 being utilized as the organizing principal of the AASHTO Guide to Systems Operations and Management under development. The CMM has already been used by several 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 them (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, most practical to achieve in urban areas;
- The cost of each travel option is known; and
- The traveler is responsible for the cost associated with whatever option is ultimately chosen, including externalities.

There is a broad spectrum regarding the willingness 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 concepts of operations is to provide readers, including decision makers, an opportunity to think about what type of transportation system it is 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 non-recurring 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 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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Evaluating Alternative Operations Strategies to Improve Travel Time Reliability

APPENDICES

Prepared for
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of
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LIST OF APPENDICES

APPENDIX A– **Reliability Performance Measures Available to Agencies**

Agency Measures

This section presents measures from some of the Departments of Transportation and Metropolitan Planning Organizations, which demonstrate management and reporting of reliability and travel-time information. The following table summarizes some of the best practices:

Agency	Performance Reporting Method	Performance Data
WSDOT: Washington State DOT	The Gray Notebook	Average Clearance time (in minutes) for major (90+ minute) incidents on key Puget Sound corridors
		Annual weekday hours of delay statewide on highways compared to maximum throughput (51 MPH) in thousand hours.
GRTA: Georgia Regional Transportation Authority	The Transportation Metropolitan Atlanta Performance (MAP) Report	Freeway Travel Time Index (TTI): the ratio of the average travel time over the free-flow travel time obtained for a certain portion or segment of the freeway system.
		Freeway Planning Time Index: the planning time index (PTI) and the buffer time index (BTI).
		- PTI is the ratio of the 95th percentile travel time - or planning time - over the free-flow travel time obtained for a certain portion or segment of the freeway system.
		- BTI is defined as the difference between the 95th percentile travel and the average travel time.
		Daily Vehicle Miles Traveled per Licensed Driver/Person
		Roadway Clearance Time: 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.”
FDOT: Florida Department of Transportation	The 2020 Florida Transportation Plan - Florida’s Mobility Performance Measures	Person miles traveled
		Truck miles traveled
		Vehicle miles traveled
		Person trips
		Average speed
		Delay
		Average travel time
		Average trip time
		Reliability
		Maneuverability
		% system heavily congested
		% travel heavily congested
		Vehicles per lane mile
		Duration of congestion
San Antonio-Bexar City MPO	The 2030 Metropolitan Transportation Plan - the Texas Congestion Index (TCI)	Texas Congestion Index (TCI), 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 (America’s Best Plan)	HOV lanes, ITS, and reliability of transit service
Metropolitan Transportation Commission - San Francisco Bay Region	Transportation 2030 Plan - Reliability is listed as one of the six goals	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	The Final 2008 Regional Transportation Plan	The statistical concept of standard deviation. The indicator is computed by dividing the standard deviation of travel time for a given trip by the average travel time of that trip, measured over many days and weeks.

Source: State DOT websites

The following information was obtained in an effort to summarize the current activities by public agency programs and private entity sources regarding travel time reliability:

Washington State DOT (WSDOT)

The *Gray Notebook* is WSDOT's main performance assessment, reporting, and communication tool. The Gray Notebook (http://www.wsdot.wa.gov/accountability/default.htm) provides quarterly, in-depth reports on agency and transportation system performance. The purpose of the Gray Notebook is to keep WSDOT 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/performance measures are included in the Performance Dashboard: safety, preservation, mobility/ congestion relief, environment, and stewardship. The only measures related to travel time reliability are included under the mobility/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 (GRTA)

The Georgia Regional Transportation Authority (GRTA) produces an annual report, titled the *Transportation Metropolitan Atlanta Performance (MAP) Report*, which reports on 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 (TTI) 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 using GDOTs NaviGator video detection cameras.
- **Freeway Planning Time Index** - Two travel time reliability measures are reported: the planning time index (PTI) and the buffer time index (BTI). Measurements for the planning time index were created using GDOTs NaviGator video detection cameras, similar to the freeway travel time index.
    - 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 it is going to take to make a trip under congested conditions compared to free-flow conditions - so that the traveler arrives on-time 95 percent of the time.
    - BTI is defined as the difference between the 95th percentile travel and the average travel time. BTI is the size of the buffer time expressed as a percentage of the average travel time and 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 percent 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.

The following **safety** measure is also reported. This measure indirectly impacts travel-time reliability:

- **Roadway Clearance Time** – This 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 Department of Transportation (FDOT)

Florida's mobility performance measures (http://www.dot.state.fl.us/planning/statistics/mobilitymeasures/) 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. The following table depicts 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[1]
Quantity of Travel	Person miles traveled	☐	☐	☐	☐	AADT * length * vehicle occupancy
	Truck miles traveled	☐	☐	☐	☐	AADT * length * % trucks
	Vehicle miles traveled	☐	☐	☐	☐	AADT * length
	Person trips				☐	Total person trips
Quality of Travel	Average speed	☐	☐	☐		Average speed[2] weighted by PMT
	Delay	☐	☐	☐	☐	Vehicle hours of delay
	Average travel time			☐		Distance / speed[2]
	Average trip time				☐	Door to door trip travel time
	Reliability			☐	☐	% of travel times that are acceptable
	Maneuverability			☐		Vehicles per hour per lane
Utilization	% system heavily congested	☐	☐	☐	☐	% miles at LOS E or F
	% travel heavily congested	☐	☐	☐	☐	% daily VMT at LOS E or F
	Vehicles per lane mile	☐	☐	☐	☐	AADT * length / lane miles
	Duration of congestion	☐	☐	☐	☐	Lane-mile-hours at LOS E or F

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

[2] Speed based on models using HCM procedures.

AADT - annual average daily traffic
PMT - person miles traveled
VMT - vehicle miles traveled
LOS - level of service
HCM - Highway Capacity Manual

As shown in the table above, three related dimensions of mobility are measured by the FDOT:

- 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; and

- 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:

- Real-Time Traffic Information: www.traffic.com;
- Noblis: www.noblis.org; and
- ITS deployment site: http://www.itsdeployment.its.dot.gov/

Traffic.com

Traffic.com (www.traffic.com) is an independent provider of traffic information serving 51 cities across the U.S. 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 via the Internet. The Traffic.com site and the companion site 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 US.

Traffic.com obtains information from three types of sources: digital traffic sensors, commercial and government partners, and traffic operations center staff members. Their own network of sensors is already deployed in many major metropolitan areas, and is rapidly expanding to additional cities. Where local or state government agencies have available data from their sensors or systems, Traffic.com integrates as much of that data as possible. Finally, they maintain 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 (www.noblis.com) is a nonprofit science, technology and strategy organization that helps clients solve complex systems, processes and infrastructure problems. Over the past two decades, Noblis have 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:

- Pioneering new technologies to protect travelers from bad weather and road hazards;
- Data mining vast amounts of system usage data for major cities in order to understand traffic trends and support informed strategic decisions;
- Partnering with government agencies and auto makers to develop an integrated telecommunications infrastructure that will connect vehicles and the transportation infrastructure;
- Designing more efficient mass transit systems to ease congestion; and
- Analyzing the lessons learned, costs, and benefits across a wide variety of Intelligent Transportation System applications.

The following is a summary of experience and work activities by Noblis relevant to the SHRP2 L11 research project:

QuickZone Traffic Delay Estimation Tool (2001-ongoing)
The purpose of QuickZone is to develop estimates of work zone traffic delays. It also allows the 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. QuickZone also supports construction cost and delay cost trade-off analyses.

511/Travel Information Services Assessment (2003-ongoing)
This 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 Utah DOT to enhance Salt Lake City's 511 from an advisory to a travel-time based service. Similar work has been initiated with the MTC in San Francisco.

Urban Congestion Reporting (2002-ongoing)
The purpose of the Urban Congestion Reporting is to monitor and report monthly congestion in 20+ cities across the nation and characterize trends as well as contributing factors (weather, accidents, special events, etc.). Measures were developed that describe the intensity, duration and day-to-day variation in congestion, as well as a series of graphical one-page summaries for traffic managers and decision makers.

ITS Deployment Site

The ITS Deployment Statistics Web Site (http://www.itsdeployment.its.dot.gov) is administered by the Research and Innovative Technology Administration (RITA) who coordinates the U.S. Department of Transportation's (DOT) 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 DOT in:

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

As part of the ITS Deployment site, RITA provides access to data that were gathered by the United States Department of Transportation (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) 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 the 50 states. It generally includes survey data from 2004 through 2007 on various topics such as the following:

- Arterial Management
  - Characteristics of Signalized Intersections
  - Roadside Technologies to distribute en-route traveler information
  - Information Dissemination to the Public
- Freeway Management
  - Freeway Surveillance

  - Ramp Control
  - Lane Management

- Transit Management
- Public Safety (Law Enforcement)
- Public Safety (Fire Rescue)
- Electronic Toll Collection
- Metropolitan Planning Organization
- Crash Prevention
- Operations & Maintenance
- Surface Transportation Weather
- Traffic Management
- Traveler Information

APPENDIX B – **Determining the Economic Benefits of Improving Travel-Time Reliability**

Determining the Economic Benefits of Improving Travel-Time Reliability

The purpose of this appendix is to present an approach for determining the economic benefits of improving travel-time reliability under recurring-event scenarios. In the approach, uncertainty arising from recurring events 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 us to express the value of reliability 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. Based on the likelihood of 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. Mr. A has foregone the chance at $100, but has also avoided the equal possibility of receiving no payment. Thus, a variable that can be characterized by its probability distribution can be converted to a certainty-equivalent measure.

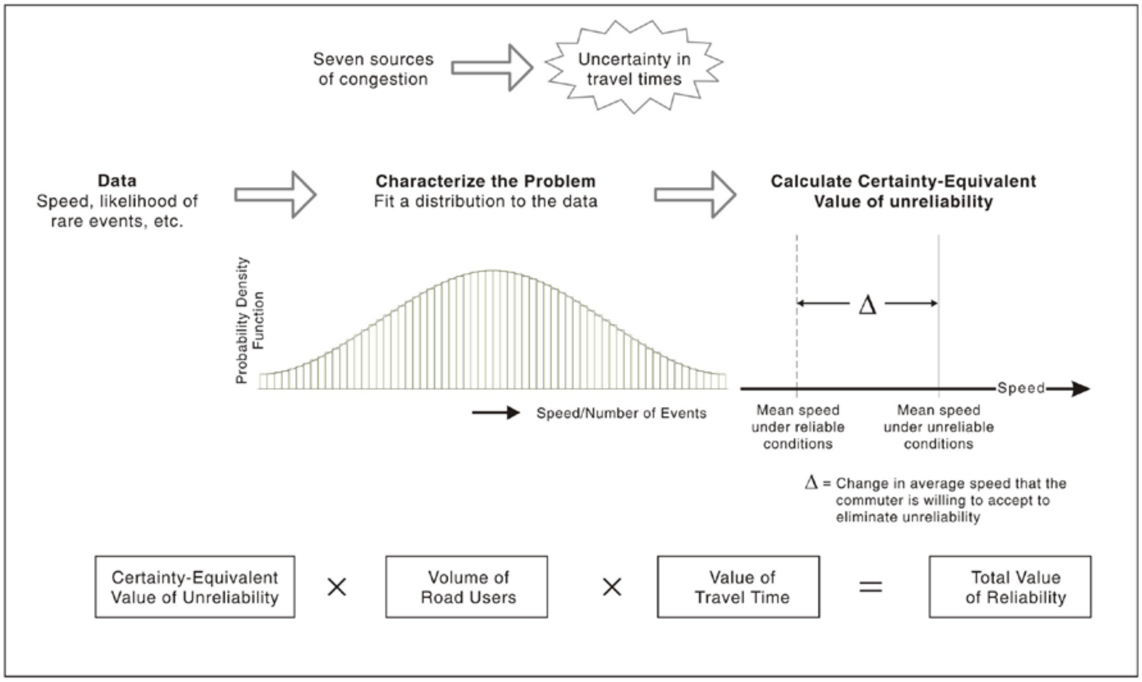
The approach presented for determining the value of reliability associated with recurring is extended to rare events in Appendix C. Recurring and rare events (and the unreliability produced by them) differ in the probability distributions that characterize them. Unreliability produced by recurring events is assumed to display statistical behavior that is best represented by normal distributions (often, a log-normal 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 due to recurring congestion. Imagine 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 percent of the wage rate for average trips, and a much higher rate (around 85 percent of the wage rate) for commuting and intercity trips. The value of time for freight movement depends on the size of truck and value of the commodity hauled, typically with a value ranging between $30 and $60 per hour.

Using the above mentioned certainty-equivalent value of 1 minute per mile and assuming that the average value of time of users of the roadway is $20 per hour (33.3 cents per minute), the roadway segment is 10 miles long, and it is used by 6000 users per hour during the time of day when unreliability in travel times is experienced, the cost of unreliability to users on the facility over a one-hour period is approximately $20,000 (1 minute/mile X 33.33 cents/minute X 10 miles X 6000 = 2,000,000 cents or $20,000). This concept for calculating the value of travel-time reliability is illustrated in Figure B.1.

Figure B.1 – Concept for Valuing Travel-Time Reliability



The concepts for determining the economic benefits for improving travel-time reliability are presented in detail in the following sections of this appendix:

- Measuring the Value of Reliability
- Valuing Reliability for Recurring Events
- Measuring Network-wide Impacts
- Quantifying the Value of Time
- Applying the Methodology
- Conclusions for the Options Theoretic Approach
- 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 using the value of time measures described above. This methodology is adaptable to both recurring reliability issues and the degradation of network performance due to 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 for 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 our 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:

- Options Theory
- A Real Option for Travel Time
- Measuring the Economic Cost of Unreliability
- Evaluating Reliability Management Policies
- 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, pre-arranged 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, we might ask how large an insurance premium I should 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 anytime 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/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, since 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. Formulae 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 insures 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 the term 'real option.' Usually, the term refers to real assets in the capital budget context. Since we know of no one else who has studied travel time reliability using the options approach, it is not clear what the exact proper terminology is to use. However, Professor Lenos Trigeorgis, a well-known expert in the field of real options, has applied the real options terms in an analogous setting: 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 our options theoretic approach for the valuation of travel time reliability since our certainty-equivalent measure is easily converted to minutes (time).

Application of Black-Scholes type options formulae to non-financial 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 Black-Scholes type option pricing models 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 (p. 84) point out:

> *We believe that a categorical denial of the validity of the models to real option problem 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, development of real options and proper adjustment make development of a real option possible, despite the fact that the commodity is not traded in a market where the arbitrage condition is necessarily assured.

Damordaran (2005), *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 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 us to the conclusion that the travel time has an average value, but 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, our observations reveal that, over the period of our observation, the travel times experienced are distributed log-normally.

We are interested in 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. Since 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 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. 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.

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 us to answer 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 roads' unreliability.

Specifically, let us assume that the option value of the travel-time unreliability is one minute per 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 were 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 twenty dollars per hour, then the value of time is 33.3 cents per minute, per mile, per user. If the certainty-equivalent value of delay is one minute per mile, the road segment displaying this unreliability is 10 miles long and there are 6000 users per hour at the time of day that this unreliability is displayed, the cost of unreliability is approximately $20,000 per hour or $7 million per year for each hour of the day that this level of unreliability occurs.

Using 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 one minute per mile. Using 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.

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

Road User Group	Share of Volume	Volume	Value of Time per hour	Dollar Value of Reliability per Hour
Single Occupancy Vehicle	70%	4,200	$26	$18,200
High Occupancy Vehicle, 2	15%	900	$30	$4,500
High Occupancy Vehicle, 3+	8%	480	$38	$3,040
Vanpool	2%	120	$102	$2,040
Heavy Trucks	5%	300	$50	$2,500
Total		6,000		$30,280

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 (VoT per hour/60 minutes) x facility length (10 miles).

Evaluating Reliability Management Policies

Having established the cost of unreliability, 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 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 per mile on the roadway segment described above. There is now a savings of approximately $3.5 million per year for each hour of the day that is affected by the treatment.

Thus, a treatment that costs less than $3.5 million per year would be worthwhile (cost-effective) to implement due to 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 are 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

Travel-time reliability options formulations 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 than the uncertainty that characterizes recurring events. Whereas recurring events (like crashes, weather-related events, and other common sources of travel-time variation) can generally be characterized using a log-normal distribution, 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 (GEV) distribution has been adopted and is presented in Appendix C.

Since both recurring and rare events cause unreliability, 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, log-normal 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 numbers of bridge failures may 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 log-normal frequency distribution. This is achieved by recasting the question of reliability in terms of a speed insurance problem, which, in turn, can be addressed using 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 we are interested in knowing 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 log-normality, it is better to compute the real option in terms of speed.

Equation 1 - Speed Guarantee for Recurring Events

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

where

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

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

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 log-normally

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 1 illustrates how the travel-time reliability option can be formulated following standard insurance options formulations, i.e., 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 (and, hence, 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 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 fix 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 its different speed distribution is involved. In this sense, it is akin to what is called a "capped" option, and 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.

Equation 1 - Speed Guarantee for Recurring Events

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

where

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

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

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

$\approx$ a random variable, distributed log-normally

$I =$ the guaranteed speed, in mph

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

$\sigma =$ 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

To implement the option, we need to provide the inputs listed in Equation 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 five-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 log-normal distribution of speed for a five-minute interval in the a.m. peak period using data from the Puget Sound Region for a one-year period.

Figure B.2 - Illustration of a Log-Normal Distribution of Speed

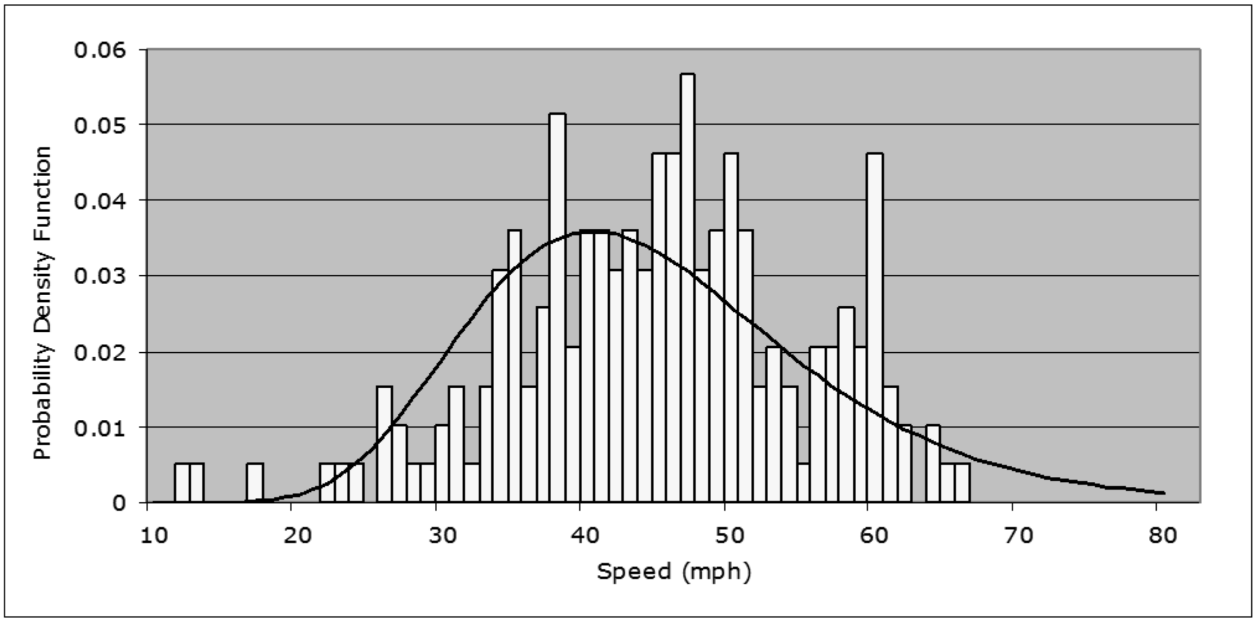


Table B.2 illustrates the value of the implied put option at various average annual speeds and log-variability. This exhibit displays the certainty-equivalent value both in miles per hour and in minutes of delay.

The data suggest that speed variability imposes a burden on highway users. A rational and risk-neutral user would be willing to sacrifice speed in order 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.

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

Time of Day	Average Annual Speed (mph)	Log Average Annual Speed	Std Dev Log Speed	Option Value (mph)	Option Value (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, South Bound, 2007. The calculations apply a guarantee equal to the average speed for each time of day.

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 the other inputs to the options formulation previously described using Equation 1.

Using Equation 1, 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 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.

Figure B.3 - Illustrative Option Values (in MPH) vs. Average Speed

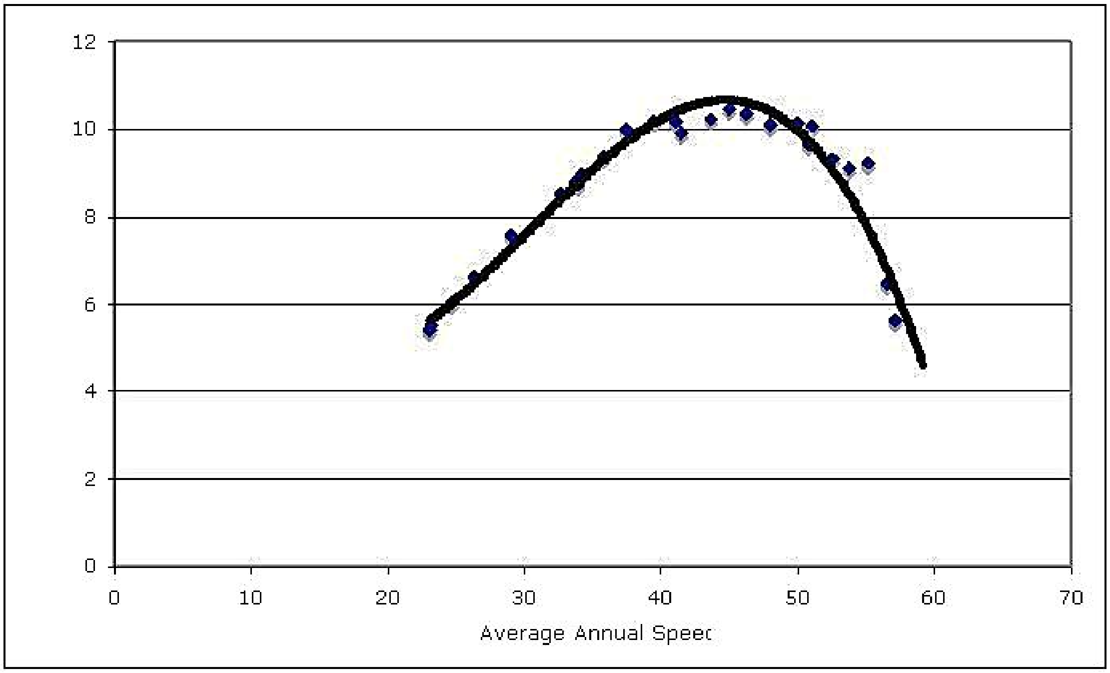
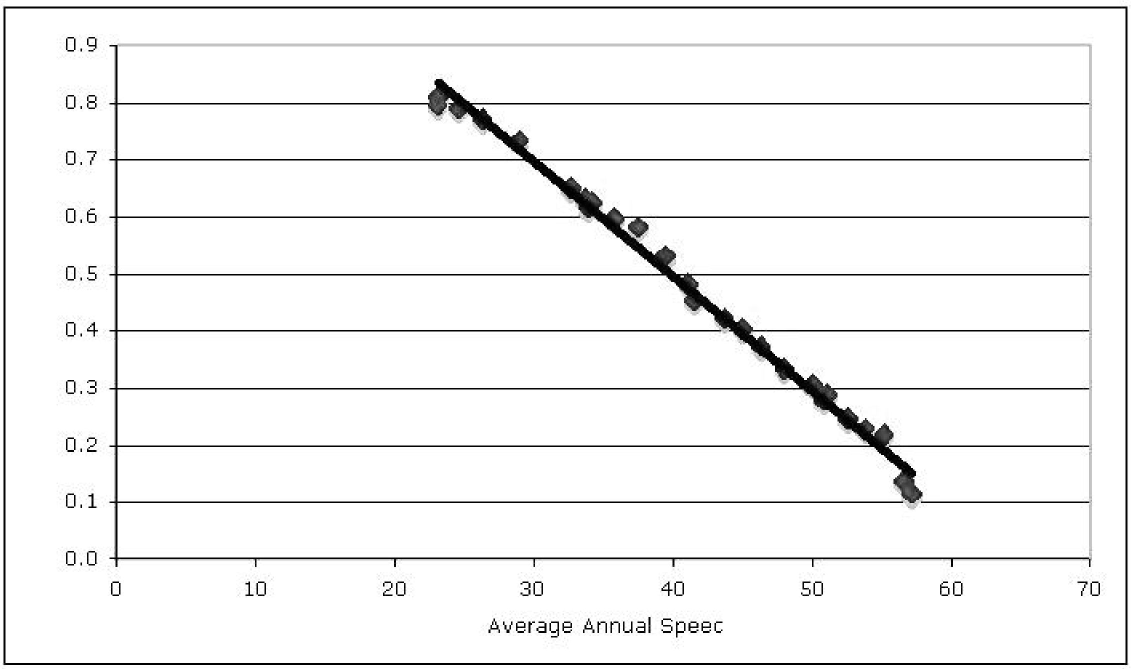


Figure B.4 - Illustrative Option Values (in Minutes) vs. Average Speed



Using 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 miles per hour is approximately 0.8 minutes per mile, whereas the value of unreliability at a speed of 60 miles per hour is only about 0.1 minutes per 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 2, which has been adapted from McDonald (2002).The option in Equation 2 can be valued in a case where the log-normal 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*.

Equation 1 - Valuing a Perpetual American Put Option

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

where

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

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 speed variability of the morning commuting period over a long period of time. The parameters of the log-normal speed distribution must then be estimated in a manner that is 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 log-normally. The same method can be applied to circumstances other than the volatility of speed measured in five-minute intervals.

The parameters of the options formulation should be measured so that they are 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, etc. 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 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 one 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 based on the speeds and travel times experienced on the facility. This approach does not necessarily rely on specific information about the source of the unreliability, so long as the source and the speeds are log-normally distributed. Thus, system performance data determine the underlying stochastic nature of unreliability on a facility. Table B.3 summarizes the disruption data identified in the SHRP2 L03 project for use by agencies in reporting reliability performance measures.

Reliance on the normal or log-normal distribution is standard in options theory, and a requirement for the use of the Black-Scholes formulation. The Black-Scholes model is based on the normal (or log-normal) distribution of the underlying asset. In the real option for travel time reliability, the assumed asset is speed, and so the assumption of the log-normality of speed (e.g., to compute the certainty-equivalent measure in minutes of travel time) is an assumption for the options theoretic approach.

The log-normal 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 log-normal distribution for travel time and speed. The lower bound of zero and longer right tail of the distribution make the log-normal particularly appropriate for the typically skewed speed data. SHRP2 L03 cites Rhaka et al (2006), which confirms the use of the log-normal 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).

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 the nature (size, severity, duration) of the accident; Disruption of roadway operations (the number of lanes closed); Response after accident; and 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 (NCDC) of the National Oceanic and Atmospheric Administration (NOAA)	Area-wide
Work Zones/ Construction	Planned Construction activity (number of lanes closed, period of time)	DOTs State Database	Urban/Rural
Fluctuations in Demand/Special Events	For a Large Event: Time & Date, Nature of the 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/In adequate Base Capacity	Change in geometry (lane drops)	All Roadway Agencies	Good data
	Traffic patterns (weave/merge sections)		
	Visual Disruptions (Sightseeing, Rubbernecking)		No record
	Minor changes in functional capacity		Potentially

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

Monetizing the Certainty-Equivalent Values

Since 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 that is 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 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 characterize the stochastic nature of future system performance.

Valuing Reliability for Rare Events

While a sufficiently long time series of high-resolution traffic performance data (e.g., highway speeds) tends to display log-normal distribution, one can imagine many situations where 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/rare flooding. Examples would 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, including Long-Term Capital, and elements of the financial crisis that precipitated. One of the reasons that we distinguish between recurring and rare events in our 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 using new options formulations aimed at addressing rare events, specifically events that follow extreme value distributions (EV). Research on options theory using EV distributions is relatively new, and has not been applied, to our knowledge, to settings other than an example application for research and development (R&D) in the pharmaceutical industry. Therefore, we present the rare event methodology in a separate appendix and recommend future research aimed at addressing uncertainty arising from rare events in investment decision-making.

Measuring Network-Wide 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 so long as the appropriate data exist to provide the necessary parameters. At times, the analysts may be asked to extrapolate the effects of unreliability on 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 alternate approaches to addressing the aggregation of reliability considerations on the network level. Each of them 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 this can be accomplished, then 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 VMT and 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 using 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 using conventional benefit-cost techniques, so long as the strategy or policy can be characterized by a change in the reliability performance measures.

Measurement using 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 using 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 that occur 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 (using 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 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

MPOs and other agencies to evaluate network improvements because they are pure mathematical constructs rather than simulation models, per se. They 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 offer a way to evaluate generic policies in abstract network representations. Examples of these models include 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 network wide.

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 groups, 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. The literature that concerns 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/shipper surveys or from studies of traveler behavior on facilities such as high-occupancy toll (HOT) lanes.

Though 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 the 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, where 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 data has been difficult to obtain, the alternative for researchers has been to conduct stated-preference surveys. Stated preference 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 revealed preference data and stated preference surveys for HOT-lane facilities in Southern California, Brownstone and Small (2005) observed that the stated preference surveys tend to yield much lower results than the revealed preference data.

Revealed preference data from HOT-lane facilities have also been used to improve stated-preference survey instruments, and vice versa. This has allowed researchers to create scenarios reflecting realistic trip alternatives, thereby reducing measurement errors from respondent perceptions, as these scenarios are more familiar to the respondents.

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 a well-established relationship. 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 percent of the wage rate for commuting trips and a much higher percentage (around 85 percent 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 percent of the wage rate to more than 200 percent of the wage rate. Consistent with the findings published by Waters, Small (1992) also observed that the value of time with respect to user income varied from 20 to 100 percent of the wage rate across different 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 drivers’ value of time is 60 percent of the wage rate and the passengers’ value of time is 40 percent 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. Based on this finding, Miller suggested that the driver value of time in congested conditions is approximately 90 percent of the wage rate and that the passenger value of time in congested conditions is 60 percent of the wage rate.

While 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 and/or on the schedule delay associated with departing at a less-congested time. 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.

Observing travelers on the New Jersey Turnpike, Ozbay *et al.* (2008) found that the value of time is higher during the peak period than the pre-peak and post-peak 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 the pre-peak and post-peak periods for both commuting trips and leisure trips, with the exception of pre-peak 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—$22.00 per hour (75 percent 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 AM, built throughout the morning, and dropped sharply by 9:30 AM.

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

Table B.4 - Passenger Value of Time from Stated Preference and Revealed Preference Studies

Travel Type/Model Type	Value of Time per hour (or % wage rate)	Data or Study Year	Study Type	Reference
Pre-Peak Commute	$16.72	2005	RP, NJTPK	Ozbay *et al.* (2008)
Peak Commute	$19.72	2005	RP, NJTPK	Ozbay *et al.* (2008)
Post-Peak Commute	$17.35	2005	RP, NJTPK	Ozbay *et al.* (2008)
Pre-Peak Leisure	$17.03	2005	RP, NJTPK	Ozbay *et al.* (2008)
Peak Leisure	$17.16	2005	RP, NJTPK	Ozbay *et al.* (2008)
Post-Peak Leisure	$15.33	2005	RP, NJTPK	Ozbay *et al.* (2008)
MnPass subscribers that were early or on-time PM Peak	$10.62	2007	SP, I-394 MNPass	Tilahun & Levinson (2007)
MnPass subscribers that were late	$25.42	2007	SP, I-394 MNPass	Tilahun & Levinson (2007)
Non-subscribers that were early or on-time	$13.63	2007	SP, I-394 MNPass	Tilahun & Levinson (2007)
Non-subscribers that were late AM peak	$10.10	2007	SP, I-394 MNPass	Tilahun & Levinson (2007)
Median VoT per hour	$21.46 (93%)	2000	RP, SR-91 & I-15	Small, Winston, & Yan (2005)
Median VoT per hour	$11.92 (52%)	2000	SP, SR-91 & I-15	Small, Winston, & Yan (2005)
Route choice model	$19.22	1998	RP & SP, SR-91	Lam & Small (2001)
Route and time of day choice model	$4.74	1998	RP & SP, SR-91	Lam & Small (2001)
Route and mode choice model	$24.52	1998	RP & SP, SR-91	Lam & Small (2001)
Transponder and route choice model	$18.40	1998	RP & SP, SR-91	Lam & Small (2001)
Transponder, mode, and route choice model	$22.87 (72%)	1998	RP & SP, SR-91	Lam & Small (2001)
Passenger travel-$125,000 to $175,000 annual income	$7.11	1998	SP	Calfee & Winston (1998)
Passenger travel-$7,500-$12,500 annual income	$3.06	1998	SP	Calfee & Winston (1998)
Major U.S Metro Areas, Median	$3.88 (19%)	1998	SP	Calfee & Winston (1998)
A.M. peak period	$30	1998	RP, I-15	Brownstone *et al.* (2003
Passenger vehicles	$8-$16	1999-2000	RP, SR-91	Sullivan (2000)
Peak period commuters	$13-$16	1999-2000	RP, SR-91	Small & Sullivan (2000)
A.M. peak period	$22 (75%)	1998	RP, I-15	Ghosh (2001)
Median	$15 (52%)	1998	RP, I-15	Ghosh (2001)
Afternoon commute	$9 to $22 (30% to 75%)	1998	RP, I-15	Ghosh (2001)

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 percent of the wage rate.

Freight Mover Value of Time

There are few studies 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), which 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 comprising 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 one hour of travel-time savings. The third method is the stated-preference survey, using 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, 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 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. Though 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 using the revenue approach. Hanning and McFarland 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 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."

Using data collected from a stated preference 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 carriers who have fixed-salary drivers. In addition, for-hire carriers have a higher value of time than private operators.

Smalkoski and Levinson (2003) implemented an adaptive stated-preference survey for carriers and shippers in Minnesota, analyzing 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 other groups.

Table B.5 - Truck Value of Time by Truck Operator Type: Findings from a Stated Preference Survey

Truck Operator Type	Value of Time
Truck-All	$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) converted to 2008 dollars.

FHWA Freight Management and Operations publications have reported the value of time for freight as a range between $25 and $200 per hour (FHWA 2008). The high end of the FHWA range is based on the Small *et al*. (1999) truck value of time estimated range of $144-$192 per hour. Given the likely idiosyncrasy of the estimates from the stated preference data collected by Small *et al*. (1999), the upper end on the range for freight mover value of time may likely 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 per 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, working with the freight working group at the Washington State DOT, adopted truck value-of-time estimates of $40 for light trucks, $45 per hour for medium trucks, and $50 per hour for heavy trucks (Outwater and Kitchen, 2008).

Value-of-time estimates derived using a cost-based approach have consistently placed the value of time for freight at around $25 to $30 per 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. Department of Transportation Departmental Guidance on the Valuation of Travel Time in Economic Analysis. The U.S. DOT Guidance is the basis for the FHWAs Highway Economic Requirements System value-of-time estimates. This guidance is also used in the FHWA Freight Logistics Reorganization Benefits Estimates Tool.

The empirical basis for the U.S. DOT Guidance on the Valuation of Travel Time in Economic Analysis (2003) is the clustering of estimates for passenger travelers at around 50 percent of the hourly wage rate. The U.S. DOT Guidance provides the recommended values for the value of time as a percent of the hourly wage, differentiating values for local passenger personal travel, local passenger business travel, intercity passenger personal travel, intercity passenger business travel, 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 analysis. The U.S. DOT recommended values of travel time are shown in Table B.6. The value of travel time as a percentage of the wage rate is converted to a dollar value using wage data from the Bureau of Labor Statistics for business travel and truck-driver wage rates. The median household income from the U.S. Census Bureau is used for personal travel. The U.S. DOT Guidance for truck travel time is similar to the cost-approach-based method, with one-hundred percent of the full driver compensation recommended for the truck-driver value of time.

Table B.6 - U.S. Department of Transportation Recommended Values of Time (2008 dollars)

User Group	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

The Highway Economic Requirements System (HERS) uses the value of time for seven different vehicle classes: two passenger vehicle classes and five truck configurations. The value of time is computed using the USDOT 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.7 - Value of Time from the FHWA Highway Economic Requirements System (2008 dollars)

User Group	Small Auto	Medium Auto	4-Tire Truck	6-Tire Truck	Truck 3-4 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				
Percent 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: Highway Economic Requirements System, HERS-ST v2 Technical Report, 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 4- and 5-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 4-axle combination truck would be lower than the payload for a 5-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 (3-4 axle and 6-tire trucks) are assumed to be negligible and personal vehicles are assumed not to transport goods. The HERS inventory costs do not include spoilage costs, damage, or inventory depreciation—only the cost of holding the inventory during transport (HERS 2002, p. 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 FHWAs 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 4-axle and 5+axle combination trucks is based on a study of team drivers. The six-tire truck and 3-4 axle truck AVOs are assumed values.

While 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 that are shown in Table B.8 are based on the strongest relationships empirically demonstrated in the literature. They 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.

Table B.8 - Passenger Traveler Value of Time as a Percentage of Average Wage Rate

Trip Purpose/ Time of Day	Value of Time (as a percentage of wage rate)	Range of Values for Sensitivity Analysis
Personal Travel		
A.M. Peak Period (Morning Commute)	75%	50%-90%
P.M. Peak Period	60%	40%-70%
Leisure/Other Trip Purpose	50%	30%-60%
Intercity Travel	70%	60%-90%
Business Travel	100%	80%-120%

Using 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 value per vehicle by using average vehicle occupancy assumptions to scale the dollar value per person-hour.

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
Personal Travel		
A.M. Peak Period (Morning Commute)	$18.80	$12.60 - $22.60
P.M. Peak Period	$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 based on wage and compensation, other trip purposes based on National Median Household Income following U.S. DOT Guidance.

The freight mover value of time, shown in Table B.10, should be based on one-hundred percent 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.

Table B.10 - Freight Mover Value of Time

Freight Mover Group	Value of Time (Dollars per hour)	Range of Values for Sensitivity Analysis
Freight Movers		
Light Truck (Single Unit or 6-Tire Truck)	$30	$30 - $55
Medium Trucks (3-4 Axle Truck)	$50	$40 - $75
Heavy Trucks (4-Axle and 5+Axle Combination)	$60	$40 - $80

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 user 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 (HPMS) data for sample segments.

The 2003 U.S. DOT Guidance suggests creating a weighted average for automobile travel by assuming that 94.4 percent of vehicle-miles are personal trips and 5.6 percent of vehicle-miles are business related. Household travel surveys conducted by state DOTs or regional metropolitan planning organizations or the 2008 National Household Travel Survey are other sources for determining the volume by user group or by trip purpose.

Applying the Methodology

Using 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 due to events that cause speeds to be distributed log-normally, 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 situation in which highway performance metrics are not collected comprehensively over a long period of time, but in which there is data available on the events that cause unreliable travel conditions. Formal statistical tests for the goodness of fit, like 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, then a perpetual options formulation may be more appropriate. Thus, one might evaluate recurring congestion phenomena 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. This data should identify the necessary probability distributions.

In summary, the options formulation will be determined based on 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 formulae 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-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. They should also use similar time frames.

Comparison of Methodologies for the Valuation of Travel Time Reliability

The options theoretic approach for the valuation of travel time reliability 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, using stated preference (SP) or revealed preference (RP) data. Given the limited number of natural experiments that allow for the collection of revealed preference data, the majority of this work has tended to focus on stated preference 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 the SP/RP approach. Some of these considerations call into question the practical utility of the SP/RP approach.
- A numerical comparison of the value of reliability of the options approach and that estimated by the RP/SP approach. For the latter, we use the estimates produced by Small, Winston and Yan (2005). Using their data, we compute the necessary parameters to implement the options theoretic approach using the same speed distribution and values of time in their paper.

Conceptual Considerations in Relying on Revealed or Stated Preference Methods

There are numerous aspects of the RP/SP approach that make reliance on this method problematic in practice. Some of the contrasts between the options and RP/SP approaches are the following:

1. The RP or SP approaches are not economical to apply, requiring costly studies for its application. Putting aside any general skepticism about the reliability of SP procedures in particular, even this method is a 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 are not agnostic procedures free of functional form assumptions akin to those of the options approach. In particular, they implicitly adopt utility function specifications that are usually asserted, rather than demonstrated. The function form is usually linear in its arguments (or some non-linear specification to introduce risk-aversion). This is analogous, in a mathematical sense, to the fact that the Black-Scholes approach 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.
3. The RP and SP analyses usually also postulate a fairly specific characterization of the context of unreliability–e.g., 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, drawn from a log-normally distributed delay process.
4. A major difference is that the options theoretic approach 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 (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. 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 microsimulation model settings.

Numerical Comparison

A numerical comparison demonstrates that the options theoretic approach yields values of unreliability similar to RP-derived estimates of Small, Winston and Yan (2005).

The additional complexity and cost of measuring and implementing RP/SP-derived measures 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, Winston and Yan (2005) ("SWY"). This work is a highly regarded implementation of the RP/SP approach.

SWY (2005) use 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 allows SWY to estimate both the value of travel time savings and the value of unreliability. Using the revealed preference data, SWY measure the value of travel time at $21.46/hour (93 percent of the average wage rate). The study was conducted under 4-hour AM peak conditions, which expose general-purpose lane users to considerable volatility in speeds and travel times. Under the conditions in place, their model yields a value of unreliability of $19.56 per hour. When applied to the 10-mile segment of SR-91, the value of unreliability is then measured to be $0.52 (for the 10-mile segment).

The SWY 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. This speed data, combined with the assumption of a log-normal distribution of speeds, yields a log-mean speed of 3.9703 and the log-standard deviation of speed of 0.1683. Using 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 our characterization of unreliability, the average speed experience of travelers, measured over time, is taken as the speed against which they measure unreliability and, thus, is the desired "guaranteed" speed. Unfortunately, SWY do not know the average speed experience at the various times their RP sample travels. All they know is the median speed over across the entire 4-hour AM peak (53 mph). However, we can test various speed guarantees in the options formula and see what speed guarantee corresponds to SWY's revealed $0.52 value of reliability over the 10-mile facility. That speed is 57 miles per hour.

Alternatively, 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 via 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, SWY also estimate a stated preference model, which ends up producing a value of reliability that is much smaller than the revealed preference-based estimate. 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. Whereas 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, providing 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 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 on Table B.11. Given the unfamiliarity with such methods and questioning of the approach due to 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, 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 stated-preference 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 log-normal 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.

TABLE B.11 –SUMMARY OF REVIEWER COMMENTS AND RESPONSES

Comment #1:
Although one can create many different classification schemes within the field of options and financial derivatives, in view of the need to impute dollar values to improvements in travel time reliability in Project L11, the literature suggests there are three relevant classes:

1. Financial options – these are concerned with valuing a financial asset given the underlying's price, the strike price, the time to expiration, the volatility (variability), and the risk free interest rate

2. Real Options – the valuation of one or more contingencies that unfold over time, such as a decision to proceed with Phase II of a project after making a positive feasibility determination under Phase I.

3. Valuing Insurance Contracts – 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. 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:
I have read and pondered your email of yesterday and the portion of the options theoretic that you included. 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/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 3-5% interest rate is commonly used when considering money because these are 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/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.

<u>Comment #5:</u>
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 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 have 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 we consulted does not think this approach is applicable to valuing travel time reliability:

<u>Response #5:</u>
The reviewer is correct that the common use of the term Real Options is in a capital budgeting context, and from the fact that this setting involves real (vs. 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. Since we know of no one else who has studied travel time reliability 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 analysis, applied the Real Options term in an analogous setting; i.e., a decision to increase flexibility of production processes as a defense against exchange rate variability. (In this case, value arose from increasing flexibility.)
file://localhost/<http/::sloanreview.mit.edu:executive-adviser:articles:2007:4:49410:stay-loose:>

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, it 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 his initial investment. These features are routinely valued 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 log-normality in the simpler (recurring events) setting. Although it is true that little formal testing of the log-normality of speed data goes on, it is a widely appreciated feature in practice. Vehicle counting systems PeMS, TRAK, and others are installed in thousands of locations on US highways. These systems produce large quantities of high-resolution traffic volume and speed data, and the log-normality 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, SHRP2 L03 cites the following paper, which confirms the use of lognormal distribution for speed in the context of travel time reliability.
Rakha, Hesham, El-Shawarby, Ihab, and Arafeh, Mazen, Trip Travel Time Reliability: Issues and Solutions, Intelligent Transportation Systems Conference, 2006. ITSC 2006. IEEE.

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 where the distributions should be joined; there is no discussion of this in the appendix. The justification for using mixtures is that while recurring events, where there is often ample data for analysis, might be well-characterized by a normal distribution, rare events tend to fall into an extreme tail which 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 addresses the question 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, UK, 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 obtains using the options theoretic approach. Comparing the approaches is a useful suggestion since 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 or 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 non-linear 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–e.g., 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 log-normally 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 S-P or R-P 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 S-P and R-P methods, as we detailed in Appendix B.

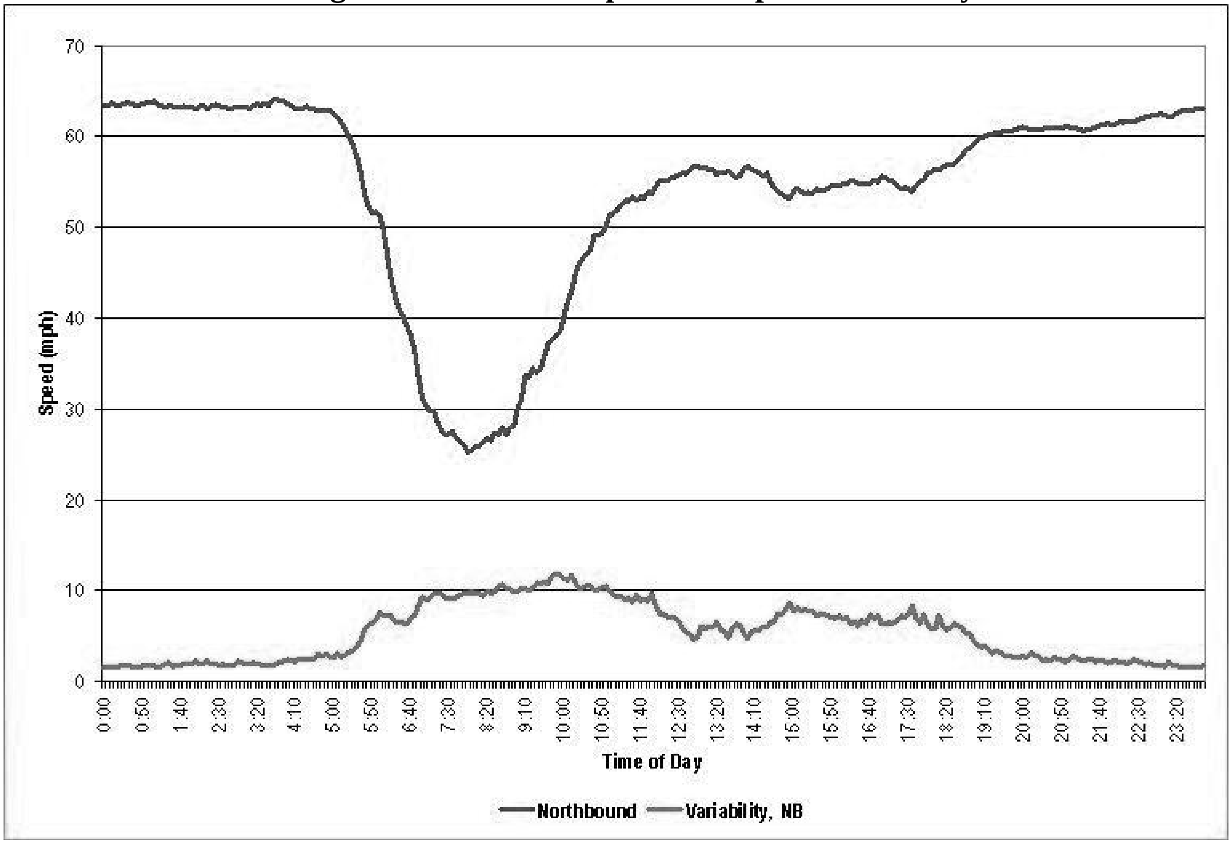
Recurring Event Reliability Valuation Example

The Issue

The transportation agency oversees a stretch of highway that experiences significant and variable congestion in the a.m. peak period (6:00 a.m.-10:00 a.m.). This facility is 10 miles long, running north/south, with the central business district (CBD) 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 am 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 due to travel-time variability. The agency is interested in knowing the value of the time that would be saved if a strategy that would improve travel-time reliability was implemented. This would help the agency to perform a Benefit-Cost Analysis (BCA) for the strategy and decide whether it is worth implementing.

Figure B.5 - Diurnal Speed and Speed Variability



The 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 tells us 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
- Volume data by vehicle type

Cautions

- Applicable to data for which travel-time variation can be suitably characterized by the log-normal distribution

Procedure

- 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).
B. Calculate the average speed and the standard deviation of the log of speed.
C. Construct log-normal distribution using the log mean and log standard deviation of the speed to confirm the speed data are log-normally distributed.

Step 1 – Characterize the Recurring Congestion Problem

A.

Table B.12 - Speed Data

Date	**Time**					
	6:00	6:05	6:10	……..	9:50	9:55
1/2/2007						
1/3/2007						
…..						
…..						
…..						

Step 2 – Calculate Certainty-Equivalent Value of Unreliability

A. Choose the appropriate option formulation (European Put option 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 using the options formula.
E. Convert the certainty-equivalent value from miles per hour to minutes per mile.

Step 2 – Calculate Certainty-Equivalent Value of Reliability

A. 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 tell us the commuter value of unreliability for a period of time, appropriate for the evaluation of a strategy.
   - The European Put option is based on values of variables that are distributed log-normally, as is the speed data on a facility leading to a fitting application.

B. A value of 5.00% risk-free interest rate is chosen.
   Thus, r = 0.05

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

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

D. The certainty-equivalent value of reliability, $P(V_T, t)$ is calculated by first calculating σ, d1 and d2. σ is calculated using the formula for volatility in finance, which is the standard deviation of the log speed divided by the square root of the contract length:

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

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

   $V_T =$ The desired speed = 32.67 mph

   $I =$ The guaranteed speed = $\bar{X}$ = 32.67 mph

Thus,

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

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

$$= 0.18176 - 39.12\sqrt{0.0000863} = -0.18173$$

Evaluate the standard normal distribution at d_1 and d_2.

$$N(d_1) = N(0.18175) = 0.4279$$

$$N(d_2) = N(-0.18174) = 0.57211$$

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

$$= 32.67e^{-0.05(0.0000086)}(0.57211) - 32.67(0.4279)$$

$$= 4.71 \text{ mph}$$

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

E. The new average speed at which the commuter is willing to travel if unreliability is eliminated = 32.67-4.71 = 27.96mph

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

$\therefore$ The certainty-equivalent time per mile that the user is willing to "pay" to eliminate unreliability is given by

$$P(V_T, t) = \left(\frac{1}{27.96} - \frac{1}{32.67}\right) \times 60 = 0.31 \text{ minutes per mile}$$

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 3 – Evaluate the Change that Affects Unreliability

A. "Smart" systems, including collision-warning systems and systems that automatically adjust cruise-control speed based on the relative distance of the car ahead, can reduce speed variability and travel-time unreliability as they are 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
- $\alpha = 0.5 \times 0.3635 = 0.1817$

B. 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 due to 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 using the formula for volatility in finance, which is the standard deviation of the log speed divided by the square root of the contract length:

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

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, new certainty-equivalent value in minutes per mile is

$P(V_T, t) = (\frac{1}{30.3} - \frac{1}{32.67}) \times 60 = 0.14$ 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 for the average a.m. peak hour only.

Step 4 – Calculate the Road User Value of Reliability Change

A. Value of time for different vehicle classes

Vehicle Class	Volume[1] (Avg AM (4 hours))	Value of Time ($/minute)
Single Occupancy	11,484	$ 0.30
High Occupancy	2,871	$ 0.60
Truck	1,595	$ 0.83

[1] Average a.m. hourly volume (over 4 hours for a 3 lane facility)

B. Value of Reliability Improvement for:
- Single occupancy vehicles = 11,484 X 0.30 X (0.31-0.14) = $585.68/mile
- High occupancy vehicles = 2,871 X 0.60 X (0.31-0.14) = $292.84/mile
- Trucks = 1,595 X 0.83 X (0.31-0.14) = $225.05/mile

C. 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) X 10 (miles) ≈ $11,036

D. Total Annual Value of Reliability Improvement = 252 Weekdays/Year
∴ Total Value of Reliability Improvement per Year (average a.m. peak hour)
= $11,036 X 252 days ≈ $2,781,000

It is important to note that these savings are for the average AM peak hour only and not for the entire day. This example could be repeated for other periods of the day where the speed and variability can be appropriately aggregated, as was done for the AM peak period in this example.

The annual value of reliability improvement could be compared to the annual costs of the strategy or improvement in a Benefit-Cost Analysis.

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APPENDIX C- **Valuation of Travel-Time Reliability for Rare Events**

Valuing Reliability for Rare Events

In this appendix, options theory from financial economics is once again applied to the problem of unreliability, this time in the context of rare events and the decision to invest given the probability of 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 due 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 mathematically complex, 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 during which the transportation agency may make plans for dealing with rare events is often much longer than the time horizon that the agency has to deal 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 better represent the incidence of rare events than normal distributions. Extreme value 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.

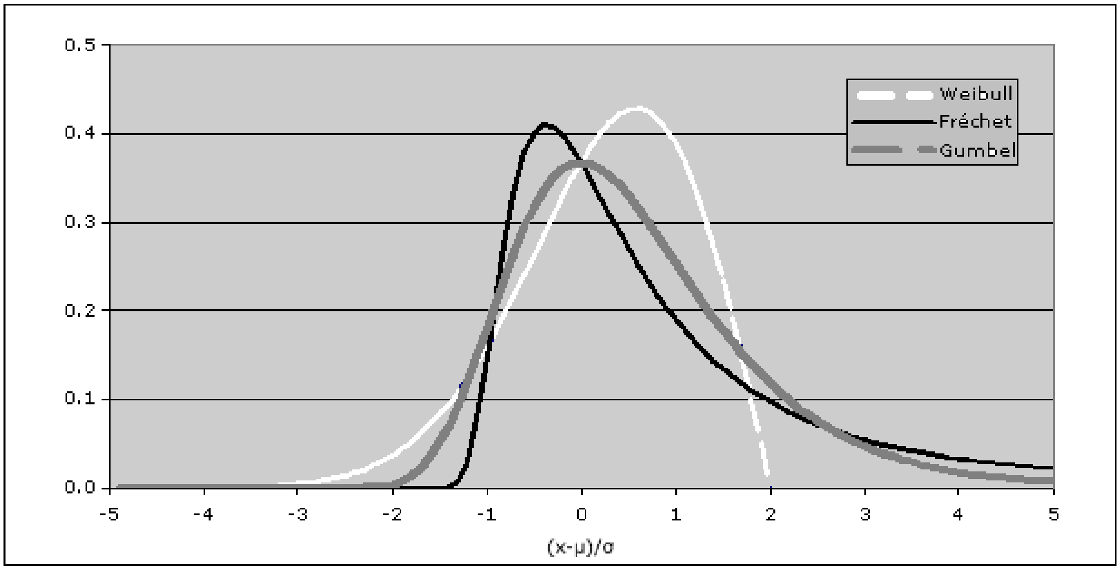
The extreme value distributions used to characterize rare events are referred to as Type I, II, and III distributions. They are also known as Gumbel, Fréchet, and Weibull distributions, respectively. Each of these distributions is a variation of the Generalized Extreme Value (GEV) distribution, differing 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 Generalized EV probability density function formulation is presented in Equation 1. It has three parameters: the location (μ), scale (σ) and shape (ξ) parameters. These parameters can be used to distinguish the three distribution types. Similar to the mean and standard deviation of a normal distribution, the location parameter μdetermines the "location" of the distribution, shifting the distribution to the right or left, without changing the shape of the distribution. The scale parameterσdetermines the spread of the distribution. The shape parameter ξ controls the shape of the distribution—in particular the tail behavior of the distribution.

The Figure C.1 below illustrates the standard shapes of the respective distributions for μ=0, σ=1 and ξ=-0.5 (Weibull), ξ= 0.5 (Fréchet) and $\xi \rightarrow 0$ (Gumbel). Since these are the standard distributions, the distributions are located over zero and have a standard scale parameter of one, 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 since 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 distribution that is most widely used to characterize rare events because it can be estimated using a two parameter specification (location and scale). The Gumbel probability density function is presented in Equation 2.

Figure C.1 - Typical Extreme Value Distributions



Equation 1 - Generalized EV Probability Density Function

$$f(x;\mu,\sigma,\xi)=\frac{1}{\sigma}\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{(-1/\xi)-1} e\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right]\right\}$$

where

$1+\xi(x-\mu)/\sigma>0$

$\mu=$ location parameter

$\sigma=$ scale parameter

$\xi=$ shape parameter

and where

x is a random variable, distributed GEV

Equation 2 - Gumbel Probability Density Function

$$P(I,t) = e^{-r(T-t)}\left\{ I\left(e^{-h^{-1/\xi}} - e^{-H^{-1/\xi}}\right) - V_0\left((1-\mu+\sigma/\xi)\left(e^{-H^{-1/\xi}} - e^{-h^{-1/\xi}}\right) - \frac{\sigma}{\xi}\Gamma\left(1-\xi, h^{-1/\xi}, H^{-1/\xi}\right)\right)\right\}$$

where

$$H = 1 + \frac{\xi}{\sigma}\left(1 - \frac{I}{V_0} - \mu\right)$$

$$h = 1 + \frac{\xi}{\sigma}(1-\mu)$$

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. This could include 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 using the Gumbel distribution fitting options from these statistical software packages or by using standalone software.

Valuing Unreliability for Processes Characterized by Extreme Value Distributions

Valuing options when the value of the process of interest follows an EV distribution is conceptually similar to the process described earlier for log-normally 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 log-normal 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* using Equation 3.

Equation 3: European Put Option with EV Variability

$$f(x;\mu,\sigma)_{Gumbel} = \frac{1}{\sigma} e^{\frac{-(x-\mu)}{\sigma}} e^{-e^{\frac{-(x-\mu)}{\sigma}}}$$

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 where speeds are distributed log-normally.

An Illustrative Example of the European Put Option

A more-typical case occurs when the events that precipitate unreliability are known to be distributed EV, but there is no record of associated traffic metrics. This can be because insufficient data is 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 regarding 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 using 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 distributed EV, then Equation 3 can provide us with 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, though 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 that is 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

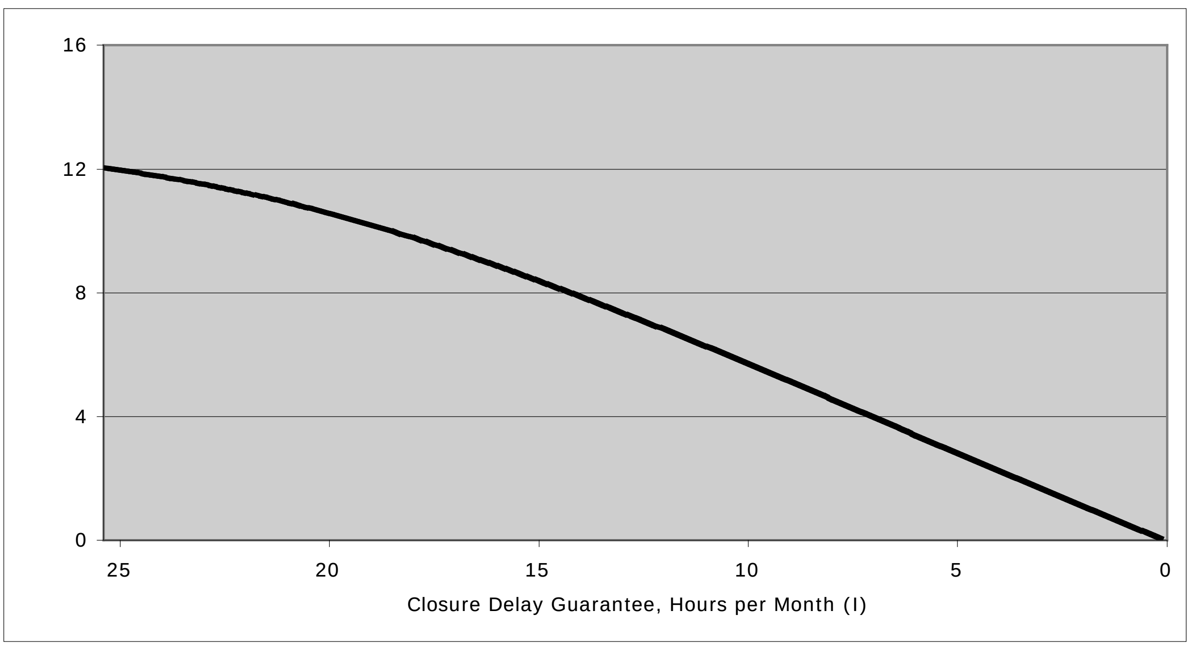
April) using data from a 13-year historical series of avalanche closures for the I-90 Eastbound direction of Snoqualmie Pass.

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 five 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. (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.)

Figure C.2 - Illustrative Example of European Put Option for Avalanche Closure Delay



There often is an additional complexity of the reliability problem associated with rare events. That complexity is that truly rare events play out over very long time periods and can occur at any time in this interval—not at the end of the interval. This makes the use of the European option inappropriate, since it assumes a finite horizon and exercise at the end of that interval. In such cases, it is more logical to use an American option with a perpetual life.

Coupling a perpetual life option with EV distributional assumptions complicates the arithmetic of the unreliability-valuation process considerably. There are only a handful of published papers that address this concept. Work by Koh and Paxson (2005) has been adapted to value decisions to invest in rare-event ventures. This work provides some guidance regarding 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 to 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 recognizing that potential benefits of the strategy are highly uncertain. Only 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 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 Generalized EV is a potentially valuable way to derive certainty-equivalent economic values of highway management strategies.

There is limited literature on the use of perpetual American options, so the Koh and Paxson paper is particularly interesting. The mathematics become doubly complex due to both rare-event and perpetual-option considerations. The Koh and Paxson option is a perpetual American call option. However, put-call parity allows us to use this formulation by restating the problem slightly. Equation 4 presents the Koh and Paxson method for the Gumbel EV distribution.

Equation 4 - The Option Value of a Rare Event Process Distributed EV (Gumbel)

$$F(V;K,x,\pi,s)_{Gumbel} = \frac{V^{\beta}\left(e^{\frac{-(x-\mu)}{\sigma}} e^{-e^{\frac{-(x-\mu)}{\sigma}}}\right)^{\beta}}{\beta\left(\frac{K\beta}{\beta-1}\right)^{\beta-1}} \text{ if } V < V^{*} \text{ or}$$

$$= V\left(e^{\frac{-(x-\mu)}{\sigma}} e^{-e^{\frac{-(x-\mu)}{\sigma}}}\right) - K \text{ if } V \geq V^{*}$$

where

$$\beta = \frac{1}{2} - \frac{\pi}{s^2} + \sqrt{\left(\frac{\pi}{s^2} - \frac{1}{2}\right)^2 + \frac{2r}{s^2}} > 1$$

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^{*} = the value of the event below which it is worth continuing to wait to invest K

μ = location parameter for the Gumbel distributuion

σ = scale parameter for the Gumbel distributuion

The formulation in Equation 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 the value of mitigation (*V*) and the cost of mitigation (*K*) associated with the project compare.

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 4 is then solved for F( ) for various values of V (the mitigation value) and K (the project cost).By reviewing Equation 6, it can be determined that the project value function, F( ) varies in the following way with the 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. Using data from a 13-year history of avalanche events in the area, a Generalized EV-Gumbel (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.

Figure C.3 - Gumbel Probability Function for Avalanche Closures per Year, I-90 Eastbound

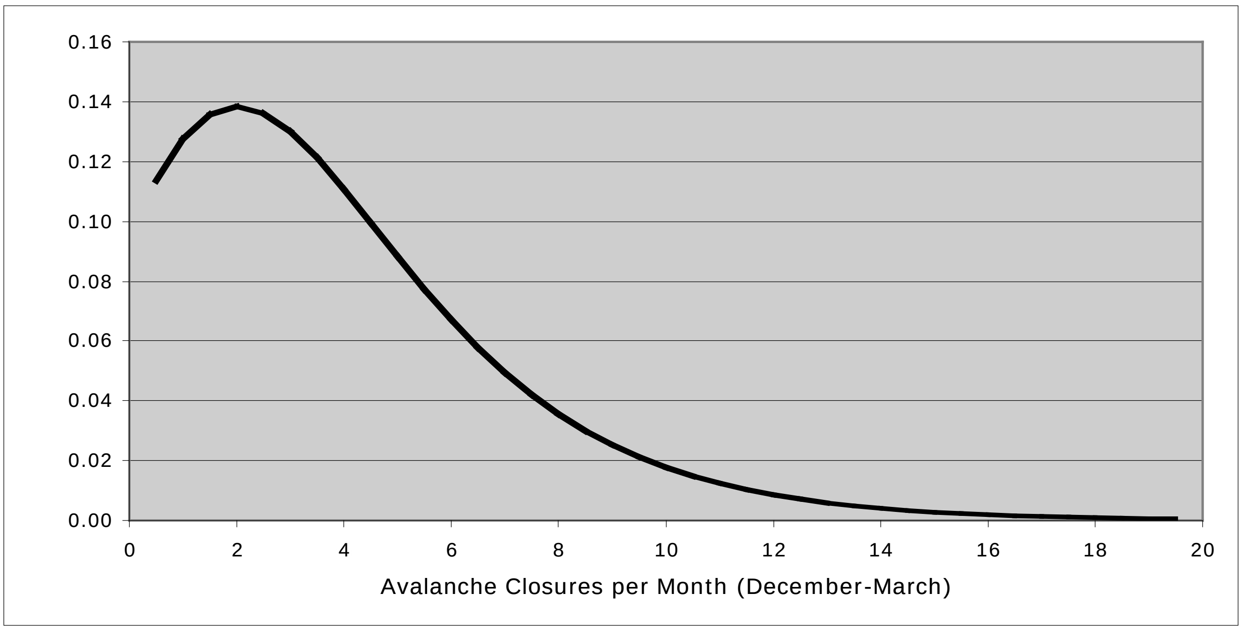
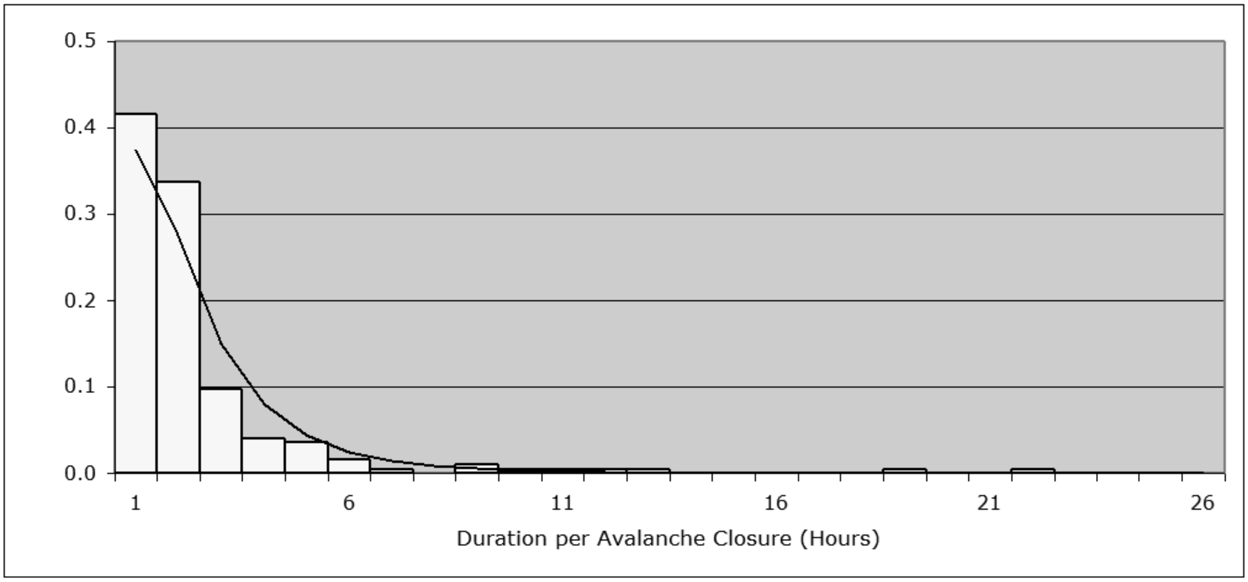
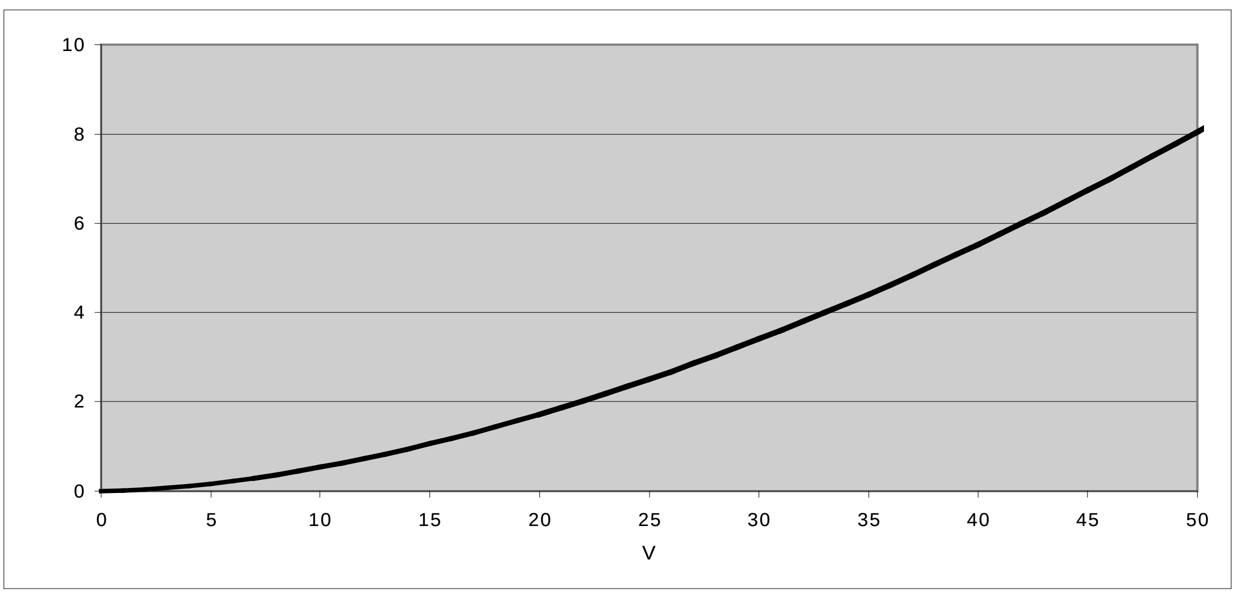


Figure C.4 - Duration per Avalanche Closure (Hours)



Data on the duration of the closure associated with avalanches was 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, π=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.5 - Example of Option Value, F(V) for Avalanche Closure Events



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, as 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, i.e., that a project or strategy intended to remediate multiple avalanches does not have high value because it is such a rare event.

Figure C.6 - Certainty Equivalent benefit for Different Mitigation Costs, K

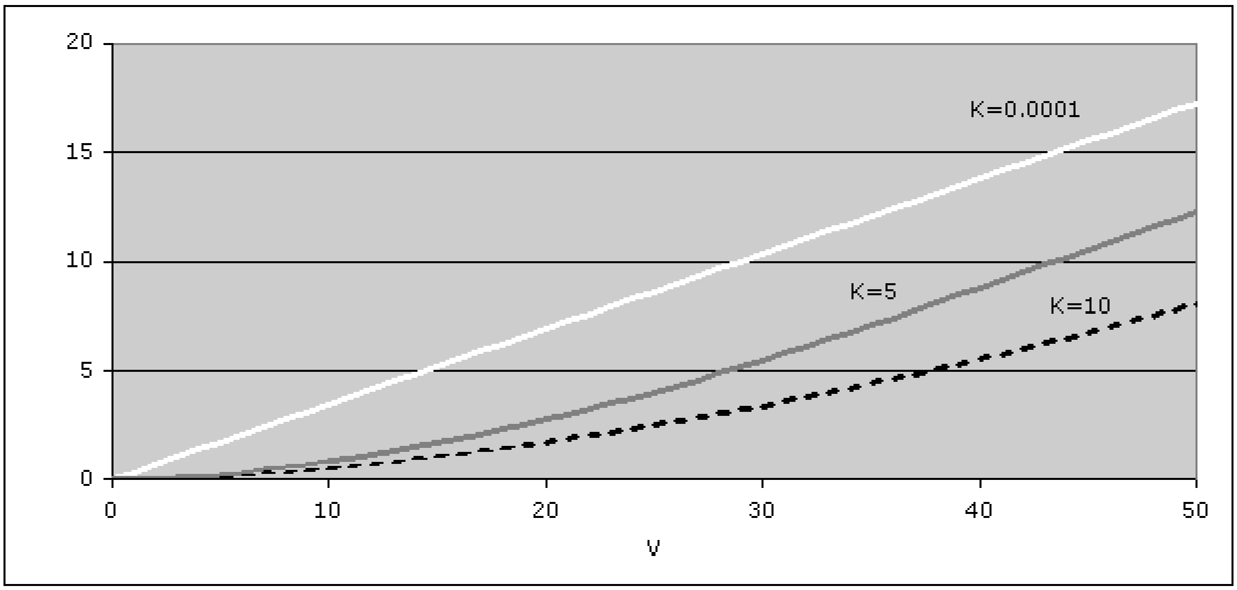
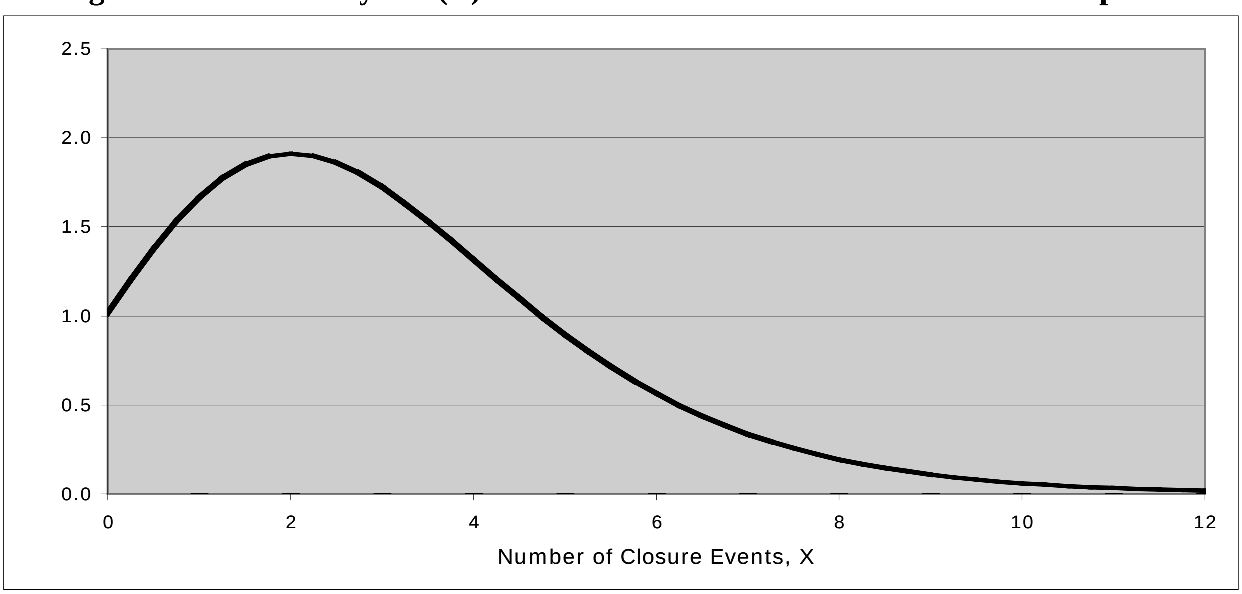


Figure C.7 - Sensitivity of F(V) to different Numbers of Avalanche Closures per Month



The Koh and Paxson approach is very flexible, because it allows for the case in which events are only meaningful if multiple instances occur simultaneously. For example, a highway network might be such that there are three alternative passes at risk of avalanche, but significant delays only occur if all three 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 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, we find the highest values of F(V) occurs 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 extreme value distribution and a perpetual, American option formulation), the present value of benefits and costs are incorporated (as V and K, respectively) directly in the project option value function. The reason 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 we have extended an approach first proposed by Koh and Paxson to the context of transportation investment decision-making under uncertainty due to rare events. The method relies on extreme value 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. Though 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.

PROBLEM 2

RARE-EVENT RELIABILITY VALUATION EXAMPLE

The Issue

A transportation agency in the northeastern region of the U.S. 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 using 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 using this method equals $100 million ("impact cost") and would be borne by the agency and/or the *public 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.*

The Solution

The options theoretic approach could be used to calculate the certainty-equivalent value of the uncertainty regarding the occurrence and number of hurricanes.

Data Needs

- Information or data on the likelihood of hurricane events in the region to construct a distribution of hurricane events.

Cautions

- By their very nature, it will be unlikely that the probability distribution for the rare event can be estimated from historical data.

Procedure

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 generalized extreme value (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 1 – Characterize the Rare Event

A. Location parameter = μ = 1.67

Scale parameter = $P(V_T,t)$ = 0.88

B. The probability distribution using the Gumbel probability density function is given by:

$$f\left(x;\mu,\sigma\right)_{Gumbel} = \frac{1}{\sigma} e^{\frac{-(x-\mu)}{\sigma}} e^{-e^{\frac{-(x-\mu)}{\sigma}}}$$

$$= \frac{1}{0.88} e^{\frac{-(x-1.67)}{0.88}} e^{-e^{\frac{-(x-1.67)}{0.88}}}$$

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 Event

Here, the investment opportunity is to spend $101 million to avoid $100 million in costs per hurricane event. Equation 4 can be used to derive the certainty equivalent value of uncertainty associated with the occurrence of hurricanes.

A. Use Equation 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 Paxon (2005). Because the Koh and Paxon formulation embeds the option value into an investment framework, the interest rate is 9% to reflect a risk premium and inflation.

Step 2 – Calculate Certainty-Equivalent Value of Unreliability associated with Rare Event

A. For the given example,

V = the total present discounted value of the cost incurred

= Expected cost per event $\times$ Expected number of events = \$100 million $\times$ 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

$$F(V;K,x,\pi,s)_{Gumbel} = \frac{V^{\beta}\left(e^{\frac{-(x-\mu)}{\sigma}} e^{-e^{\frac{-(x-\mu)}{\sigma}}}\right)^{\beta}}{\beta\left(\frac{K\beta}{\beta-1}\right)^{\beta-1}} \text{ if V} < \text{V}^*$$

$$= V\left(e^{\frac{-(x-\mu)}{\sigma}^{-e^{\frac{-(x-\mu)}{\sigma}}}}\right) - K \text{ if V} \geq \text{V}^*$$

where

$$\beta = \frac{1}{2} - \frac{\pi}{s^2} + \sqrt{\left(\frac{\pi}{s^2} - \frac{1}{2}\right)^2 + \frac{2r}{s^2}} > 1$$

$$V^* = \frac{K\beta}{\left(e^{\frac{-(x-\mu)}{\sigma}^{-e^{\frac{-(x-\mu)}{\sigma}}}}\right)(\beta-1)}$$

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 1 C

For $x = 2$

$$\beta = \frac{1}{2} - \frac{\pi}{s^2} + \sqrt{\left(\frac{\pi}{s^2} - \frac{1}{2}\right)^2 + \frac{2r}{s^2}}$$

$$= \frac{1}{2} - \frac{0.05}{0.1^2} + \sqrt{\left(\frac{0.05}{0.1^2} - \frac{1}{2}\right)^2 + \frac{2 \times 0.09}{0.1^2}}$$

$$= 1.68$$

$$V^* = \frac{101 \times 1.68}{\left(e^{\frac{-(2-1.67)}{0.88}-e^{\frac{-(2-1.67)}{0.88}}}\right)(1.68-1)} = \$719 \text{ million}$$

Since $\because V < V^*$

$$F(100,101,2,0.05,0.1)_{Gumbel} = (2 \times 100)^{1.68}\left(e^{\frac{-(2-1.67)}{0.88}} e^{-e^{\frac{-(2-1.67)}{0.88}}}\right) \Big/ 1.68\left(\frac{101 \times 1.68}{1.68-1}\right)^{1.68-1}$$

= \$17.09 million

Step 3 – Perform analysis to decide if it is worth implementing the strategy/policy

A. Calculate the total cost of implementing the strategy/policy.
B. Calculate the total benefits as a result of implementing the strategy/policy.
C. Perform the analysis to decide if it is worth implementing the strategy/policy.

Step 3 – Perform analysis to decide if it is worth implementing the strategy/policy

A. Total cost of installing the pumping system = \$101 million

B. The present value of the damage per hurricane event calculated using the capital planning methods = \$100 million
   Option value of the investment opportunity associated with the occurrence of 2 hurricane events per year = \$17.09 million
   Total benefits = 2 $\times$ 100 + 17.09 = \$217.09 million

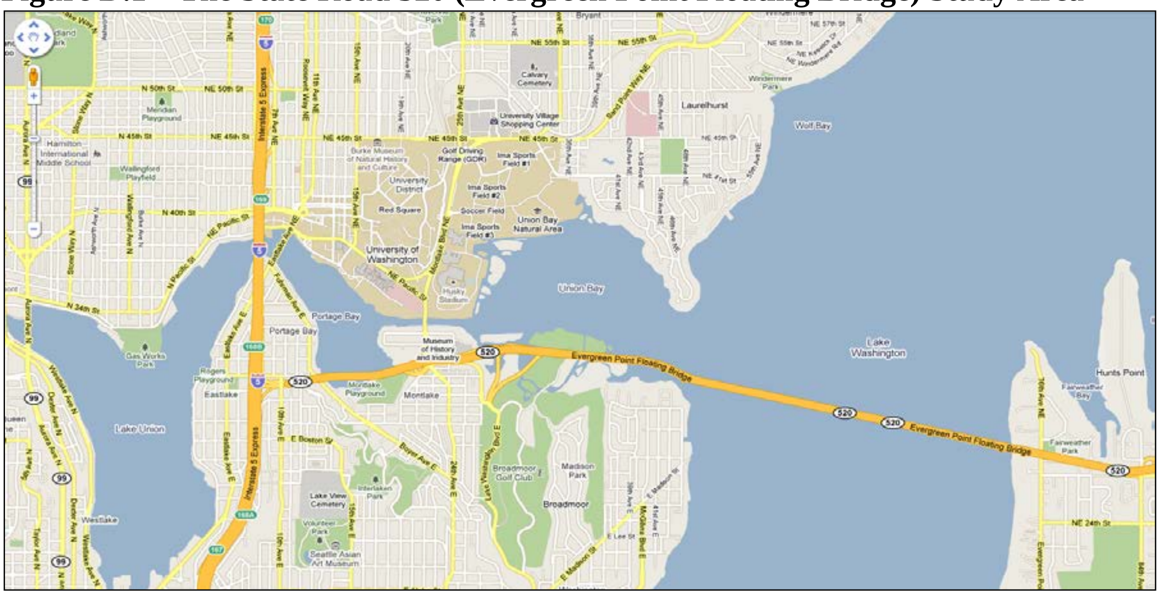
C. Because the benefits are more than the cost in the case of two hurricanes, which is most likely, it is worth the investment to install the pumping system.

APPENDIX D– **Sample Problem – Quantifying the Economic Benefit of Improving Travel-Time Reliability**

The Issue

State Road 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 State Road 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 due to the population growth of Bellevue and due to 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. In an effort 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.

Figure D.1 – The State Road 520 (Evergreen Point Floating Bridge) Study Area



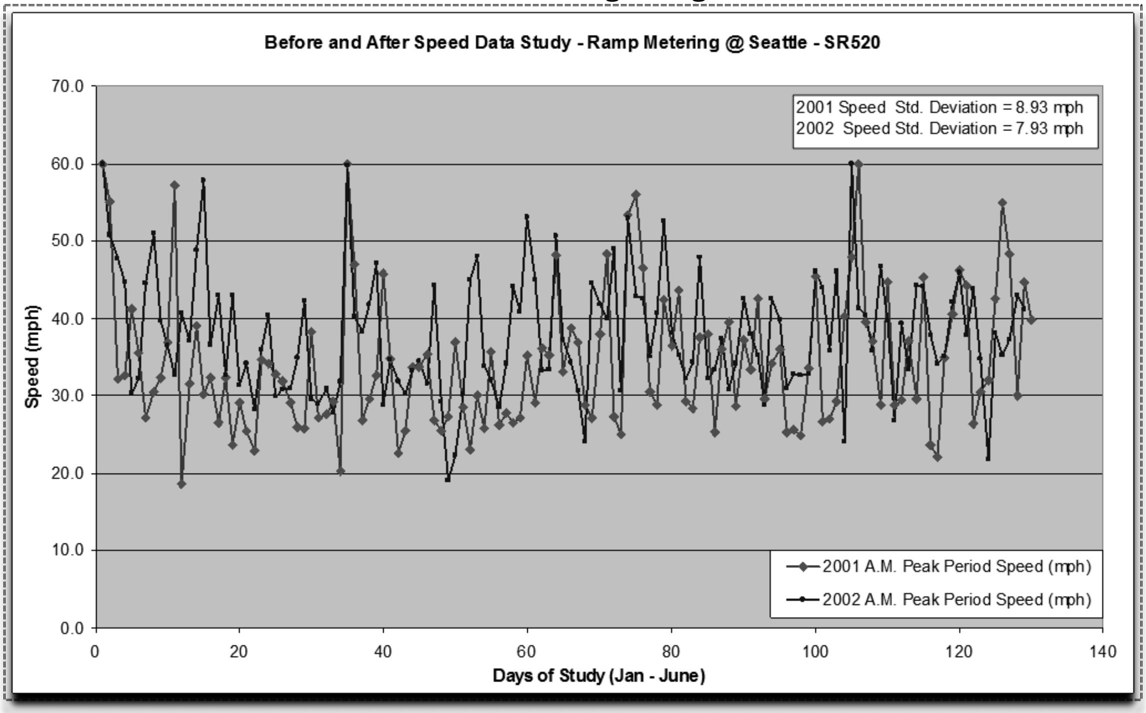
Source: Google Map

Problem Statement

<u>This sample problem presents a methodology for determining how the activation of these two on-ramp meters for eastbound State Road 520 traffic has affected travel-time reliability during the morning peak period.</u> Six months of weekday 5 minute-interval travel time data from before and after the initiation of morning ramp metering were analyzed. Travel times during the before period (January 1, 2001 to June 29, 2001) were compared with travel times during the after period (January 1, 2002 to June 28, 2002). This comparison included travel-time measurements taken during each weekday in a comparable six-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 based on the approximately four-mile length of State Road 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.

Figure D.2 – 2001 and 2002 Speed Data for Eastbound SR 520 from I-5 to east of Evergreen Point Floating Bridge



The Solution

The travel-time variability during the a.m. peak period in the eastbound direction on State Road 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-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 five-minute (or fifteen-minute) time intervals
- Volume data by vehicle type

Cautions

- This procedure is applicable to data where the variation in travel-times can be characterized by a log-normal distribution.

Procedure for quantifying the economic benefit of improving travel-time reliability

Six steps were followed to solve this problem:

1. Characterize the recurring congestion problem
2. Calculate the certainty-equivalent value of unreliability
3. Evaluate the treatment that reduces unreliability
4. Calculate the value of the reliability improvement to the road user

5. Calculate the reliability measures and the benefit-cost ratio
6. Compare the 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 log-normal distribution using the log mean and log standard deviation of the speed to confirm that the speed data are log-normally distributed

A. Obtain speed data and calculate data parameters.

The following parameters were calculated from the speed data. Refer to Exhibit 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
- Free Flow Speed = 60 mph
- Corridor Length = 4 miles

Table D.1 shows the eastbound State Road 520 freeway volumes for the three-hour weekday a.m. peak period (from 6 a.m. to 9 a.m.) before and after implementation of the ramp metering.

Table D.1 - Vehicular Volumes

Vehicle Class	2001 Volume	2002 Volume
Passenger Car	6,516	6,921
Truck (3% of Total Volume)	202	214

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 (http://www.fhwa.dot.ov/infrastructure/asstmgmt/hersdoc.cfm).

Table D.2 - Value of Time for Different Vehicle Classes

Vehicle Class	Value of Time ($/minute)
Passenger Car	0.30
Truck	0.83

B. Calculate the average speed and the standard deviation of the natural log of speed for 2001 conditions.

Average speed $(\bar{X}) = \frac{\Sigma S_i}{N}$

Where,

$S_i =$ Speed during interval i

$N =$ Total number of intervals

For this, $I =$= 32.41 mph

Average ln speed $(\mu) = \frac{\Sigma \ \ln \ (S_i)}{N}$

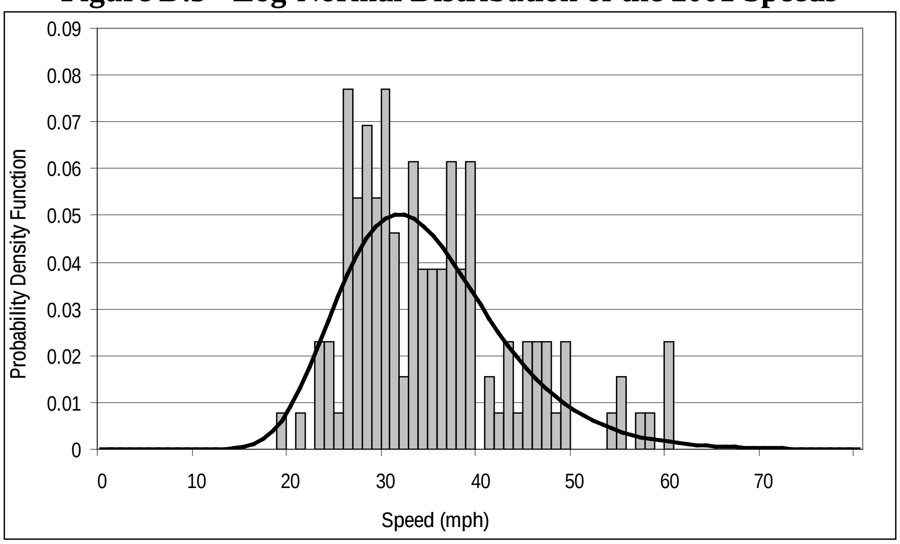
For this example, μ= 3.51

Standard deviation of ln speed or speed volatility $(\alpha) = \sqrt{\frac{1}{N}\Sigma(\ln(S_i) - \mu)^2}$

α = 0.2451

C. Construct a log-normal distribution using the log mean and the log standard deviation of the speed to confirm that the speed data are log-normally distributed.

Figure D.3 - Log-Normal Distribution of the 2001 Speeds



Note: Weekends were excluded from the data.

Step 2 – Calculate the Certainty-Equivalent Value of Reliability

A. Choose the appropriate option formulation (European Put option 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 95^{th} percentile speed.
D. Calculate the certainty-equivalent value of reliability for the roadway using the options formula.
E. Convert the certainty-equivalent value from miles per hour to minutes per mile.

A. Choose the appropriate option formulation (European Put option or American Put option).

For this example, the European Put option was employed because:

- The European Put option gives us 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 tell us the commuter value of unreliability for a period of time, appropriate for the evaluation of a strategy.
- The European put option is selected since the option is formulated using a finite time horizon, where the option is exercised at the end of the option life (i.e., once the traveler has traversed the bridge segment.)

B. 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

C. Calculate the contract length, based on the 95^{th} percentile speed.

The contract length (T-t), is calculated as the travel time to cover the segment at the 95^{th} percentile speed, determined 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 since the interest rate is an annual rate.

$$T - t = \left(\frac{\frac{60}{23.65}}{365 \times 24 \times 60} \right) \times 4 = 0.0000193 \; years$$

D. Calculate the certainty-equivalent value of reliability for the roadway using the options formula.

The certainty-equivalent value of reliability $T-t=\left(\frac{60/13.22}{365\times24\times60}\right)\times10$ is calculated by first calculating three parameters: $P(V_T,t)$, d1 and d2. $P(V_T,t)$ is calculated 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 d1 and d2 are two points on the cumulative log-normal distribution, N(d), N(d1), and N(d2) are thus probabilities that the cumulative probability will be less than d1 or d2, respectively. In the Black Scholes formula, N(d2) is the probability the option will be exercised and N(d1) is called the option delta. It 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

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

$$= 32.41e^{-0.05(0.0000193)}(0.5488) - 32.41(0.4512)$$

= 3.16 mph

From this calculation, a commuter is willing to accept a reduction of 3.16 mph in his/her average speed to eliminate travel-time variability.

E. <u>Convert the certainty-equivalent value from miles per hour to minutes per mile.</u>

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

$$P(V_T, t) = \left(\frac{1}{29.25} - \frac{1}{32.41}\right) \times 60 = 0.20\ minutes\ per\ mile$$

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.

A. <u>The new set of speed data parameters (after implementation of the treatment) is calculated as follows:</u>

Assumptions for the new scenario:

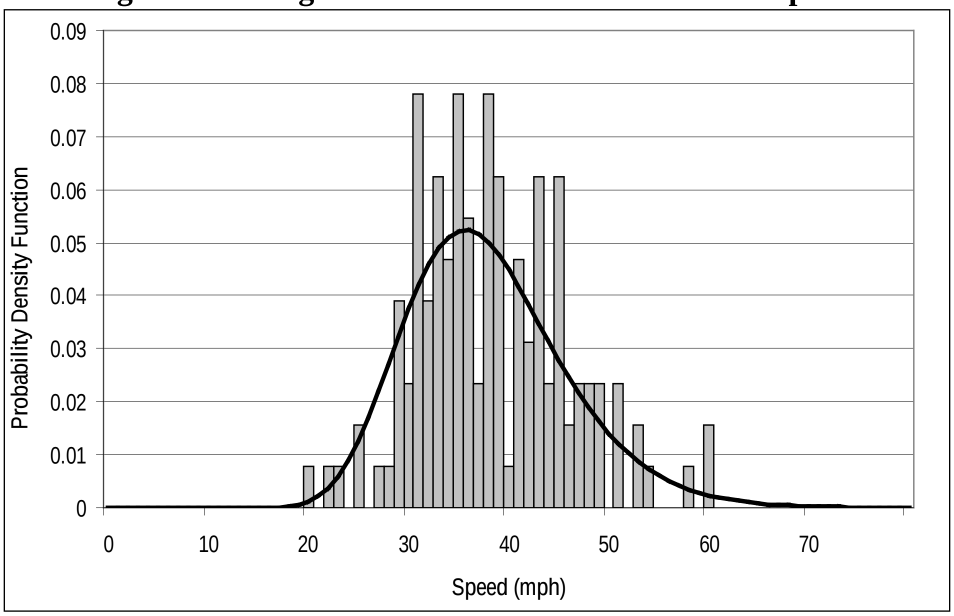
- The new average speed (V_T) = 36.39 mph (the 2002 average speed)
- The guaranteed speed (equivalent to the 2002 average speed) (I) = 36.39 mph

Standard deviation of ln speed or speed volatility (α)= $\sqrt{\frac{1}{N}\Sigma(\ln(S_i)-\mu)^2}$

α = 0.2094 for this example

The log-normal distribution using the log mean and the log standard deviation of the speed is shown on Figure D.4 to confirm the speed data are log-normally distributed.

Figure D.4 - Log-Normal Distribution of the 2002 Speeds



Note: Weekends were excluded from the data.

B. <u>Calculate the certainty-equivalent value for the after (2002) scenario.</u>

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:

$$T-t=\left(\frac{\frac{60}{27.91}}{365\times 24\times 60}\right)\times 4 = 0.0000164\ years$$

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

$$\sigma=\frac{\alpha}{\sqrt{(T-t)}}=\frac{0.2094}{\sqrt{0.0000164}}=51.76$$

The intermediate and final option value calculations are performed:

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

$$d_1 = \frac{\ln\left(\frac{36.39}{36.39}\right) + \left(0.05 + \frac{51.76^2}{2}\right)(0.0000164)}{51.76\sqrt{0.0000164}} = 0.10469$$

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

$$= 0.10469 - 51.76\sqrt{0.0000164} = -0.10469$$

N (d_1) = N (0.10469) = 0.4583

N (d_2) = N (-0.10469) = 0.5417

The certainty-equivalent value of reliability is:

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

$$= 36.39e^{-0.05(0.0000164)}(0.5417) - 36.39(0.4583)$$

= 3.03 mph

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 of a reduction in speed in exchange for eliminating variability. The commuter is willing to give up less to eliminate variability since the 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.

A. <u>The value of time for different vehicle classes is shown in Step 1 Part A.</u>

B. <u>The value of the reliability improvement for each vehicle class during the three-hour a.m. peak period is shown below:</u>

- Passenger vehicles =
  6,921 X ($0.30/minute) X (0.20-0.15 minutes/mile) = $103.82/mile
- Trucks = 214 X ($0.83/minute) X (0.20-0.15 minutes/mile) = $8.88/mile

C. The value of the reliability improvement for the three-hour a.m. peak period is calculated as:
Total length of the highway = 4 miles
∴ Total value of the reliability improvement for the three-hour a.m. peak period
= ($103.82 + $8.88) X 4 (miles) ≈ $450.80

D. The total annual value of the reliability improvement
The total number of days considered = 252 Weekdays/Year
∴ Total value of the reliability improvement per year (for the three-hour a.m. peak period)
= $450.80 X 252 days ≈ $113,601.60

Step 5 – Calculate the Reliability Measures and the Benefit-Cost Ratio

A. Calculate before and after Buffer Index (BI) and Planning Time Index (PTI).
B. Calculate the benefit-cost ratio.

A. Calculate the reliability measures

The Buffer Index (BI) and the Planning Time Index (PTI) were calculated using the collected speed data. By definition, the Buffer Index 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 required input data is listed below:
2001 95th percentile travel time: 605.8 sec
2002 95th percentile travel time: 513.4 sec
2001 average travel time: 442.1 sec
2002 average travel time: 393.8 sec
2001 free flow travel time: 238.8 sec
2002 free flow travel time: 238.8 sec

Table D.3 shows the computed PTI and BI values from the data collected during 2001 (before) and 2002 (after).

Table D.3 - 2001 and 2002 Buffer Indices and Planning Time Indices

Reliability Measure	**Before (2001)**	**After (2002)**
Planning Time Index	2.54	2.15
Buffer Index	0.37	0.30

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.

B. Calculate the Benefit-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 (*1, 2, 3 and 4),* 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 five-year period is estimated to be $78,403. The net present value of the reliability improvement over five yields $520,264 in savings.

Thus, the Benefit-Cost ratio is estimated to be 6.6:1. These calculations are summarized in Table D.4. It should be noted that this is a rough estimate that only considers the benefits of the morning peak period and is provided for illustrative purposes. If the safety benefits and the reduction in fuel emissions were considered, a higher benefit-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.

Table D.4 - Summary of Benefit-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) (1)	Travel Time Reliability Benefits (Evaluation Year Dollars) (2)	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

(1) Cost reflects two ramp meters
Year 1 Cost=Installation and O&M in year 1.
(2) 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.

Step 6 – Compare the Results with other Similar Treatments

As a final step in this analysis, a literature review was conducted to estimate the benefit of other ramp metering projects toward improving 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 E):

Efficiency

- The benefit-to-cost ratio of the Minneapolis-St. Paul ramp metering system was found to be 15:1. *(1)*

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 percent, or 54 seconds per vehicle. *(1)*
- 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. *(5)*
- 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%. *(6)*
- Ramp meters in the Netherlands have helped to regulate traffic flow on highways, have led to measured speed increases, and have allowed for capacity increases of up to 5%. *(7)*
- Ramp meters at the Oakland-Bay Bridge toll facility in San Francisco, CA 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. *(8)*

Safety

- Crash frequency increased by 26 percent after the ramp meter system on Minneapolis-St. Paul freeways was deactivated. *(1)*
- A survey of traffic management centers in eight cities found that ramp meters reduced the accident rate by between 24 and 50%. *(2)*

Energy/Environment

- Ramp meters saved between 2% and 55% of the fuel expended at each ramp in a simulation study in Minneapolis-St. Paul. *(1)*

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APPENDIX E– **Strategy Framework for Agency Management, Organization, and Resource Allocation**

Agency Institutional Requirements

In this appendix, specific institutional treatments are identified to improve travel time reliability based on the SHRP 2 L06 project findings. The key drivers that impact agencies' development levels are different from the future alternative scenarios presented in Chapter 4. The agencies development (maturity) level is defined in terms of institutional organization and how their Systems Operations and Management (SO&M) activities are handled. Three development levels are identified as follows:

- Development Level 1 – Ad Hoc: Systems Operations and Management (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: In this level, 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: In the highest level 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., snow storms, hurricanes, tornados)
- Financial Incentives (e.g., dedicated funds towards ITS programs)
- New Regional Political Configuration (e.g., MPOs, local governments)

If agencies experiences one of these key drivers, they are likely to move to one or another of these levels. Events such as these can present a "window of opportunity" that can help move agencies towards the 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 Objective 1 – Improve agency management, organization, and resource allocation for all three future scenarios are shown in Table E.1.

Table E.1 - Summary of Key Treatments for Institutional Strategies (Objective 1)

Strategy	Treatments	Strategy Level of Development 1 – Ad Hoc	Strategy Level of Development 2 – Rationalized	Strategy Level of Development 3 – Mainstreamed
Culture/Leadership				
1.1 Systems Operations and Management Awareness	Undertake educational program, re: 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 non-recurring congestion relative to other programs 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 among CEOs, senior and middle staffs at the agency level to mainstream SO&M.	Visible Senior Support Agency-Wide: Top management is visible in supporting and articulating SO&M leverage, cost-effectiveness and risks across disciplines in the DOT.	Visible Senior Support Agency-Wide: SO&M is understood and supported by stable career leadership as a key mission.
	Establish formal core program	SO&M 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, etc.	SO&M 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 and/or traditions regarding 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 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/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.

Table E.1 - (Continued) Summary of Key Treatments for Institutional Strategies (Objective 1)

Strategy	Treatments	Strategy Level of Development 1 – Ad Hoc	Strategy Level of Development 2 – Rationalized	Strategy Level of Development 3 – Mainstreamed
Organization/Staffing				
1.2 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. 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 central office and districts.	Integrated, with Organizational Equivalency: a top-level management position with SO&M orientation is established in central office and districts.
	Establish appropriate organizational structure	Functions Fragmented and Unclear: SO&M units are fragmented and responsibilities unclear, at central office division/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, TMC management, 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, Trained: 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, 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 based on program, unit, and individual responsibilities related to SO&M effectiveness.	SO&M Responsibilities Clarified within All DOT Units: accepts accountability for its SO&M activities (recognizing the DOT does not control all the variables that affect performance).
Resource Allocation				
1.3. O&M as 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, and/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 – 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 – capital, operating, and staffing.	Sustainable Budget Line Item: SO&M becomes a first tier budget item.

Table E.1 - (Continued) Summary of Key Treatments for Institutional Strategies (Objective 1)

Strategy	Treatments	Strategy Level of Development 1 – Ad Hoc	Strategy Level of Development 2 – Rationalized	Strategy Level of Development 3 – Mainstreamed
1.3. O&M as High Priority Budget Item	Develop acceptance of sustainable resourcing from state funds	SO&M Lacks Clear Position in State Funding: resources are sub-allocated 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-offs between SO&M and capital expenditure is considered as part of the planning.
Partnerships				
1.4. 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/MPOs	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 partners' 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 practice.	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.	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, Quade and Douglas (PBQD). Institutional Changes to Support Improved Congestion Management: A Report and Guidance Volume II: Guidance. Prepared for SHRP2 – L06 Project. Transportation Research Board. September 2009.

1.1. Systems Operations and Management Awareness

It is important that agency staff and leadership understand the impacts and benefits of a SO&M structure and to also 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.

1.2. Systems Operations and Management Structure

Executive leadership (at the central office and in the field) needs to be on 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/capabilities with appropriate authority—at district and central office levels and between them. Furthermore, SO&M requires technical specialties regarding planning, engineering, Traffic Management Centers (TMCs), 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 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 staff within the organization needs 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.

1.3. Systems Operations and Management as High Priority Budget Item

The development of a sustainable program involving a multi-year 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.

1.4. Identify Opportunities for public partnerships

Effective delivery of key SO&M strategy applications requires close cooperation between DOTs and public safety agencies (PSAs). 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 government. 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 individually because they do not have shared objectives and do not communicate with other communities. 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 everyone.

APPENDIX F– **Additional Description and Quantitative Benefits of Travel-Time Reliability Strategies**

Additional Description of Strategies

Information Collection and Dissemination

2.1. Surveillance and Detection

A variety of surveillance and detection technologies are able to detect incidents quickly. These include inductive loops, acoustic and microwave vehicle detectors, and camera systems that provide frequent still images or full-motion video. These 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 traffic and travel conditions monitoring system *(9)*.

Additionally, reducing annual road accidents and deaths requires more than improved vehicle and roadway technologies. Surveillance treatments also include evaluating the capability of drivers to safely operate a motor vehicle 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 *(10)* have proved successful in other nations

2.2. Probe Vehicles and Point Detection

Probe Vehicles and Point Detection (GPS, Video Detection, Radar, Transponders, Bluetooth MAC Readers)—Doppler radar, video image processors (VIP) and Global Positioning System (GPS) are technology devices that are used by roadway agencies for vehicle detection in order to provide near-real-time travel time estimation. The application of each technology varies among agencies according to agencies' knowledge of each technology *(11)*.

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 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). 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 based on 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, etc.

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 Mobile Access Code (MAC) readers have similar architecture—detecting and logging a Bluetooth wireless device's addresses, and matching the presence and times of detection of these addresses at successive receivers allow 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. Transponder systems (antennas, readers and checkpoint stations) tend to have a higher cost than video detection and radars (point detection)—one disadvantage of this system.

<u>2.3. Pre-trip Information</u>

Providing information on planned disruptions in advance, whether it is for construction zones or special events can greatly increase reliable travel since travelers can better plan for their trip 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 pre-trip information.

National Traffic and Road Closure Information. The FHWA National Traffic and Road Closure information website *(12)* provides real-time information regarding weather, road, and traffic conditions for travelers and freight shippers nationwide. Pre-trip 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 proactively manage and control traffic to accommodate the increased travel demand generated by the event and use the available roadway capacity in the most efficient and effective manner *(6)*.

<u>2.4. Real-time Information</u>

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 including 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 the vehicle and connections to the Traffic Management Subsystem for monitoring and control. This 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 impacts 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 traveler information. Additional information about traveler information systems can be found in the NCHRP Synthesis 399 – Real Time Traveler Information Systems *(13)* report.

Pre-trip information by 511, real-time navigation systems, web sites, subscription alerts. Pre-trip information provides motorists data through the internet, television, or radio. Many Cities have Advanced Traveler Information Systems (ATIS) with growing sophistication. These systems incorporate close-to-real-time information from cameras and traffic reports and provide data via the internet *(14)*. 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 agencies' websites (e.g., 511.org in San Francisco and 511.ksdot.org in Kansas City) are starting to provide service to cell phones, which allows people to also obtain information on the go *(6)*.

Road Weather Information Systems. Road weather management systems 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. Road Weather Information Systems (RWIS) are now critical components of many agencies' winter maintenance programs. Accurate and timely road weather information helps maintenance managers react proactively before problems arise; thereby improving safety while also reducing costs *(9)*.

Freight Shipper Congestion Information. Freight Shipper Congestion Information refers to real-time information along significant freight corridors. ITS technologies such as DMS, VMS, GPS, and RFID are used to provide travel-time information to freight operators. As an example, these technologies are evaluated by FHWA *(6)* 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 (via partnership with ATRI) are not available or used for real-time monitoring. Many trucks are tracked via GPS, which is a great probe source. The challenge is to gain access to this data (it is all private data) and use it to provide real-time information.

Weight-in-motion (WIM) technologies are another treatment to relieve congestion for freight shippers. Even though WIM doesn't 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. Additionally, data archived from WIM systems can be used to estimate truck volumes at stations (and adjacent highways) and to better plan truck routes.

2.5. Roadside Messages

Roadside Messages (DMS). Roadside messages consist of dynamic message signs (DMS), also known as variable message signs (VMS) that display information to travelers while they are driving. DMS devices provide overhead or side-of-roadway warning, regulation, 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. DMS are ITS solutions that provide safety and mobility benefits in urban, suburban, rural, and work-zone settings. DMS are becoming more prevalent and are a very effective way to convey expected travel conditions to travelers *(6, 9, and 14).*

Vehicle Technologies

3.1 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, on-board computer processing, advanced vehicle-sensors, GPS navigation, smart infrastructure, and others to help vehicles identify threats and hazards on the roadway and communicate this information over wireless networks to give drivers alerts and warnings. The following are some informational products:

- Route guidance
- Traffic advisories
- 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 *(7, 15)*.

3.2 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. ITS can help to eliminate a large number of crashes and reduce the severity of crashes that do occur. 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, including determining whether drivers are fit to drive. The following is a list of active safety technology:

- Forward and rear collision avoidance
- Intersection collision avoidance
- Lane departure prevention

All of these 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/Stability control
- Traction control
- Lane departure warning
- Work zone, pedestrian crossing and rail-highway intersection warnings

Incident and Special Event Management

4.1 Pre-event Strategies

Safety Service Patrols. 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. More 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 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.

4.2 Post-event Strategies

Automatic Crash and Incident Detection, 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 be aware of and able to convey the nature and degree of the injuries, entrapments, hazmat 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 the public safety agencies and transportation agencies to ensure rapid and appropriate incident detection, response, traffic control, and clearance *(3, 14)*. Today, insufficient attention is paid by the first responders (fire, police, etc.) to traffic operations management. They are mostly concerned with protecting the site and managing any injuries or fatalities.

Work-Zone Management. The objective of work-zone management is to safely move traffic through work zones 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 non-recurring delay (*1*, 16).

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 rapidly detect incidents 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/portable DMS, dynamic lane-merge systems, variable speed-limit systems, and portable traffic management systems including 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 *(5, 9).*

Examples of work zone management applications in the United States include Colorado DOTs traffic incident management program for several long-term construction projects (the T-REX project in Denver and the COSMIX project in Colorado Springs), and the North Carolina DOTs real-time work-zone information system on I-95 north of Fayetteville in 2002 *(14)*. Also, Caltrans has a software package for work-zone management designed to address traffic impacts. .

Infrastructure Improvements and Demand Optimization

5.1 Geometric Design Treatments

Bottleneck Removal (Weaving, Alignment). The improvement or elimination of weaving sections can be accomplished through changes in striping and/or lane assignments, the use of medians to physically separate traffic flows, reconfiguring ramps to add/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/diverge area.

Horizontal and vertical alignment modifications primarily apply to older facilities (arterials and freeways) that were designed and built before modern day roadway design standards were established. Sharp horizontal or vertical curves affect the speed profile of vehicles and, anecdotally, can lead to sudden breaking that increases the probability for a breakdown *(6)*.

Geometric Improvements (Interchange, Ramp, Intersections). Geometric improvements refer to spot reconstruction or minor geometric widening performed within the existing paved area. They are considered low to moderate cost improvements 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 *(6, 14).*

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 non-conventional intersections. This includes intersections where left-turn movements are converted to other intersection movements in order 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.

5.2 Access Management

Access Management (Driveway location, raised medians, channelization, frontage road). 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 *(6, 14)*.

Driveway consolidation (reducing the number of driveways on a roadway) has 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, while the Florida Department of Transportation has determined that poorly designed driveways can reduce arterial travel speed by up to 10 mph (14).

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/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 where safe and appropriate. Raised medians improve flow and performance by redirecting mid-block left-turning movements to signalized intersections.

Another strategy is to channelize or separate right-turn movements to minimize impedances to through movements.

5.3 Signal Timing/ITS

Poor signal timing accounts for 5–10% of all traffic delay *(1))*. 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 Center (TMC). TMCs are centralized facilities that gather traffic information through cameras, loop detectors, radars, etc. 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 to help agencies 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 AVL component) and make it possible to implement a TMC in smaller urban areas.

In Europe, many countries have implemented regional traffic management centers. 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 where reliable travel is one of the important services agencies are able to provide. For example, the government in Germany has a goal to ensure that 80% of all journeys have adequate, standardized real-time traffic and traveler information services by 2010 (8, 17 and 18).

Signal Retiming/Optimization. Traffic-signal-timing optimization and coordination minimizes vehicle stops, delay, and/or 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, leading to lower travel times, improved reliability and reduced driver frustration. For optimal performance, traffic-signal-timing plans need to be updated at least every three to five 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 (*6*, *14)*.

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, Canada, signal retiming at 62 intersections lowered travel time by 7% *(9)*. The National Traffic Signal Operation Self Assessment program sponsored by the National Transportation Operations Coalition (NTOC) in partnership with the Federal Highway Administration 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 two years that summarizes the results of self-assessments conducted by cities nationwide. The document evaluates how signal retiming/optimization are being conducted by the survey participants and points out outstanding needs to improve traffic signal operations (19).

Traffic Signal Preemption at Highway-Railroad Grade Crossings (HRGC). 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 HRGC area. From a traffic engineer's perspective, the current traffic signal preemption strategies are viewed as a reactive action to trains approaching a nearby HRGC as the 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 up to a cycle length before the train arrival at the HRGC to the signalized intersection control system, safer and more proactive preemption strategies could be adopted to provide improved safety and highway traffic operations in the HRGC area (11).

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 (FRA) for the past several years. Several publications and test beds have been successfully implemented by universities and DOTs. Most recently, Positive Train Control (PTC) systems have been identified as the leading edge to the future of railroad and highway operations. Positive train control systems are defined as "integrated command, control, communications, and information systems for controlling train movements with safety, security, precision, and efficiency" *(11)* as focus. PTC systems will reduce delays at HRGC by providing advance notice of train arrival and traffic signal preemption optimization. PTC systems are currently tested by the major Class I railroads in the U.S.

Traffic Adaptive Signal Control/Advanced Signal Systems. Responsive traffic operation systems select a prepared timing plan based on the observed/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 based on that prediction. Traffic adaptive signal control systems coordinate the control of traffic signals along arterial corridors, and adjust the signal phase lengths based on prevailing traffic conditions. Adaptive signal control systems use algorithms that perform real-time optimization of traffic signals based on 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 UK (used in Los Angeles), SCATS, developed in Australia, and OPAC and Rhodes (used in Tucson, AZ and Seattle, WA) developed in the United States *(6, 9, and 14).*

Advanced Transportation Automation Systems. Research is currently underway 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:

- 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.
- Automated on-board monitoring and inspection systems for safety, weight, and cargo clearance of commercial vehicles.

Smart Freight. A number of different technology-based systems will improve the efficiency of freight flows as follows:

- Due to 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 underway in Europe to tag freight and use that information with control models to automatically route freight so 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.

5.4 Traffic Demand Metering

Traffic Demand Metering strategies 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, etc.). The metered traffic is allowed to enter the freeway or major road at a rate that is 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.

Metering can also improve travel-time reliability. An experiment where ramp meters were shut down for a six-week period in Minneapolis-St Paul during 2000 indicated that travel times were nearly twice as predictable when the meters were on, as compared to the off condition *(6)*.

Traffic demand metering treatments consist of mainline metering, on-ramp metering, and peak-period ramp closures.

Ramp Metering, Ramp Closure. 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 Route 217, San Diego I-8, and Los Angeles I-710 *(6)*. Post-implementation 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 two 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 (14).

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 (9).

5.5 Variable Speed Limits

A variable speed limit 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, variable speed limits 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 variable speed limits 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 *(5, 6)*..

Variable speed limits (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 variable speed limits. In Germany, variable speed limits are currently used on approximately 750 miles (1200 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, whereas in the US, 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 (8, 17 and 18).

In the United States, variable speed limits 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 (regulatory speed for all traffic based on weather conditions) (14).

A major challenge of variable speed limits is motorist compliance. Inappropriate signs and arbitrary speed restrictions, particularly at low volumes, lead to reduced compliance *(6)*.

5.6 Congestion Pricing

Congestion pricing, also known as value pricing, uses variable and area-wide 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 itself or on a parallel facility. The objective of congestion pricing is to preserve high operating speeds by employing 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 *(6, 8, 17 and 18)*. In the U.S. variable pricing schemes are currently applied along managed and express lanes (i.e., SR 91 in Orange Country and I-95 in South Florida).

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-Z Pass system in the northeast region of the United States and Autopass out of 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 in order to pay the toll. Some systems are able to collect tolls at full freeway speeds 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 (Area wide). Cordon pricing imposes tolls for vehicles entering a central area street network during certain hours of certain days. Singapore, London, and Stockholm 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 *(6, 8, and 14)*.

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.

5.7 Lane Treatments

Lane treatments consist of strategies that result in an added or dedicated travel lane for a directional movement of traffic and/or a specific vehicle/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, HOT lanes, truck only lanes, TOT 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 usage to multi-occupant vehicles for the entire day or for the peak traffic hours. There are several types of HOV lanes including 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 to 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 *(3, 5, 6, 9, and 11)*. An inventory of existing and planned HOV facilities is provided through the FHWA Office of Operations' website for HOV facilities (20).

High-occupancy toll (HOT) lane facilities charge single-occupancy vehicles (SOV) for the use of a HOV lane. Access to HOT lanes is free for transit vehicles, vanpools, and carpools. The toll charges for SOVs varies based on the level of congestion to ensure traffic volume does not exceed an established threshold for all vehicles in the HOV lanes such that free-flow travel conditions are maintained. Toll collection is performed electronically using open-road tolling to allow high-speed toll collection. Tolls are charged at fixed points along the facility (9).

Changeable Lane Assignments (Reversible, Temporary Shoulder Use, Variable). Reversible lanes are used on arterial roadways, freeways, and bridges/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 *(5, 14)*.

Examples of this treatment include I-15 in San Diego, the Kennedy Expressway in Chicago, I-5 and I-90 in Seattle, 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 *(6, 14)*.

In Europe, temporary shoulder use is implemented to reduce congestion levels. This strategy has been used with the automated variable speed limits in the Netherlands and Germany (8).

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 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 *(6, 9)*.

The use of variable lanes to add turn lanes requires adequate turning radii, adequate departure/receiving lanes, variable-mode signal phasing, and advance warning signs.

5.8 Multimodal Travel

Integrated Multimodal Corridors. Integrated Multimodal Corridors allows various partner agencies to manage the transportation corridor as a system rather than 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 USDOT launched a five-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 USDOT 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 (21, 22).

5.9 Travel Reduction

Rideshare Programs. Rideshare programs involve online carpool matching and assistance to employers to match their employees and vanpools. Vanpools that meet program criteria such as traveling at least 20 miles round-trip are given a partial subsidy as an incentive.

Telecommuting. Telecommuting refers to employees that 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.

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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 – Institutional Strategies. However, quantitative benefits have been determined for the 18 strategies in Categories 2 – 5. Table F.1 quantifies information related to travel time reliability improvements and congestion reduction.

Table F.1 - Key Quantitative Benefits for Operational Strategies (Categories 2 - 3)

Strategy	Treatments	Key Quantitative Benefits
2.0 Information Collection and Dissemination		
2.1 Surveillance and Detection	Remote Verification (CCTV)	5% reduction in travel times in non-recurring congestion and overall 18% reduction in travel times *(3, 11)*.
	Driver Qualification	Reduces non-recurring congestion by reducing accidents *(55)*
	Automated Enforcement	Reduces travel time *(60,61)*and improves safety *(56, 57, 58)*
2.2 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
2.3 Pre-trip Information	National Traffic and Road Closure Information	Reduces delays (early and late arrivals) by 50% *(5)*
	Planned Special Events Management	Reduces delay due to special events *(20)*
2.4 Real-time Information	Pre-trip information by 511, web sites, subscription alerts, radio	Potential reduction in travel time from 5% to 20% *(1)*
	Road Weather Information Systems (RWIS)	Reduces delay by up to 12% *(3, 4)*
	Freight Shipper Congestion Information/Commercial Vehicle Operations (CVO), Load Matching Systems/ Terminals and port gates	Reduces freight travel time by up to 10% *(1, 3, 4)*, Using access technology and appointments at port gates could increase by vehicle productivity by 10 to 24% (Namboothiri Cite)
2.5 Roadside Messages	Travel Time Message Signs for Travelers (DMS & VMS)	Improves trip time reliability with delay reductions ranging from 1% to 22% (*1, 5, 6)*
3.0 Vehicle Technologies		
3.1 Vehicle Infrastructure Integration	Vehicle Infrastructure Integration (VII)	Unknown benefit towards reducing congestion
3.2 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% *(32)* and reduces travel times by 4% to 10% *(1)*

Table F.1 (Continued) Key Quantitative Benefits for Operational Strategies (Categories 4 and 5)

4.0 Incident and Special Event Management		
4.1 Pre-event	Service Patrols	Can reduce incident response time by 19% to 77% and incident clearance time by 8 minutes *(4)*
4.2 Post-event	On-Scene Incident Management	Traffic incident management programs have reported reductions in incident duration from 15% to 65% (*5, 26)*
	Work Zone Management	Reduces work zone related delays by 50% to 55% *(1, 2)*
5.0 Infrastructure Improvements and Demand Optimization		
5.1 Geometric Design Treatments	Bottleneck Removal (Weaving, Alignment)	Reduces travel time by 5% to 15% *(23,52)*
	Geometric Improvements (Interchanges, Ramps, Intersections, Narrow Lanes, Temporary Shoulder Use)	Geometric improvements increase overall capacity by 7% to 22% *(25)*
5.2 Access Management	Access Management (Driveway location, Raised medians, channelization, frontage road)	Unknown benefit towards reducing congestion.
5.3 Signal Timing/ ITS	Transportation Management Center (TMC)	Reduces delay by 10% to 50% *(12, 32)*
	Signal Retiming/ Optimization	Traffic signal retiming programs result in travel time and delay reductions of 5% to 20% *(20)*
	Traffic Signal Preemption at Grade Crossings	Simulation models show that delays at grade crossings can be reduced by up to 8% *(17)*
	Traffic Adaptive Signal Control/ Advanced Signal Systems	Adaptive signal control systems have been shown to reduce peak period travel times 6% to 53% *(1)*
	Advanced Transportation Automation Systems, Signal Priority and AVL	Reduces transit delays by 12% to 21% *(1,3)*
5.4 Traffic Demand Metering	Ramp Metering, Ramp Closure	A study regarding the use of ramp meters in North America found that the mainline peak period flows increased 2% to 14% due to on-ramp metering *(51*.
5.5 Variable Speed Limits	Variable Speed Limits (VSL)	Increases throughput by 3% to 5% *(25)*
5.6 Congestion Pricing	Electronic Toll Collection (ETC)	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 *(1)*
	Cordon Pricing (Area wide)	Congestion pricing in London decreased inner city traffic by about 20% *(1)*
5.7 Lane Treatments	Managed Lanes: High-Occupancy Vehicles (HOV) lanes, High-occupancy Toll (HOT) lanes, Truck-only Toll (TOT) lanes	Provides reduction in travel times up to 16% *(25)*
	Changeable Lane Assignments (Reversible, Variable)	Unknown benefit towards reducing congestion
5.8 Multimodal Travel	Integrated Multimodal Corridors (IMC)	Unknown benefit towards reducing congestion
5.9 Travel Reduction	Travel Alternatives (Ride Share Programs, Telecommuting, Home office, Video conferences)	Unknown benefit towards reducing congestion

Strategy: 2.1. Surveillance and Detection

Category: 2. Information Collection and Dissemination

TREATMENTS AND IMPACTS:

Remote Verification (CCTV)

- 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 *(1)*.
- Traffic surveillance, lane control signs, Variable Speed Limit (VSL), and Dynamic Message Signs (DMS) in Amsterdam, Netherlands have led to a 23 percent decline in the crash rate *(5)*.
- 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 percent reduction in non-recurring congestion is reported *(3)*.

  The Automated Traffic Surveillance and Control Program in Los Angeles, CA in operation since 1984 has reported an 18 percent reduction in travel time and 16 percent increase in average travel speed *(11)*.
- Efficiency: B/C Ratio of 5.6:1 for initial operations of the The Maryland CHART program *(3)*.

It was estimated that the CCTV system installed by FDOT D4 ATMS in Fort Lauderdale, FL can reduce incident response time by 13%. *(4)*

Driver Qualification

- Safety: According to analyses of NASS (1981-85) and FARS data (1983), 58 percent of heavy-truck drivers involved in accidents did not receive prior training. For fatal accidents that number is 74 percent *(55)*.

  National estimates from NASS data (1981-85) show that 30 percent or more of truck drivers involved in hazardous cargo 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 prior to the recorded one *(55)*.

  Drivers under 25 years of age are six times more likely than other heavy-truck drivers to be involved in an accident (Hackman, et al., 1978) *(55)*.

  Studies indicate that drivers with less than a year of experience constitute 1 percent of the carrier workforce, yet account for 3 percent of the accidents (Jovanis, 1987) *(55)*.

Automated Enforcement (Speed, red-light, Toll, HOV)

- Safety: The installation of speed enforcement cameras in the UK led to a decrease in casualties by an average of 28 percent *(56)*.

  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 percent *(56)*.

  Research conducted by PA Consulting Group and University of Liverpool showed that there was a 22% reduction in personal injury collisions (PICs) at sites after cameras were introduced. Overall 42% fewer people were killed or seriously injured. At camera sites, there was also a reduction of over 100 fatalities per annum (32% fewer fatalities) *(57)*.

  Research regarding 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 *(58)*.

- Mobility: A survey of I-30 motorists (a facility with HOV lanes) in 1995 determined that the transit users perceived travel time savings as 13 minutes during the AM peak and 12 minutes in the PM peak. The I-30 carpoolers perceived they save 16 minutes during the AM peak and 13 minutes in the PM peak over the general-purpose lanes *(60)*.

  Travelers saved about 20 minutes per trip on HOT lanes on I-10 in Houston *(61)*.

  In Southern California, SR-91 customers estimated they saved nearly 30 minutes during their morning and afternoon commutes *(61)*.

  Average speed during the AM peak on the Katy Freeway in Houston, Texas was 25 mph on the general purpose lanes and 59 mph on the HOT lanes *(61)*.

- Efficiency: A four year research conducted by PA Consulting Group and University of Liverpool showed that after speed and red-light cameras were introduced there was a positive cost-benefit of around 2.7:1. 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 *(57)*.

  One study of British Columbia's automated speed enforcement program examined the avoided costs of speeding-related fatalities and injuries and concluded that it produced annual savings of over 38 million Canadian dollars *(59)*.

  Bus operating speeds have more than doubled since the opening of the HOV lanes on I-30 and I-35E North during the AM and PM peak hour, and because of the time savings the operating cost of DART buses using the lane has been reduced by approximately $350,000 per year *(60)*.

- Energy/Environment: A study conducted by NCTCOG estimated that the 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 due to the HOV lanes on each of these facilities *(60)*.
- Customer Satisfaction: Research conducted by PA Consulting Group and University of Liverpool showed that 82% of people questioned support the use of speed and red-light cameras *(57)*.

  Research regarding automated speed enforcement in Montgomery County, Maryland indicated that 74% of Montgomery County drivers thought speeding on residential streets was a problem and 62% supported the automated speed enforcement (58).

Strategy: 2.2. Probe Vehicles and Point Detection

Category: 2. Information Collection and Dissemination

TREATMENTS AND IMPACTS:

GPS, Video Detection, Microwave Radar, Transponders, Bluetooth MAC Readers

- Safety: Speed camera programs can reduce crashes by 9 to 51% *(1)*.
- A 2007 NHTSA literature review documented studies of speed camera programs worldwide, which reported crash reductions from 9 to 41 percent *(5)*.
- A study of 2 years of crash data following deployment of speed cameras at study sites throughout the U.K. found a 35 percent reduction in the number of people killed or seriously injured at camera locations and 14 percent decline in the number of personal injury crashes *(5)*.
- Mobility: A simulation experiment in one segment of Baltimore-Washington Parkway in Maryland showed the ad hoc networks can provide accurate information regarding vehicle's travel time *(8)*.
- Efficiency: In Montana, weigh-in-motion (WIM) sensors were installed directly in freeway travel lanes to continuously collect truck weight and classification data 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 *(5)*.
- Customer Satisfaction: Fifteen (15) months after extensive deployment of automated speed enforcement cameras in the United Kingdom, a nationwide survey found 70 percent of those surveyed thought that well placed cameras were a useful way of reducing crashes and saving lives, while 21 percent thought that speed cameras were an infringement of civil liberties.101 Public opinion surveys indicated 60 to 80 percent support for red light enforcement camera programs *(15)*.

Strategy: 2.3. Pre-trip Information

Category: 2. Information Collection and Dissemination

TREATMENTS AND IMPACTS:

National Traffic and Road Closure

- Mobility: A simulation study in the Washington, D.C. area found that regular users of pre-trip traveler information reduced travelers' frequency of early and late arrivals by 56 and 52 percent, respectively. (5)
- Efficiency: Modeling studies in Detroit, Michigan and Seattle, Washington have shown slight improvements in corridor capacity with the provision of traveler information (5).
- Energy/Environment: In Boston, Massachusetts, a modeling study estimated that changes in travel behavior due to better traveler information would result in a 25 percent reduction in volatile organic compounds, a 1.5 percent decline in nitrogen oxides, and a 33 percent decrease in carbon monoxide (5).
- Customer Satisfaction: During the 2002 Winter Olympic Games in Salt Lake City, Utah, a survey about the CommuterLink Web site showed that 41 percent of visitors and 70 percent of residents were aware of the Web site. Overall, 98 percent of visitors and 97 percent of residents who used the Web site said it worked well for them (5).

Planned Special Events

- Mobility: Dynamic Message Signs (DMS) 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 traveler information consisted of three "Smart Zones" that integrate DMS, detection devices, and surveillance cameras as well as 12 portable DMS and four HAR transmitters. During the first race weekend in June 2001, with approximately 45,000 fans, no significant delays entering the facility due to 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 *(20).*
- 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, has tested traveler information in the form of real-time bus departure signs and on-board 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 on-board announcements helped them decide to use the Island Explorer bus. And almost half of 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 the transit *(20)*.

Strategy: 2.4. Real-Time Information

Category: 2. Information Collection and Dissemination

TREATMENTS AND IMPACTS:

Pre-trip information by 511, web sites, subscription alerts, 511, real-time navigation systems

- Safety: ITS Deployment Analysis Systems (IDAS) models of Advanced Regional Traffic Interactive Management Information System (ARTIMIS) in Cincinnati and Northern Kentucky estimated traveler information reduced fatalities 3.2% *(1)*.
- 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 DC metropolitan area *(1)*.

  Modeling studies in Detroit, Seattle, and Washington, DC have shown slight improvements in corridor capacity with provision of traveler information *(2)*.

  Modeling performed as part of an evaluation of 9 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 *(3)*.

  A study conducted in Salt Lake City, Utah show that 511 users can reduce peak period late arrivals by 14% when compared to nonusers. The combination of 511 and DMS showed that the reductions can be up to 24% *(4)*.

  Internet traveler users saved 8.4% of travel time in San Antonio Area *(14)*.

  The Vehicle Information and Communication System (VICS) in Japan provides the latest road traffic information to drivers via car navigation systems since 1996. The Japanese Ministry of Construction estimates that with a national deployment rate of 30%, VICS would reduce traffic congestion by 6%. *(33)*.
- Efficiency: The simulation study in the Washington, DC area found that 40 percent of travelers who use pre-trip traveler information would save $60.00 or more per year *(1)*.
- Energy/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% *(1)*.

- Customer Satisfaction: An evaluation of Arizona 511 telephone traveler information system found that more than 70 percent of users surveyed were satisfied with the enhancements *(1)*

In Houston, real-time travel time information posted on Dynamic Message Signs (DMS) influenced drivers' route choice. Eighty-five (85) percent of respondents indicated that they changed their route based on the information provided. (Of these respondents, 66 percent said that they saved travel time as a result of the route change, 29 percent were not sure). Overall, drivers were primarily interested in seeing incident and travel time information *(5)*.

Road Weather Information Systems (RWIS)

- Safety: A wet pavement detection system In North Carolina on I-85 yielded a 39 percent reduction in the annual crash rate under wet conditions *(1)*.

Anti-icing systems deployed on bridges in Utah, Minnesota, and Kentucky found crash reductions from 25% to 100%. *(3)*.

In Vantage, Washington, the deployment of an automated anti-icing system on I-90 was projected to eliminate up to 80 percent of snow and ice related crashes *(5)*.

A Variable Speed Limit (VSL) system implemented along I-75 in Tennessee to control traffic during foggy conditions, and close the freeway if necessary, has dramatically reduced crashes. While there had been over 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 *(5).*

- Mobility: Signal timing plans implemented in Minnesota to accommodate adverse winter weather resulted in an 8% reduction in delay *(1)*.

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% *(4)*.

In Finland, a Road Weather Information Systems (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. *(5)*

- Efficiency: The benefit-to-cost ratios in Oregon for two automated wind warning systems were 4.13:1 and 22.80:1. *(1)*

In Salt Lake City, Utah, staff meteorologists stationed at a Traffic Operations Center (TOC) provided detailed weather forecast data to winter maintenance personnel, reducing costs for snow and ice control activities, and yielding a b/c ratio of 10:1. *(2)*

Benefit-to-cost ratios for Road Weather Information Systems (RWIS) and anti-icing strategies range from 2:1 to 5:1 *(5)*.

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, using conservative assumptions, to 24:1 or higher based on moderate assumptions *(5)*.

A study of a weather and road condition controlled system of VSL signs in Finland showed favorable results for deployment along heavily traveled road segments. The benefit-to-cost ratios ranged from 1.1:1 to 1.9:1 *(5)*.

- Energy/Environment: Evaluation data show that anti-icing and pre-wetting strategies can reduce sanding applications by 20% to 30%, decrease chemical applications by 10%, and reduce chloride and sediment runoff in local waterways. *(1)*

Winter maintenance personnel from several agencies indicated that use of RWIS decreases salt usage and anti-icing techniques limit damage to roadside vegetation, groundwater, and air quality (in areas where abrasives are applied *(5)*.

- Customer Satisfaction: Planned Special Events: 94 percent of travelers surveyed indicated that a road weather information website made them better prepared to travel; 56 percent agreed the information helped them avoid travel delays in a mountainous area of Spokane, Washington *(1)*

80% of motorists surveyed in Idaho who used Road-Weather Integrated Data System information as a traveler information resource indicated that the information they received made them better prepared for adverse weather *(2)*.

Survey results in Finland indicate that 90 percent of drivers found weather-controlled VSL signs to be useful *(5)*.

Freight Shipper Congestion Information/Commercial Vehicle Operations (CVO)/Border Technology Systems/Smart Freight/Terminals and Port Gates

- Safety: With 25 % of truck using Commercial Vehicle Information Systems and Networks (CVISN) technology, 25,000 to 38,000 crashes avoided nationally *(29)*.
- 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% *(1)*.

Simulation study at the Peace Bridge between U.S. and Canada found that time inspection of trucks equipped with electronic border crossing system would decrease by 14 to 66 percent *(3)*.

Real-time information systems can reduce travel time and costs by up to 9% based on a simulation model *(4)*.

A simulation analysis in British Columbia, Canada to study travel time savings of e-screening trucks showed savings up to $8.6 million in terms of travel time and up to 4% pavement load reduction *(15)*.

Time savings using CVO/CVISN are estimated to be 3-5 minutes per bypass *(28)*.

In Colorado, an automated commercial vehicle pre-screening system installed at three ports of entry check stations saved approximately 8,000 vehicle hours of delay per month *(2)*.

- 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 *(1)*.

With potential cost saving benefits ranging from $11.77 to $16.20 per air-freight shipment, Electronic Supply Chain Manifest could save the freight industry more than $2 billion per year *(2)*.

In Maryland, electronic screening and credentialing systems provide a B/C ratio ranging 3.28 to 4.68 *(3)*.

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 percent *(5)*.

In Washington State, it is 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 government and motor carriers *(30)*.

Use of e-seals at for a for a dedicated ITS Truck lane at the border Washington/British Columbia order indicates a B to C ratio ranging from 29:1 to 42:1. These lanes allow freight, equipped with transponders, to pass through the border with lower rate of inspection *(31)*.

A study of port controls and access appointment systems indicated technology could increase vehicle productivity by 10 to 24% and access capacity by 30%.

- Energy/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 *(1).*

  In Colorado, an automated commercial vehicle pre-screening system installed at 3 ports of entry check stations saved 48,200 gallons of fuel per month *(2)*.

- Customer Satisfaction: Carriers surveyed indicated they were very satisfied with the ability of electronic supply chain manifest systems to duplicate paper-based systems *(1).*

Strategy: 2.5. Roadside Messages

Category: 2. Information Collection and Dissemination

TREATMENTS AND IMPACTS:

Travel Time Message Signs for Travelers (DMS & VMS)/Queue Warning Systems

- Safety: San Antonio, Texas, reduction of 2.8 percent in crashes *(3)*.

As a result of queue warning system in Netherlands, a reduction of 15% to 25% in primary incidents and reduction of 40% to 50% incidents on the system was observed *(25)*.

- Mobility: Dynamic message signs with delay information were found to reduce system delay 6.7% using models of increased traffic flow at San Antonio rail crossing *(1)*.

Simulation study in Detroit, Michigan showed that DMS combined with ramp metering would reduce vehicle delay by up to 22 percent *(3)*.

ITS Deployment Analysis System (IDAS) program estimates that on average, 11 minutes per traveler can be saved by implementing DMS systems *(4)*.

Available data shows that Dynamic Message Signs and integrate 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 percent *(5)*.

A study in six European countries showed that an average of 8% of all drivers diverted from their intended route based on the information displayed by DMSs *(6)*.

As a result of queue warning system in Netherlands, throughput on facilities in the system increased between 4 to 5% *(25)*.

Research suggests that 8% to 10% of drivers react to the information provided on the DMS in Netherlands which may lead to a 0% to 5% improvement in network performance *(27)*.

- Efficiency: In South Carolina, dynamic message signs and highway advisory radio 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 percent less than the traffic volume during the return trip when inbound traffic used both sides of the freeway *(5)*.

Positive results were found by using DMS to display queue warning information. In the A8 Motorway in German, a pilot study showed fewer accidents, reduced incidents severity, harmonized speed and slightly increase in capacity *(25)*.

- Customer Satisfaction: 85% of motorists surveyed changed their route after viewing real-time travel time information on freeway dynamic message signs in Houston *(1)*.

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 DMS throughout the state. A total of 221 questionnaires were returned and analyzed. The results indicated that 12 percent of respondents used the information more than 5 times per month to adjust travel routes during winter months, and 18 percent of respondents used the information more than 5 times per month to adjust travel routes during non-winter months *(5)*.

Strategy: 3.1. Vehicle Infrastructure Integration

Category: 3. Vehicle Technologies Treatments 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 risk by four percent as a result of improved wrong turn performance and the tendency of the system to select routes with improved (normally safer) facilities *(5)*.
- Mobility: Simulation study showed that VII can reduce travel time (VHT) by 22.5% if implemented in a network system *(4)*.

Strategy: 3.2. Driver Assistance Products

Category: 3. Vehicle Technologies

TREATMENTS AND IMPACTS:

Driver Assistance Systems (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)

- 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 percent and estimated that the combined system could eliminate about 10 percent of all rear-end crashes *(5)*.

  A 1999 FHWA study suggested that lane departure warning systems have the potential to reduce road departure crashes by 10 percent for passenger vehicles and 30 percent for heavy trucks *(32)*.

  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 percent where ESC was expected to be effective *(32)*.

  Widespread deployment of integrated countermeasure systems could prevent over 48 percent of rear-end, run-off-road, and lane change crashes *(32)*.

- Mobility: In-vehicle navigation/route guidance devices can reduce travel times by 4 to 10 percent under normal traffic conditions or recurring traffic congestion *(1)*.

- Efficiency: A simulation study of roadways in Orlando, Florida found that, assuming a market penetration of 30 percent, dynamic route guidance would allow the road network to handle a 10 percent increase in vehicle volumes *(1)*.

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 *(2)*.

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 *(32).*

A NHTSA modeling study indicated that forward collision warning systems, lane change/merge crash avoidance systems, and road-departure countermeasure systems would yield and annual economic benefit of $25.6 billion *(32)*.

- Energy/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 percent during scenarios with frequent acceleration and deceleration *(4)*.

In-vehicle computer visioning technology designed to detect and warn truck drivers of lane departure and driver drowsiness reduced fuel consumption by 15 percent, increased safety, and provided drivers with more comfortable working conditions *(32)*.

- Customer Satisfaction: In San Antonio, Texas, 60 percent of drivers of paratransit vehicles equipped with in-vehicle navigation devices reported that they saved time and felt safer than using paper maps *(1)*.

Survey data collected from tractor-trailer drivers with one to three years of experience driving with intelligent vehicle safety systems—including radar-based CWS, ACC systems, and advanced electronic braking systems—indicated that invehicle safety systems lowered their perceived workload by 14 to 21 percent over a range of driving conditions (good conditions, heavy traffic, and low visibility) *(5)*.

Strategy: 4.1. Pre-event

Category: 4. Incident and Special Event Management

TREATMENTS AND IMPACTS:

Service Patrols

- Safety: The Navigator incident management program in Georgia reduced secondary crashes from an expected 676 to 210 in the twelve months ending April 2004 *(1)*.

- Mobility: Several studies showed that Service Patrols can reduce incident response by 19% to 77%. And incident clearance time by 8 min *(4)*.

  An analysis of nearly 10,000 incidents arising in the Hudson Valley region of New York State showed that the implementation of a FSP program would save approximately 33 vehicle-hours in travel delay per incident *(53)*.

  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 veh-h. Savings for assisted accidents were 20.32 veh-h/incident, and 9.35 veh-h for the non-assisted ones *(54)*.

- Efficiency: A survey conducted by the University of California, Berkeley found that the benefits of the Los Angeles Metro Freeway Service Patrols outweighed the costs by more than 8 to 1 in 2004 *(1)*.

  The Florida's Road Ranger program documented a savings of 1.7 million gallons of fuel across the state in 2004 due to incident-related delay *(3)*.

  The Hoosier Helper freeway service patrol 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 *(5)*.

  A study of two highways in Northern Virginia show that Service Patrols can reduce traffic delays and the computed b/c ratio was 5.4:1 and 4.7:1 *(6)*.

- Energy/Environment: A comprehensive evaluation of the FSP program at a San Francisco Bay Area freeway section showed a reduction of air pollutant emissions which include 77.2 tons of carbon monoxide, 19.1 tons of oxides of nitrogen and 7.6 tons of hydrocarbons *(54)*.
- Customer Satisfaction: Satisfaction with motorist assistance patrols ranged from 93% to greater than 95% in two surveys of drivers already aware of the service in Atlanta *(1)*.

Strategy: 4.2. Post-event

Category: 4. Incident and Special Event Management

TREATMENTS AND IMPACTS:

On-Scene Incident Management (Incident Responder Relationship, High visibility garments, Clear Buffer zones, Incident Screens)

- Safety: The Maryland State Coordinated Highway Action Response Team (CHART) highway incident management system facilitated a 28.6% reduction on the average incident duration leading to an estimated 377 fewer secondary incidents *(1)*.

San Antonio, Texas, Dynamic Message Signs (DMS) combined with incident management program resulted in a 2.8% reduction in crashes *(3)*.

Implementation of Closed Circuit TV (CCTV) and Service Patrols can reduce up to 20 minutes the incident response duration *(4)*.

The Coordinated Highway Action Response Team in Maryland reduced incident duration and related secondary incidents by 29 percent in 2002, eliminating 377 crashes within its coverage area *(5)*.

The expansion of the San Antonio TransGuide freeway management system had an estimated annualized crash reduction of 2.8% a year *(33)*.

- 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 one year *(1)*.

Traffic incident management programs have reported reductions in incident duration from 15 to 65 percent *(5)*.

The Netherlands incident management program has achieved a 25% reduction in process time in 4 years *(26)*.

On Toronto freeways, the COMPASS traffic management system saved 185 vehicles-hours of delay for every million vehicles kilometers of travel *(33)*.

The expansion of the San Antonio TransGuide freeway management system had an estimated annualized delay reduction of 5.7% *(33)*.

- Efficiency: An ambulance provider in Albuquerque, New Mexico increased its efficiency by 10 to 15 percent using AVL/CAD to improve route guidance *(1)*.

The HERO motorist assistance patrol program and NaviGAtor incident management activities in Georgia saved more than 187 million dollars yielding a benefit-to-cost ratio of 4.4:1 *(2)*.

Incident Management Assistance Patrol (IMAP) program in Raleigh, North Carolina shows a 4.3: 1 b/c ratio *(4)*.

- Energy/Environment: The NaviGAtor incident management program in Georgia reduced annual fuel consumption by 6.83 million gallons, and contributed to decreased emissions: 2,457 tons less Carbon monoxide, 186 tons less hydrocarbons, and 262 tons less Nitrous oxides *(1)*.

A Simulation Study in Seattle showed that incident management system with traffic information system provided a fuel economy improvement of 1.3 percent *(3)*.

- Customer Satisfaction: Transportation Management Center staff in Pittsburgh indicated that a real-time traffic information system used to monitor traffic density and congestion was useful and helped improve coverage for incident management *(5)*.

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 dynamic message signs located upstream of the work zone *(1)*.

  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 mi/hr as vehicles approached the work zone lane merge area in Nebraska *(2)*.

- Mobility: An automated work zone information system on a California interstate greatly reduced traffic demand through the work zone resulting in a maximum average peak delay that was 50 percent lower than expected *(1)*.

  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 *(2)*.

  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 *(3)*.

- Efficiency: Traffic speed data in the Minneapolis/St. Paul collected at two interstate work zones showed that when portable traffic management systems were deployed, work zone traffic volumes increased 4% to 7% during peak periods *(1)*.

  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 *(4)*.

  The use of ITS for temporary construction zone management in Lansing 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 *(5)*.

- Customer Satisfaction: A survey of local residents near Smart Work Zone systems found that over 95% would support use of these systems in the future in North Carolina *(1)*.

Strategy: 5.1. Geometric Design Treatments

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Bottleneck Removal (Weaving, Alignment)

- Safety: Bottleneck removal on I-15, north of the Seattle central business district, resulted in an accident reduction of 39% *(43)*.

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% *(51)*.

- Mobility: Bottleneck removals on US-59, Houston, I-40 and I-25, Albuquerque, I-25 and I-225, Denver resulted in an estimated total delay reduction of 19.2, 14.9 and 9.3 million hours respectively *(23)*.

  Bottleneck removal on I-17 between Union Hills Drive and Van Buren Street by adding auxiliary lanes decreased morning peak hour travel time by 1,384 passenger-hours (6%) *(52)*.

  Bottleneck removal on I-10 between 99th Avenue and 32nd Street by widening EB I-10 decreased morning peak travel time by 2,555 passenger-hours (13%) *(52)*.

  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%) *(52)*.

  Bottleneck removal on I-10 Eastbound between 24th Street and Baseline Road by constructing an EB collector-distributor road decreased evening peak hour travel time by 4,671 passenger-hours (37%) *(52)*.

- Efficiency: As part of the T-Rex Project in Denver, bottlenecks on I-25 and I-225 were removed by the 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 *(18)*.

Geometric Improvements (Interchange, Ramp, Intersections, Narrow Lanes, Temporary Shoulder Use)

- Safety: 13 case studies in Texas of minor geometric improvements showed an average reduction of 35% on injury crash rates *(24)*.
- Mobility: Assessment of temporary shoulder use a.k.a hard shoulder lane in Netherlands since 2003 revealed increased overall capacity by 7% to 22% (depending on usage levels) , decreased travel times by 1 to 3 minutes with increasing traffic volumes up to 7% during congestion periods *(25)*.
- Efficiency: 13 case studies in Texas of minor geometric improvements showed b/c ratios from 400:1 to 9:1 *(24)*.

Strategy: 5.2. Access Management

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Access Management (Driveway location, Raised Medians, Channelization, Frontage Road)

- Safety: A research undertaken by the Kentucky Transportation Center estimated that access management could reduce total statewide annual crash by over 20% *(36)*.

An access management research project conducted by the Iowa Department of Transportation in seven communities shows that after implementation of a series of access management techniques, total accidents were reduced by approximately 39 percent and rear-end and left-turn accidents were reduced by 41 and 42 percent, respectively *(37)*.

A study on New York State Route 27 indicated that access management had the potential to reduce the number of accidents by 53 percent, 77 percent, and 48 percent, respectively, for NY 27 at Unqua Road/westerly Sunrise Mall driveway, Philips Plaza driveways, and Old Sunrise Highway *(38)*.

- Mobility: Application of access management in HuaiRou County, China increased the average travel speed by 16.3% and reduced the travel delay by 25.8s *(35)*.
- A research 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 *(36)*.
- Efficiency: The 2009 Urban Mobility report identified that access management programs in 90 cities in the U.S. was able to reduce delay by a total of 61 million hours *(19)*.
- Energy/Environment: A study by 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 *(50).*
- Customer Satisfaction: A study of the effects of access management conducted in 1996 indicated that close to 80 percent of businesses reported no customer complaints about access to their businesses after project completion. Over 90 percent 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 *(49)*.

Strategy: 5.3.Signal Timing/ITS

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Transportation Management Center (TMC)

- Safety: A traffic management system in Espanola, New Mexico on NM 68 provided a decrease in total crashes of 27.5 percent and a reduction in vehicle delay of 87.5 percent *(1)*.

The Camera Deployment and Intelligent Transportation Systems (ITS) Integration project in Monroe County, New York reduced incident validation times by 50 to 80 percent saving between 5 and 12 minutes per incident *(2)*.

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 *(32)*.

The Wisconsin DOT's freeway traffic management system resulted in a decrease in crashes of 14.8 percent *(32)*.

A study of the INFORM system on Long Island, New York found a 15 percent accident reduction and a 9 percent increase in speed *(32)*.

- Mobility: A Freeway Management System in South Africa estimated by up to 48% reduction in travel times and up to 25% of additional throughput. These remarkable results were due to the combined implementation Closed Circuit TV (CCTV) systems, Dynamic Message Signs (DMS), in vehicle monitoring and toll collection (*12)*.

The Michigan Intelligent Transportation System Center reduced delays from incidents by about 40 percent and increased the speed by 8 percent *(32)*.

The Wisconsin DOT's freeway traffic management system reduced the travel time by 9, 12, and 16 percent on three separate roadway segments. AM peak period average speed increased 3 percent while volume increased 22 percent. Net savings of 1,454 driver hours per peak hour were calculated as a result of ramp metering alone *(32)*.

An estimate of average freeway incident time savings as a result of the Houston 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 *(32)*.

Because of Atlanta's NaviGAtor, 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 percent faster *(32)*.

- Efficiency: An evaluation of the effect of Wisconsin DOT's highway TMC in the Milwaukee metropolitan area on highway operations revealed 5:1 benefit-cost ratio excluding cost savings from crashes *(41)*.

A statewide TOC-based freeway management program in Maryland yielded an overall benefit-cost ratio of 7:1 *(41)*.

The Total annual delay savings at Houston TranStar, a multiagency TMC at Houston Texas, is estimated at 573,095 vehicle-hours, resulting in about $8.4 million in savings per year *(42)*.

- Energy/Environment: The Michigan Intelligent Transportation System Center lead 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 *(42)*.

Signal Retiming/Optimization

- Safety: Signal retiming in Lexington, KY, USA, reduced stop and-go traffic delays by about 40 percent and accidents by 31 percent *(39)*.

122 standard four-leg intersections on Long Island were studied for signal retiming in New York, Eight percent fewer reportable crashes were recorded during the 36 months relative to the control sites. Crashes involving pedestrians and bicyclists dropped 37 percent relative to the control group of intersections. The researchers found a 12 percent reduction in injury crashes. The experimental sites were 9 percent less likely than the controls to report multiple vehicle injury crashes *(40)*.

- Mobility: The Texas Traffic Light Synchronization Program reduced delay by 23 percent by updating traffic signal control equipment and optimizing signal timing on a previously coordinated arterial. Travel Time lowered by 14% *(1)*.

Traffic signal retiming programs resulted in travel time and delay reductions of 5 to 20 percent, and fuel savings of 10 to 15 percent across the nation *(2)*.

Traffic Signal retiming at 11 intersections on U.S. Route 1 in St. Augustine, Florida reduced delay by 36% and travel time by 10% *(3)*.

Burlington, Canada had travel time lowered by 7 percent after retiming 62 intersections *(3)*.

- Efficiency: Benefit-to-cost ratios for traffic signal optimization range from 17:1 to 175:1 *(1)*.

On San Jose Boulevard in Jacksonville, FL, retiming traffic signals at a 25-intersection section reduced average arterial delay by 35 percent, arterial stops by 39 percent and arterial travel time by 7 percent, resulting in estimated annual fuel savings of 65,000 gallons and overall annual cost savings of $2.5 million (2001 *(39)*.

On U.S. 1 in St. Augustine, FL,USA, retiming traffic signals at a 11-intersection arterial reduced average arterial delay by 36 percent, arterial stops by 49 percent and arterial travel time by 10 percent, resulting in estimated annual fuel savings of 26,000 gallons and overall annual cost savings of $1.1 million (2001) *(39)*.

- Energy/Environment: Signal retiming projects were found to reduce fuel consumption by 2 to 9% in several U.S. and Canadian cities *(1)*.

Traffic Signal Preemption at Grade Crossings

- Safety: Automated enforcement systems have reduced highway-rail crossing violations by 78 to 92 percent along two corridors in Los Angeles, California *(1)*.

In Baltimore, a ""second train coming"" warning system decreased the frequency of the most common risky behavior at crossings (i.e., drivers that crossed the tracks after the protection gates began to ascend from the first train before the protection gates could be redeployed for the second train) by 26 percent *(1)*.

- Mobility: In San Antonio, a modeling study found that if traffic congestion were to increase by 25 percent, posting nearby railroad crossing closing delays on freeway dynamic message signs would reduce total network delay by up to 6.7 percent *(1)*.

The integration of a simulation model with optimization techniques showed that delays at grade crossings can be reduced by up to 8% *(17)*

Traffic Adaptive Signal Control/Advanced Signal Systems

- Safety: The 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 percent *(45)*.
- Mobility: Adaptive signal control systems have been shown to reduce peak period travel times 6-53% by field studies in several cities *(1)*.

Adaptive signal control integrated with freeway ramp meters in Glasgow, Scotland increased vehicle throughput 20% on arterials and 6% on freeways *(2)*.

In Los Angeles, Broward County and Newark, travel time decreased by 13 to 25 percent *(3)*.

Application of ACS-Lite (FHWA adaptive control software) in Gahanna, OH; Houston, TX and Bradenton, FL resulted in travel time reductions of up to 11% and due signal timing optimization. Delay reduction were estimated to be up to 35%. *(9)*.

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 *(11)*.

The implementation of the SCOOT (adaptive control technique) System in Gasgow and Conventry, UK reduce average delay at traffic signals by approximately 12% *(33)*.

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 *(33)*.

The SCATS (Sydney Coordinated Adaptive Traffic System) deployment in Park City, Utah, reduced travel times for the AM weekday period by an average of 7.6% and 3.9% for the PM weekday period. Weekend travel times were reduced by 1.9%. Travel time stopped delay was also reduced during “SCATS On” by approximately one-half minute on the weekend to one full minute during the weekday, or 13% to 20% respectively *(44)*.

- Efficiency: The Traffic Light Synchronization program in Texas shows a benefit-to-cost ratio of 62:1, with reductions of 24.6 percent in delay, 9.1 percent in fuel consumption, and 14.2 percent in stops *(1)*.

A 2005 Oakland Metropolitan Transportation Commission analysis of its traffic signal coordination program yielded a benefit-to-cost ratio of 39:1 *(2)*.

Application of ACS-Lite (FHWA adaptive control software) in Gahanna, OH; Houston, TX and Bradenton, FL resulted in fuel savings of up to 7% *(9)*.

- Energy/Environment: An Adaptive Signal Control system in Toronto reduced vehicle emissions by 3 to 6% percent and lowered fuel consumption by four to seven percent *(3)*.

The Automated Traffic Surveillance and Control System (ATSAC) in Los Angeles reported in 1994 a 13% reduction in fuel consumption and 13% reduction in pollutant emissions *(33)*.

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 to 3 to 4 minutes with the AVL system from 7 to 15 minutes previously *(62)*.
- Mobility: In Toronto, Canada transit signal priority reduced transit delay by 30 to 40 percent and travel time by 2 to 6 percent *(3)*.

Experience in 13 cities in the U.S. and abroad show 1.5 to 15 percent improvement in bus travel time due to transit signal priority *(3)*.

In Denver, transit AVL decreased early and late arrivals by 12 and 21 percent, respectively *(1)*.

In 1998, in Portland, Oregon an automatic vehicle location system with computer aided dispatching improved on-time bus performance by 9 percent, reduced headway variability between buses by 5 percent, and decreased run-time by 3 percent *(1)*.

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 percent *(3)*.

The on-time performance (from one minute early to three minutes late) of Kansas City Area Transit Authority (KCATA) (from one minute early to three minutes late) improved from 78 % to 95 % after AVL installation *(62)*.

San Pablo Corridor 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% *(64)*.

The field operational tests of the ATSP system at the seven intersections along the state highway 82 (El Camino Real) showed that the average intersection delay for testing bus runs was reduced by 50% *(65)*.

- Efficiency: In Scandinavia, vehicles equipped with a GPS-based tracking system and on-board monitoring systems were able to reduce wasted mileage and emissions in southern and central Sweden, and increase freight movement by 15 percent *(1)*.

A Kansas DOT survey of transportation agencies found that AVL applications for highway maintenance can have b/c ratios ranging from 2.6:1 to 24:1 *(2)*.

The Winston-Salem Transit Authority reports that the AVL/CAD paratransit system has decreased operating expense by 8.5 % per vehicle mile and by 2.4 % per passenger trip *(62)*.

Kansas City Area Transit Authority's (KCATA) achieved $400,000/yr saving in supervisor labor costs because 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 *(62)*.

Sweetwater County, WY, almost doubled ridership without increasing dispatching staff by implementing AVL and CADS. Operating expenses decreased 50% per passenger mile *(63)*.

- Energy/Environment: 3. Simulation of a transit signal priority system in Helsinki, Finland indicated that fuel consumption decreased by 3.6 percent, Nitrogen oxides were reduced by 4.9 percent, Carbon monoxide decreased by 1.8 percent, hydrocarbons declined by 1.2 percent, and particulate matter decreased by 1.0 percent *(3)*.

A transit signal priority system in Southampton, England reduced bus fuel consumption by 13 percent, lowered bus emissions by 13 to 25 percent, increased fuel consumption for other vehicles by 6 percent, and increased the emissions of other vehicles up to 9 percent *(3)*.

A study estimated the impact of implementing transit signal priority (TSP) on a 3.95 mile section Columbia Pike in Arlington, Virginia indicated that during the A.M. peak period, transit signal priority could decrease fuel consumption between 1.8 percent (Express buses scenario) and 2.8 percent (Cross street buses scenario) and decrease nitrogen emissions by 1.7 percent *(66)*.

- Customer Satisfaction: Over 85 % of Smart Traveler kiosk users in Los Angeles indicated that they would continue to use the kiosks to obtain travel information *(62)*.

Rochester-Genesee Regional Transportation Authority has implemented an automated transit information system which answers 70 % of information request calls. Information request calls have increased by 80 % *(62)*.

Since the implementation of an AVL CAD system, the Winston-Salem Transit Authority reports that paratransit ridership has risen by 17.5 % and their client base has increased by 100 % *(62)*.

Strategy: 5.4. Traffic Demand Metering

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Ramp Metering, Ramp Closure

- Safety: Crash frequency increased by 26 percent after the ramp metering system on Minneapolis-St. Paul freeways was deactivated *(1)*.

A survey of traffic management centers in eight cities found that ramp metering reduced the accident rate by 24-50% *(2)*.

- 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 percent, or 54 seconds per vehicle *(1)*.

Freeway volume declined 9% and peak period throughput decreased 14% after ramp meters were experimentally turned off in the Twin Cities, MN *(2)*.

A study of the integrated freeway ramp metering an adaptive signal control on adjacent routes in Glasgow, Scotland found a 20 percent increase in vehicle throughput on the arterials and a 6 percent increase on freeways *(3)*.

A ramp closure at Gardniner Expressway in Toronto, Canada led to daily travel time savings of 225 vehicle-hours per day *(6)*.

A simulation study on I-4 segment in Orlando revealed a reduction of up to 21% in travel time when Variable Speed Limit (VSL) is used together with ramp metering systems *(13)*.

Five pilot projects were tested on the A40 motorway in Germany and results showed that congestion decreased more than 50% during peak periods and traffic incidents at the ramps decreased 40% *(25)*.

Ramp metering in Netherlands has helped regulate the flow on highways and has led to measured speed increaases and allowed capacity increases of up to 5% *(27)*.

Ramp metering at the Oakland-Bay Bridge toll facility in San Francisco, CA 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 *(51)*.

A study regarding the use of ramp meters in North America found that the mainline peak period flows increased 2% to 14.3% due to on-ramp metering *(51)*.

- Efficiency: The benefit-to-cost ratio of the Minneapolis-St. Paul ramp metering system was found to be 15:1 *(1)*.

The Minneapolis-St. Paul, Minnesota shutdown study found that freeway volumes were 10 percent higher with ramp meters than they were during the shutdown *(1)*.

A study in Glasgow, Scotland found freeway volumes increased five percent with ramp metering *(3)*.

- Energy/Environment: Ramp metering saved 2% to 55% of the fuel expended at each ramp in a simulation study in Minneapolis-St. Paul *(1)*.
- Customer Satisfaction: Most drivers believed that traffic conditions worsened when the Minneapolis-St. Paul ramp metering system was shut down and 80 percent supported reactivation *(1)*.

Fifty-nine (59) percent of survey respondents in Glasgow, Scotland found ramp metering to be a helpful strategy *(3)*.

Strategy: 5.5. Variable Speed Limits (VSL)

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Variable Speed Limits (VSL)

- Safety: VSL in England supplemented with automated speed enforcement have reduced rear-end crashes on approaches to freeway queues by 25 to 30 percent *(5)*.

  Multi-year evaluation of VSL impact on traffic safety indicates a reduction in accident numbers by as much 20% to 30% after VSL installation *(6)*.

  VSL (a.k.a speed harmonization in Europe) in the A5 motorway in German was attributed with 3% reduction in crashes with light property damages, 27% reduction in crashes with heavy material damage, and a 30% reduction in personal injury crashes *(25)*.

  In Netherlands, VSL has reduced collisions by about 16% *(25)*.

- Mobility: A road weather information system with variable speed limit signs in Finland was projected to decrease the average vehicle speed by 0.4 to 1.4 percent and reduce the annual crash rate by 8 to 25 percent *(1)*.

  The use of variable speed limits with distributed traffic signal controllers were shown to reduce bottlenecks by 20% *(4)*.

  A VSL system in Copenhagen, Denmark reduced mean vehicle speeds by up to five km/h and contributed to smoother traffic flow *(5)*.

  The analysis of a European motorway equipped with VSL and controlled algorithms thresholds showed that critical occupancy is shifted to higher levels, enabling higher flows *(6)*.

  A simulation study on I-4 segment in Orlando revealed a reduction of up to 21% in travel time when VSL is used together with ramp metering systems *(13)*.

  Simulation study on I-66 and I-95 Northern Virginia showed that VSL together with Hard Shoulder resulted in travel time savings of up to 7 min per vehicle *(16)*.

  In Netherlands, VSL implementation has increased throughput 3% to 5% and reduced the cost of work zone traffic control *(25)*.

  A study in Germany found that VSL could increase the total capacity of a freeway by 10% *(34)*.

- Efficiency: A VSL system in Copenhagen, Denmark reduced mean vehicle speeds by up to five km/h and contributed to smoother traffic flow *(5)*.

- Energy/Environment: Simulation study on I-66 and I-95 Northern Virginia showed that VSL together with Hard Shoulder resulted in fuel savings of up to 4.5 mpg *(16)*.

  The researchers studied air quality along a section of the Amsterdam ring road, where 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 per cent *(46)*.

  The American Trucking Association indicates that bringing speed limits for trucks down to 65 mph would, at a minimum, save 2.8 billion gallons of diesel fuel and reduce CO2 emissions by 31.5 million tons in a decade. Limiting car speeds to 65mph would, at a minimum, reduce gasoline consumption by 8.7 billion gallons and CO2 emissions by 84.7 million tons over the same 10-year period *(47)*.

  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 NOx emission in a 24-hr period can be reduced by approximately 17 percent *(48)*.

- Customer Satisfaction: A survey of motorists in Copenhagen, Denmark found that 80 percent of respondents had favorable impressions of VSL and traveler information posted on Dynamic Message Signs (DMS) near a work zone *(5)*.

Strategy: 5.6. Congestion Pricing

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Electronic Toll Collection (ETC)

- Safety: Addition of Open Road Tolling (ORT) to an existing Electronic Toll Collection mainline toll plaza in Florida decreased crashes by an estimated 22% to 26% *(1)*.

- Mobility: The Addition of Open Road Tolling to an existing Electronic Toll Collection 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 *(1)*.

  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 percent and have minimal impacts on non-turnpike diversion routes *(5)*.

  Simulation studies on the New Jersey Turnpike showed that if 10% discount is applied to off peak electronic tolls , an 8.5 % delay reduction can be observed *(6)*.

- Efficiency: New Jersey's Turnpike EZ-Pass provided 1.2 million gallons annual fuel savings across 27 tolling locations *(3)*.

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 *(4)*.

On the Oklahoma Turnpike, the cost to operate an ETC lane is approximately 91 percent less than the cost to staff a traditional toll lane *(5)*.

A b/c analysis performed for an ETC in Taiwan revealed a b/c ratio of 3.23:1 in terms of user benefits *(10)*.

- Energy/Environment: An evaluation of electronic toll collection systems at three major toll plazas outside Baltimore, Maryland indicated these systems reduced environmentally harmful emissions by 16% to 63% *(1)*.
- Customer Satisfaction: "1. 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 *(1)*.

Public support in California for variable tolling on SR91 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 *(2)*.

Cordon Pricing (Area wide)

- Mobility: During the first few months of the Congestion charging program in London, automobile traffic declined by about 20 percent 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 percent after approximately one year after the system was implemented. Average traffic speed during charging days (including time stopped at intersections) increased 37 percent, from 8 mi/hr (13 km/hr) prior to the charge, up to 11 mi/hr (17 km/hr) after pricing was introduced *(1)*.

After 3 years of operation, access control zone in the historic core of Rome revealed a decrease by 15% to 20% in traffic, increase on average speeds by 4% and public transportation use increase by 5% percent *(27)*.

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 *(27)*.

- Efficiency: Congestion pricing in London decreased inner city traffic by about 20 percent and generates more than £97 million each year for transit improvements *(1)*.

Cordon charging in London increased bus ridership by 14 percent and subway ridership by about 1 percent. Taxi travel costs declined by 20 to 40 percent due to the reduced delays which enabled taxi drivers to cover more miles per hour, service more riders, and decrease operating costs per passenger-mile *(1)*.

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 *(5)*.

- Energy/Environment: Congestion charging in London led to reductions in emissions of 8 percent in oxides of nitrogen, 7 percent in air born particulate matter, and 16 percent in carbon dioxide when compared to data from 2002 and 2003 prior to the introduction of congestion charging *(5)*.
- Customer Satisfaction: In May 2003, members of the London First business group were surveyed, a group of approximately 500 business. The results indicated that 69 percent of respondents felt that congestion charging had no impact on their business, 22 percent reported positive impacts on their business, and 9 percent 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 *(1)*.

Strategy: 5.7. Lane Treatments

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Managed Lanes: High-Occupancy Vehicles (HOV) lanes, High-occupancy Toll (HOT) lanes, truck only lanes, Truck-only Toll (TOT) lanes, HOV By-Pass Ramp

- Safety: A study by the Texas Transportation Institute (TTI) suggested that HOV lanes increased the number of auto accidents, either in the lane or in adjacent regular lanes. In Dallas, accidents involving injury have increased by 56% in HOV zones since they were built in the 1990s *(22)*.
- Mobility: A study show that the implementation of Super HOT concept (freeway pricing strategy and managed lanes system) in the Los Angeles, CA and Atlanta, VA areas would reduce peak period congestion delay by up to 33h and 28h per traveler annually *(7)*.

  A Study for Houston HOV lanes showed that the average daily directional peak period savings ranged from around $8,300 to over $50,000 per corridor. The Katy Freeway HOV lane produced the most savings in both the AM and PM peak periods, with approximately $81,000 per day in savings. The Southwest Freeway HOV lane had the least amount of savings during both the AM and PM 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 *(21)*.

  HOV lanes on M606-M62 HOV gate in the U.K. has provide approximately 16% reduction in travel times *(25)*.
- Efficiency: A study show that the implementation of Super HOT concept (freeway pricing strategy) in the Los Angeles, CA and Atlanta, VA areas would save each traveler by up to 83 and 70 gal of fuel annually *(7)*.

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 due to crash reductions that would be equal to the cost of the system within two to three years of deployment *(1)*.
- Mobility: An assessment made on the basis of a before/after study indicated that the Changeable Lane Assignments on the A3-A86 motorway East of Paris saved daily travel time by 1204 hours *(67)*.
- The creation of an emergency vehicle and public transport lane on the A48 (Grenoble, France) reduced the travel time for buses during the morning peak period by 16% *(67)*.

Strategy: 5.8. Multimodal Travel

Category: 5. Infrastructure Improvements and Optimization

TREATMENTS AND IMPACTS:

Integrated Multimodal Corridors (IMC)

- Mobility: The implementation of the IMC in Oakland, CA (I-888) is expected to reduce freeway congestion by at least 10 percent. Moreover, overall freeway travel time reliability will be improved by the same amount *(1)*.

  As a result of the implementation of the Lund Link (IMC in Lund, Sweden) in 2003, public transportation ridership has increased by 20% in the corridor and about 120 new car parking spaces have been avoided *(27)*.

Travel Alternatives - Reduction in Trips/Diversion to other times (Ride Share Programs, Telecommuting, Home office, video conferences)

- 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 $1.00 toll by using the HOV toll bypass lane *(68)*.

  A study in 1993 found that the average one-way commute for those who work inside the Standard Statistical Metropolitan Areas (SMSA) is 22.8 minutes, while the average round-trip urban commute is 45 minutes. The study predicts over 800 million hours in saving of the commuter time annually due to lessened congestion, and a reduction of 696 million vehicle hours in congestion due to the practice of telecommuting *(73)*.

- Efficiency: Employees telecommuting two days a week can save companies 15 to 25 percent in higher productivity, as well as decrease turnover, reduce space requirements, and decrease sick-time usage by two days, resulting in a total savings per employee of an estimated $12,000 annually *(71)*.

  The telecommuting program at the city of Los Angeles resulted in a $6,100 annual cost-benefit to the city per telecommuter *(74)*.

  Georgia Power, Located in Atlanta implemented a pilot telecommuting program in 1992. This pilot program saved approximately $100,000 in leased office space *(74)*.

  Move Media, which is located in West Hollywood, was estimated to have saved approximately $30,000 per year in reduced overhead expenses through telecommuting efforts *(74)*.

- Energy/Environment: 69. 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 *(69)*.

  A study done by the Metropolitan Washington Council of Governments of four transportation emission reduction measures found that its Telework Resource Center (a program that assisted businesses in implementing telecommuting) was estimated to reduce NOx emissions by .9 tons per day, and VOC by .5 tons per day *(71)*.

  A survey of an AT&T Telework Program indicates that in 2000 the program saved 5.1 million gallons of gas and also resulted in a reduction of 50,000 tons of carbon dioxide emissions *(72)*.

  A 1993 US Department of Transportation study estimated that 5.2% of the work force telecommuting 3–4 days/week would save 1.1% of national fuel consumption *(72)*.

- Customer Satisfaction: BC Tel/Telus has had a ridesharing 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 percent of participants said they were very or quite satisfied with the carpooling program *(70)*.

- BC Hydro Telecommuting Project piloted telecommuting from October 1993 to June 1994. At the end of the pilot 100% of the telecommuters responded that they wanted to continue to telecommute while 95% of manages wanted their employees to continue with 5% being neutral *(70)*.

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APPENDIX G– **Cost Information of Travel-Time Reliability Strategies**

Strategy: 2.1. Surveillance and Detection

Category: 2. Information Collection and Dissemination

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Remote Verification (CCTV)	Medium	6	14	1.2	1.8	- Monroe County, NY, deployed five CCTV cameras at high priority intersections at a cost of $279,338.
Driver Qualification	Low	N/A	N/A	N/A	N/A	- 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.

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along an important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Intergrated Multimodal Corridors, etc)

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Strategy: 2.2. Probe Vehicles and Point Detection

Category: 2. Information Collection and Dissemination

Treatments and Impacts	**Overall Cost Range*** **Low - <200K** **Medium - >200K but < 1 million** **High - >1 million**	**(Unit)** Capital Cost ($K)**		**(Unit)** Operation Cost/year ($K/yr)**		**General Cost Info (1, 2, 3)**
		Low	**High**	**Low**	**High**	
GPS, Video Detection, Microwave Radar, Bluetooth MAC Readers	Low	15	20	1.5	2	- The city of 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 DOT added a traffic camera system to fight congestion at two of the busiest intersections in the Puget Sound area.

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 2.3. Pre-trip Information

Category: 2. Information Collection and Dissemination

Treatments and Impacts	**Overall Cost Range*** **Low - <200K** **Medium - >200K but < 1 million** **High - >1 million**	**(Unit)** Capital Cost ($K)**		**(Unit)** Operation Cost/year ($K/yr)**		**General Cost Info (1, 2, 3)**
		Low	**High**	**Low**	**High**	
National Traffic and Road Closure Information	Low-Medium	N/A	N/A	N/A	N/A	
Planned Special Events Management	Low-Medium	N/A	N/A	N/A	N/A	

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 2.4. Real-Time Information

Category: 2. Information Collection and Dissemination

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Pre-trip information by 511, web sites, subscription alerts, radio (HAR)	Variable	100 (for 511) 16 (for HAR)	1000 (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): average 1.8 million-2.5 million (six State and Tampa, Southeast Florida, and Central Florida). - 511 in Alaska (develop and implement): 1.2 million - Advanced traveler information system in Pennsylvania costs $8.2 million - The highway advisory radio (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 (RWIS)	Low-Medium	25	25	0.4	2.5	- Washington State Department of Transportation (WSDOT) installed a system in the mountainous region of Spokane to collect and communicated weather and road conditions, border crossing, and other information. The total cost was $446,807. - Automated wind warning systems in Oregon costs approximately $90,000 each and annual O&M 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 (CVO)	Low	121	261	10	20	

Notes:
***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along an important route.
******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Intergrated Multimodal Corridors, etc)

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Strategy: 2.5. Roadside Messages

Category: 2. Information Collection and Dissemination

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Travel Time Message Signs for Travelers (DMS & VMS)	High	38	94	2	5	- In Orange County, California, the cost of software for posting travel times on dynamic message signs (DMS) was $50,000.

Notes:
***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.
******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 3.1. Vehicle Infrastructure Integration

Category: 3. Vehicle Technologies

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Vehicle Infrastructure Integration (VII)	Low-High	9.6	20.3	1	2	

Notes:
***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.
******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 3.2. Driver Assistance Products

Category: 3. Vehicle Technologies

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		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

Notes:
***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.
******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 4.1. Pre-event

Category: 4. Incident and Special Event Management

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Service Patrols	High	N/A	N/A	810	990	- Operating a freeway service patrol program cost $2.4 million for 2005 in Southeast Michigan. - Colorado DOT launches service patrol program along I-70; 2005 operating costs are $1.5 million.

Notes:
***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.
******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

References:
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2 Robert P. Maccubbin, Barbara L. Staples, Firoz Kabir, Cheryl F. Lowrance, Michael R. Mercer, Brian H. Philips, Stephen R. Gordon. Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned: 2008 Update. FHWA-JPO-08-032. Sep., 2008.
3. Hadi, M. and Sinha, P. Intelligent Transportation System Deployment Analysis System Customization: Technical Memorandum No.4 - Florida-Specific Intelligent Transportation System Deployment Costs. Florida DOT, Traffic Engineering and Operations Office, ITS Section. Aug., 2005

Strategy: 4.2. Post-event

Category: 4. Incident and Special Event Management

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
On-Scene Incident Management (Incident Responder Relationship, High visibility garments, Clear Buffer zones, Incident Screens)	High	2400	3450	515	341	- The integrated freeway/incident management system covering 28.9 miles in San Antonio 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 (AHTD) leased an automated work zone information system in West Memphis for $495,000. - The ITS work zone system cost $1.5 million in Albuquerque, NM, $2.4 million in Lansing, MI. - 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, the majority of work zone ITS cost between $150,000 and $500,000.

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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3. Hadi, M. and Sinha, P. Intelligent Transportation System Deployment Analysis System Customization: Technical Memorandum No.4 - Florida-Specific Intelligent Transportation System Deployment Costs. Florida DOT, Traffic Engineering and Operations Office, ITS Section. Aug., 2005

Strategy: 5.1. Geometric Design Treatments

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Bottleneck Removal (Weaving, Alignment)	Medium-High					
Geometric Improvements (Interchange, Ramp, Intersections, Narrow Lanes, Temporary Shoulder Use)	Medium					

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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3. Hadi, M. and Sinha, P. Intelligent Transportation System Deployment Analysis System Customization: Technical Memorandum No.4 - Florida-Specific Intelligent Transportation System Deployment Costs. Florida DOT, Traffic Engineering and Operations Office, ITS Section. Aug., 2005

Strategy: 5.2. Access Management

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Access Management (Driveway location, Raised medians, channelization, frontage road)	Low					

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 5.3.Signal Timing/ITS

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Transportation Management Center (TMC)	High	2400	3450	515	341	- A new traffic management system in Espanola, New Mexico costed $862,279. - TMC physical components in Lake County, Illinois costed $1.8 million.
Signal Retiming/ 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 MTC (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 AVL	Low-Medium	10	14	0.34	0.46	

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 5.4. Traffic Demand Metering

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Ramp Metering, Ramp Closure	Low-Medium	19	31	0.94	2.2	- A freeway ramp metering system in Denver, Colorado costed $50,000. - Minnesota DOT estimated ramp metering operations for FY 2000 were $210,000.

Notes:
***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.
******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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3. Hadi, M. and Sinha, P. Intelligent Transportation System Deployment Analysis System Customization: Technical Memorandum No.4 - Florida-Specific Intelligent Transportation System Deployment Costs. Florida DOT, Traffic Engineering and Operations Office, ITS Section. Aug., 2005

Strategy: 5.5. Variable Speed Limits (VSL)

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Variable Speed Limits (VSL)	Low-Medium	3.7	5	0.3	0.5	- A variable speed limit system consisting of multiple ITS components and covering 40 miles over the Snoqualmie Pass in Washington was designed and implemented for $5 million.

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Intergrated Multimodal Corridors, etc)

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2 Robert P. Maccubbin, Barbara L. Staples, Firoz Kabir, Cheryl F. Lowrance, Michael R. Mercer, Brian H. Philips, Stephen R. Gordon. Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned: 2008 Update. FHWA-JPO-08-032. Sep., 2008.

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Strategy: 5.6. Congestion Pricing

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Electronic Toll Collection (ETC)	High	17	31	0.47	0.94	- 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. 4.A limited-access tolled expressway featuring express electronic toll collection (ETC) lanes and open road tolling (ORT) in In Florida costed $237 million.
Cordon Pricing (Area wide)	Low-Medium					- London congestion pricing annual O&M costs are estimated at £92 million.

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 5.7. Lane Treatments

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Managed Lanes: High-Occupancy Vehicles (HOV) lanes, High-occupancy Toll (HOT) lanes, Truck-only Toll (TOT) lanes	Medium-High					- Cost to convert two reversible high-occupancy vehicle lanes on an eight-mile stretch of the Interstate-15 in San Diego to high-occupancy toll lanes was $1.85 million. - Cost estimates of operational concepts for converting HOV lanes to managed lanes on I-75/I-575 in Georgia range from $20.9 million to $23.7 million
Changeable Lane Assignments (Reversible, Variable)	Medium-High	34	62	3.25	6	

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 5.8. Multimodal Travel

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Integrated Multimodal Corridors (IMC)	High	2400	3450	515	341	

Notes:

***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.

******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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Strategy: 5.9. Travel REDUCTION

Category: 5. Infrastructure Improvements and Demand Optimization

Treatments and Impacts	Overall Cost Range* Low - <200K Medium - >200K but < 1 million High - >1 million	(Unit)** Capital Cost ($K)		(Unit)** Operation Cost/year ($K/yr)		General Cost Info (1, 2, 3)
		Low	High	Low	High	
Travel Alternatives (Ride Share Programs, Telecommuting, Home office, video conferences)	Low	N/A	N/A	N/A	N/A	

Notes:
***** Overall Cost Range applies to the application of a treatment in roadway segment or corridor. For example, several DMS can be installed along a important route.
******Unit costs were found by adding the unit cost of different equipment for each treatment. This methodology does not apply to all treatments (e.g., TMC, Integrated Multimodal Corridors, etc.)

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