Does Travel Time Reliability Matter?

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16. Abstract

This primer provides an overview of the concept of travel time reliability, including why we should care about reliability and how to define and measure it. The primer also describes the cost of an unreliable system to businesses, the traveling public, and local governments and how lack of reliability can impair safety and security. Lastly, practical strategies and actions for creating and maintaining a reliable transportation system are provided along with case study examples of successful State and local efforts. This information is intended to better communicate the concept of reliability and help transportation systems management and operation professionals in designing their own approaches to improving travel time reliability in their area.

This primer is based on information from an extensive literature search and review, which located national and international publications addressing the importance of reliable transportation systems, consequences of unreliability, and successful solutions to improve reliability.

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Executive Summary

The transportation system is effective only if it is reliable. With the right mix of strategies to manage traffic and demand and respond to disruptions, road users can better predict travel time and reach destinations on time.

Unreliable transportation affects communities and commerce:

BUSINESS

TRAVELING PUBLIC

LOCAL GOVERNMENT

Travelers depend on the U.S. transportation system every day to get to work and to special events, acquire and deliver goods and services, and respond to emergencies. If the system operates as expected and enables travel within a predictable amount of time, we can rely on it. When it doesn't, we can't. This lack of reliability affects our health, jobs, families, relationships, cost of consumer goods, emergency response times, and the amount of time we have for other things. So, does travel time reliability matter? Yes. But what is travel time reliability really, what are the impacts of unreliable travel time, how do we measure it, and what can be done to improve reliability? These are the key questions addressed in this primer.

This primer starts by explaining the need to invest in reliability. Next, it defines travel time reliability, factors that affect reliability, and the relationship between reliability and congestion. From there, an explanation of how to measure and quantify reliability is provided, including various metrics and types of data that can be collected using various methods. The primer then describes the cost of an unreliable system to businesses, the traveling public, and local governments and how lack of reliability can impair safety and security. Lastly, practical strategies and actions for creating and maintaining a reliable transportation system are provided, along with case study examples of successful State and local efforts. This information is intended to assist transportation systems management and operations (TSMO) professionals in designing their own approaches to improving travel time reliability in their area and to help them better understand and explain travel time reliability to gain support for their efforts.

This primer is based on information from an extensive literature search and review, which located national and international publications addressing the importance of reliability, consequences of unreliability, and successful solutions to improve reliability in transportation and other industries. In addition to information from scientific journals and conferences, a wealth of information was collected from Federal Highway Administration (FHWA) and Second Strategic Highway Research Program Reliability Solutions publications.

Key findings from the literature review on travel time reliability that are presented in this primer include the following:

1. Travel time reliability is a relatively new concept and is being introduced as an additional factor in transportation planning and management.
2. An unreliable transportation system has adverse effects on the social, economic development, environmental, safety, health, and other aspects of communities and jurisdictions.
3. Improving travel time reliability requires integrating business processes as well as organizational and institutional changes in transportation agencies and among other stakeholders. The use of technology, better communication among agencies, training of first responders, and the changing of travel data into intelligence are a few strategies that can improve travel time reliability.
4. Plentiful information on travel time reliability is available to transportation professionals; however, educating decisionmakers and communicating to them the value of investments in improving reliability remains a challenge.

Additional resources that complement this primer, including presentation slides, a printable factsheet, flyer, and short video, are available online from the FHWA TSMO website (see **https://ops.fhwa.dot.gov/tsmo/**).

Visit the FHWA Transportation Systems Management and Operations (TSMO) website for more information:

https://ops.fhwa.dot.gov/tsmo/

Why Invest in **Travel Time Reliability?**

Drivers need a reliable transportation system to plan trips and reach destinations on time.

Reliability is important with all types of regular services:
utilities,
pay schedules,
package delivery, etc.
The same is true for the transportation system.

Have you ever been stuck in unexpected traffic on your regular commute? Or, have you been late getting your kids to school or going to a game, concert, or special event because of an incident on a route you've traveled hundreds of times before in less time? If it happens once or twice, you may think nothing of it (or consider leaving a bit earlier). But, if it happens a lot and in an unpredictable pattern, you become unsure of how much time you really need to get where you're going. Perhaps you budget even more time for your trip—time you have to take away from other things, like family or sleep. In truth, you can't rely on the transportation system you're traveling on to get where you're going in a reliable amount of time; you lack *travel time reliability*.

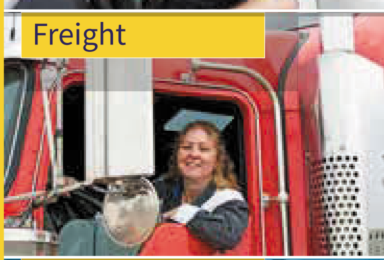
You depend on other types of reliable services, such as utilities, pay schedules, and on-time package delivery. Your life is impacted when these services are unreliable. The same is true for the transportation system. Longer-than-expected travel times could mean arriving late for work or meetings, incurring additional childcare fees, missing medical appointments, failing to catch a flight or a bus, or missing a college entrance or employment interview, among other important events. If you are an employee whose schedule affects many others, like a teacher or a pilot, or an hourly worker whose pay is docked for being late, then travel time reliability is critically important to you.

For businesses that depend on reliable transportation to deliver goods and services, delayed shipments and disrupted supply chains can have severe economic implications. Transit providers depend on reliable transportation to stay on schedule and meet expectations of transit users. Emergency responders need reliable roadways to immediately respond to incidents and carry injured motorists to local hospitals as quickly as possible. Unreliable travel time can have far-reaching impacts because road users are caught in unexpected delays or congestion, which cause stress and disrupt travel plans and scheduled activities, impede the effectiveness of emergency response, delay on-time delivery of goods and services, and reduce the quality of life of road users.

How Does Travel Time Reliability Affect Me and My Community?

Reduces Survival Rates

First responder response time is one of the most decisive factors that determines mortality rates. During cardiac arrest, survival rate decreases by **7–10 percent** for every minute of delay.[1]

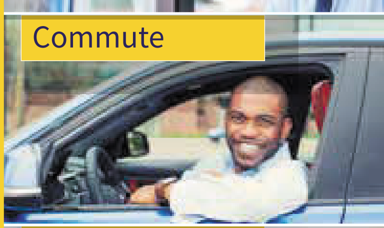


Increases Cost of Consumer Goods

Shippers and carriers value transit time at $25–$200 per hour, which can increase by **50–250 percent** during unexpected delays.[2] In Washington State, **60–80 percent** of these costs are transferred to consumers.[3]

Impacts Public Transportation Costs

Over the course of a year, the monetized opportunity cost of an unreliable transit service in the Dash route in Denver, CO, was estimated to be **$699.40** per user.[4]



Harms Worker Performance

Per recent studies, unpredictable travel time can adversely affect worker performance, including **tardiness**, **absenteeism**, **decrease in concentration**, **exhaustion**, and **stress**.[5,6]

Disrupts Time with Family and Friends

Recurring and non-recurring delays in 2014 caused urban Americans to travel an additional **6.9 billion hours** annually—over **51 hours per commuter**.[7,8]

What is Travel Time Reliability?

The U.S. Department of Transportation (USDOT) defines reliability as “the degree of certainty and predictability in travel times on the transportation system.”

Defining Reliability

Travel time reliability is a measure of the consistency, timeliness, predictability, and dependability of a trip.

The term *reliability* has different meanings in different fields of study and even within the context of road transportation systems. For our purposes, however, this primer will adopt USDOT’s definition of reliability, which defines it as “the degree of certainty and predictability in travel times on the transportation system. Reliable transportation systems offer some assurance of attaining a given destination within a reasonable range of an expected time. An unreliable transportation system is subject to unexpected delays, increasing costs for system users.”[9]

Travel time reliability is a measure of the consistency or dependability in the travel time of a trip, or time to traverse a road segment, as experienced in different hours of the day and days of the week.[10] It is measured in terms of the additional time (i.e., time cushion or buffer) that drivers need to allocate to compensate for unexpected delays. Travel time reliability is an important measure for commuters, transit riders, shippers, and other road users because it allows them to make better decisions regarding the use of their time. For example, shippers and freight carriers require predictable travel times to deliver goods and services on time. The concern is not just that travel time is excessive due to rush-hour congestion (i.e., mobility being lower than the desired level) but also that travel time is unpredictable as a function of time or road segment.

Traditionally, travel time has been communicated in terms of historical *averages* calculated over periods of a year or longer (e.g., annual average peak hour travel time). However, road users experience variations in travel time on a daily or weekly basis due to traffic, roadway, and weather conditions. Travelers are more likely to remember the few days they suffered excessive delays versus their average travel times, as shown in figure 1.[10]

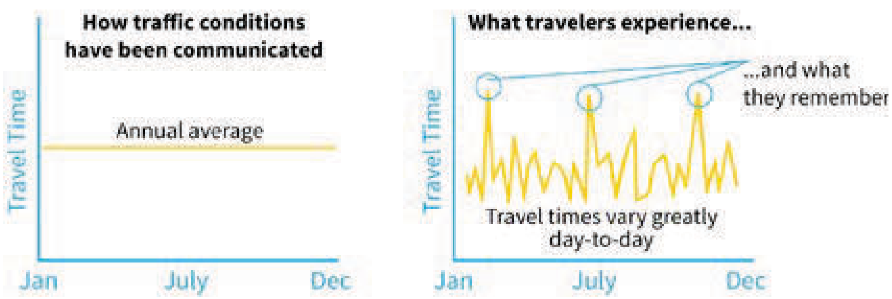


Figure 1. Average travel time and actual travel time experience.[10]

Variability in travel time can take two forms: (1) day-to-day and (2) within-day. Day-to-day travel time variation refers to changes in travel time when departing at the same time each day. Within-day travel time variability refers to changes in travel time between the same origin and destination at various times of the day. Typically, travel time is shorter during off-peak hours than during peak commuting hours, resulting in variation in travel time within the same day. Road users, passenger travelers, transit providers, and shippers are concerned with and interested in the time-of-day and day-to-day variation of travel time.

FACTORS THAT AFFECT RELIABILITY

Several factors can affect travel time reliability, namely the following sources of traffic congestion:[11,12]

RELIABILITY VS. CONGESTION

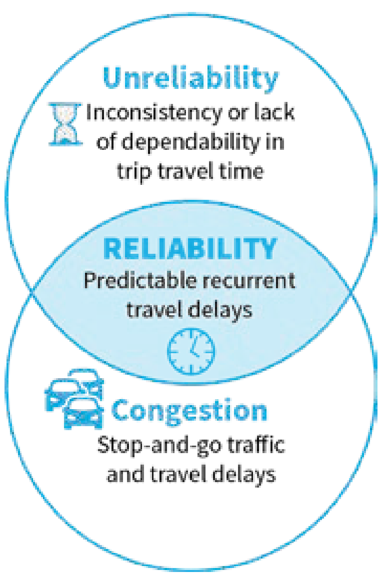
Congestion is a traffic condition characterized by slower speeds, longer travel times, and the occurrence of vehicle queues (wait lines). It can be recurrent (repeating often) or non-recurrent. Recurrent congestion includes delays that are predictable in frequency and extent (e.g., rush-hour traffic). Conversely, non-recurrent congestion is due to unexpected delays from temporary drops in road capacity (e.g., blocked lane due to a crash or work zone) or sudden surges in demand (e.g., planned special events).

Lack of reliability is different from congestion, though it is related to non-recurrent congestion. Reliability refers to the predictability of journey travel times. A highway prone to unexpected delays is unreliable. On the other hand, a highway that is typically congested and where traffic speed is consistently low can be reliable.

High levels of congestion, however, increase the likelihood of unreliability.[13] If roads are highly congested, a slight disturbance of traffic flow can result in excessive delays, have a greater impact, and take longer to recover than in a non-congested area. Therefore, lack of reliability in travel time is associated with delays caused by congestion, specifically with delays from non-recurrent events.

Congestion and reliability are so closely related that improvements in congestion can improve travel time reliability as well. For example, a bypass around Stockholm reduced delay and improved reliability. In fact, the monetary benefits of the reliability improvement were an additional 15 percent of the benefits of the delay reduction itself.[14]

How are Reliability and Congestion Related?



1. **Bottlenecks** refer to road segments that exhibit reduced traffic capacity when compared to the capacity of upstream road segments. Typical bottlenecks include lane drops, changes in alignment (e.g., horizontal curves), presence of merge and weave sections, changes in physical road characteristics (e.g., tunnels), freeway-to-freeway interchanges, hills, geometric changes, and access points to residential or commercial developments. Strategies that mitigate the effect of bottlenecks include demand management at upstream locations, efficient signage treatments, and provision of real-time traffic information and alternative routes for travelers.
2. **Traffic-control devices** are used to inform, guide, and control the flow of traffic (both vehicles and pedestrians). Malfunctioning, ineffective, or inefficient traffic-control devices cause intermittent traffic flow disruption, which, in turn, causes delays and unreliable travel time. Common problems with traffic-control devices include use of improper devices; improper device placement; use of wrong color, shape, and size; poorly timed devices; poor maintenance; and device failure. Proper maintenance and use of traffic-control devices can significantly reduce delays from this type of congestion.
3. **Weather** includes adverse weather conditions such as heavy rain, fog, snow, and wind, as well as seasonal variations such as glare from the position of the sun. These weather conditions interfere with the visibility of traffic-control devices and lane delineations, which can lead to significantly reduced capacity and result in non-recurrent congestion and delays. Weather also affects driver behavior (e.g., leave longer following distances, slow down, and change lanes). Strategies to address this non-recurrent congestion include adjusting signal timing and using efficient road clearing practices to return roadways to full operating capacity both during and after adverse weather.
4. **Work zones** are areas where roadway construction activities result in temporary physical changes to the highway environment. Factors that create delays in work zones include lane closures, lane width reductions, lane configurations, type and duration of work, work intensity, presence of police enforcement, pavement condition, and work zone length. Long-term work zones tend to have less effect on disrupting traffic compared to short-term work zones, since road users become familiar with the changed traffic pattern. Mitigation strategies for congestion due to work zones include reducing

work zone duration, keeping lanes open, and reducing other incidents induced by work zones, such as crashes.

5. **Traffic incidents** are random events that disrupt the regular flow of traffic, causing a reduction in roadway capacity. These events include crashes, vehicle breakdowns, spilled loads, and debris. In addition to reduced road capacity due to lane blockage by the incident or the responders, drivers tend to slow down near an incident to observe it (i.e., rubbernecking), which further exacerbates delays due to the incident. Time delayed due to incidents depends on the number of lanes blocked, duration of the incident, and level of travel demand at the time of the incident. On average, during a multiple-lane incident, travel time increases by as much as 205 percent compared to traffic conditions with no incidents.[15] Minimizing the lanes blocked by the incident, decreasing clearance time, and shielding incidents from the view of drivers are some techniques that decrease the effect of non-recurrent congestion due to traffic incidents.
6. **Travel demand fluctuations** are the daily and seasonal variations in travel demand that result in increased travel compared to regular traffic. For example, seasonal variations could be due to holidays, part-year residents moving out or tourists coming in, or school-related traffic during the school year at the beginning and end of the school day. In some studies, an additional travel demand of more than 5 percent of the average traffic volume is considered as higher demand than regular traffic. Demand management strategies, such as diverting excess traffic to alternate routes and promoting use of public transportation facilities, can help alleviate congestion from increased demand.
7. **Special events** can lead to sudden changes in travel demand. The resulting traffic condition will be significantly different from regular trends, causing unexpected delays. Non-recurrent congestion due to special events happens near arenas, conference centers, stadiums, and other public gathering places due to a sudden surge in demand during a short period of time (typically shortly before the event starts and after it finishes). Strategies to mitigate this type of congestion include diverting the non-event traffic, temporarily increasing capacity in the major direction of travel, and controlling on-off ramps to limit traffic entering or leaving a freeway.

The first two sources can be treated as recurrent congestion (i.e., repeating often) and the rest as non-recurrent congestion.

More than half of total congestion can be attributed to non-recurrent sources.

Data from 2008 in Atlanta, GA, showed that more non-recurrent congestion (unreliability) existed in peak periods than recurrent congestion. Primary causes included crashes, debris, and weather.(11)

According to USDOT's *2013 Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance*, more than half of total congestion could be attributed to non-recurrent sources.(16) Similar statistics were also reported by the *2015 Urban Mobility Scorecard*.(17)

Measuring Reliability

Travel time reliability is a key indicator of the efficiency of a transportation system, and improving it is a prime objective for transportation agencies. The first steps toward improvement include measuring travel time reliability and quantifying it objectively to determine the current level of reliability.

MEASUREMENT DATA

Travel time reliability studies require quality travel time data. Travel time reliability cannot be directly measured; rather, it is calculated from travel time data. Travel time is the time taken by a vehicle to traverse a route between two points of interest (e.g., the origin and destination). It is measured by noting the time a trip began and the time the destination was reached. It can also be measured by dividing the distance between the two points of interest by an average speed. Travel time includes running time, which is time spent while a vehicle is in motion, and stopped delay time due to traffic-control devices (e.g., red lights) and other operational delays (e.g., congestion).

Methods for measuring travel time include vehicles equipped with Global Positioning System (GPS) and cellular devices, license plate matching, aerial photogrammetry, vehicle-detecting devices, and road-user experience surveys. Travel time over longer periods of time is required to capture daily and seasonal variations and adequately calculate travel time reliability measures.[11] In combination with other basic traffic information, such as volume, travel time data can also be used to estimate other variables (e.g., total delays).

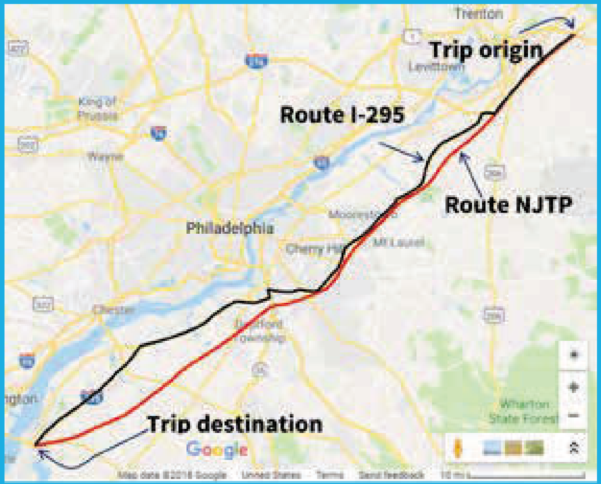
Some of the data-capturing techniques that can be used for calculating travel time reliability include the following:[18]

- **Field data collection:** The collection of traffic volume, speed, occupancy, and vehicle classification data, which are used to determine various measures of travel time reliability for different vehicle classes. Recently, probe vehicle data collected from a fleet of vehicles equipped with special instruments (e.g., GPS and cellular phone) have been widely used to derive reliability measures. The advantage of traffic count–based data is that real traffic conditions can be observed without relying on road-user interviews. However, the identification of user characteristics, their behavior, and choices is difficult.
- **Simulations:** Computer-based products that mimic vehicle and pedestrian movement and interaction with each other and traffic-control devices. Such models can simulate traffic at micro-, meso-, and macro-levels. Simulations are used to capture changes in the behavioral responses to differing travel and infrastructure options.

Each data type has its own advantages and limitations, which should be considered in the design of any reliability study. The data source has an impact on travel time reliability assessment.[19]

PROBE VEHICLE DATA COLLECTION

Travel time data of two probe vehicles traveling along I-295 and the New Jersey Turnpike (NJTP) were collected for trips made on an hourly basis from 10:00 to 19:00 on three different Sundays: May 24, June 7, and July 19, in 2009.[20] The probe vehicles were dispatched simultaneously from a common trip origin point to a common destination. One used I-295 (64 miles), and the other used the NJTP (60 miles). Average travel time for route I-295 was 58.6 minutes with a standard deviation (or measure used to quantify variation) of 2.89 minutes, while the average travel time for route NJTP was 59.5 minutes with a standard deviation of 5.53 minutes. This shows that I-295 was a more reliable route than the NJTP during this time due to its smaller variation.



Routes I-295 and NJTP for common trip origin and destination.[21]

RELIABILITY METRICS

Several metrics have been developed to measure travel time reliability, six of which are commonly discussed in literature.[11,22]

Table 1. Six commonly used metrics to measure travel time reliability.

Metric	Description	Example
1. Travel time index	**Ratio of travel time observed during peak periods compared to free-flow travel time (or steady rate at which traffic traverses a freeway segment).** This metric indicates how much longer travel time is during congested conditions relative to light traffic. It is usually computed separately for the morning and afternoon peak hours on weekdays.	If travel time between two points of interest during afternoon peak hour averages 45 minutes, and travel time during free-flow conditions is 30 minutes, then the travel time index is 1.5. $\text{Travel time index} = \frac{\text{45 minutes in peak hour}}{\text{30 minutes in free flow}} = 1.5$
2. Buffer index	**Additional time cushion that road users must budget to ensure an on-time arrival in 95 percent of trips, which is equivalent to being late for work once a month.** Buffer index is expressed in terms of a percentage of average travel time.	Assuming a buffer index of 50 percent and an average travel time of 20 minutes, then travelers must plan for an additional 10 minutes of time cushion to ensure on-time arrival in 95 percent of trips. $\text{Buffer index} = \frac{\text{allowance of 10 extra minutes}}{\text{average time of 20 minutes}} = 0.5$
3. Planning time index	**Total time a road user should allocate to arrive on time for 95 percent of trips.**	If the planning time index is 1.5, and the average travel time is 20 minutes, then the planning time is 30 minutes. $\text{Planning index} = \frac{\text{30 minutes succeeds for all but 1 day a month}}{\text{average time of 20 minutes}} = 1.5$
4. Failure and on-time measure	**The fraction of trips that are on time or late.** A successful, on-time arrival has a travel time no more than a pre-established threshold. The threshold can be the median travel time of a trip plus an additional 10 percent.	If the median travel time between a certain origin and destination is 30 minutes, and 18 of 100 trips between those points take longer than 33 minutes, then the failure rate is 18 percent. $\text{Failure rate} = \frac{\text{Number of failed trips}}{\text{Number of all trips}} = \frac{18}{100} = 18\%$ $\text{On-time rate} = \frac{\text{Number of on-time trips}}{\text{Number of all trips}} = \frac{82}{100} = 82\%$
5. Skew statistic	**Shape and size of travel time distribution as a measure of travel time reliability.** This measure relates a specified percentile travel time (e.g., 40th percentile below and above the median travel time), thus indicating the magnitude and direction of the skewness (or asymmetry) of the travel time distribution.	None
6. Misery index	**Ratio of excess travel time to average travel time.** It measures how much worse the longest trips are than normal trips. The misery index is the ratio of the average travel time of the 20 percent worst trips minus the average travel time of the all trips to the average travel time of all trips.[11] A modified formula for the misery index is the average of the worst 5 percent of travel times divided by free-flow travel time.	If the average travel time for a certain route is 30 minutes, but the average travel time for the worst 20 percent of trips over a week's time is 45 minutes, then the misery index 0.5. $\text{Misery index} = \frac{\left(\text{Average travel time for worst 20\% of trips}\right) - \left(\text{Average travel time of all trips}\right)}{\text{Average travel time of all trips}} = \frac{45 - 30}{30} = 0.5$

Figure 2 shows the relationship between the travel time index, buffer index, and planning time index.[10]

Travel Time Index, Buffer Index, and Planning Time Index

The difference between buffer index and planning time index is that the former represents the additional time cushion, whereas the latter represents the total travel time necessary for on-time arrivals for 95 percent of trips. Both travel time index and planning time index have similar numeric scales. However, travel time index is for peak hours, while planning time index is for any time of day.

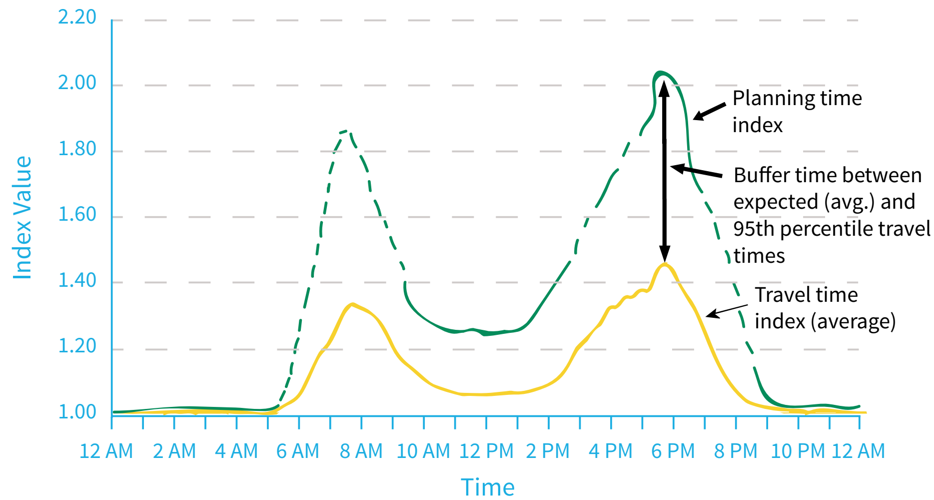
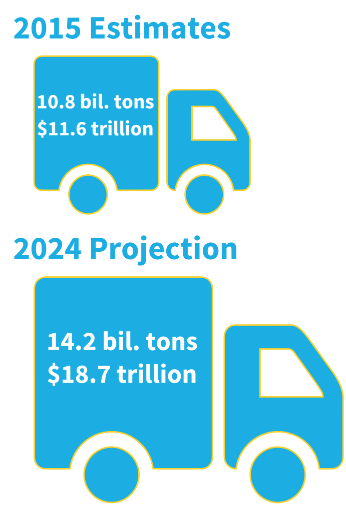


Figure 2. Relationship between travel time index, buffer index, and planning time index.[10]

FHWA recently issued a final rule with two new travel time reliability metrics as the *Moving Ahead for Progress in the 21st Century* (MAP-21) performance measures.[23,24] The objective of MAP-21 performance measures is to assess the performance of the National Highway System (NHS), freight movement on the interstate system, and the congestion mitigation and air quality improvement program. The two new reliability metrics are:

- **Level of travel time reliability (LOTTR):** The ratio of the 80th percentile travel time to the normal travel time (i.e., the 50th percentile occurring throughout a full calendar year) using data from FHWA's National Performance Management Research Data Set (NPMRDS). NPMRDS includes travel time data on the NHS, and LOTTR is used to assess the performance of the NHS.
- **Truck travel time reliability (TTTR):** The ratio of the 95th percentile travel time of trucks to the normal truck travel time, (i.e., the 50th percentile using a full calendar year of truck travel time data). TTTR assesses the freight movement on the interstate system and is reported for five time periods depending on time of day and day of the week.

Various agencies use different metrics of travel time reliability as a portion of their mobility performance assessment depending on



Total freight transported by road in the United States.[25]

BENEFIT-COST: VALUE OF TRAVEL TIME AND VALUE OF RELIABILITY

The value of travel time (VOT) and the value of reliability (VOR) are key factors in benefit-cost studies.

VOT =
monetary value of reducing travel time

VOR =
monetary value of reducing variability of travel time

VOT is the monetary value that road users place on reducing their travel time. VOR is the monetary value that road users place on reducing the variability of their travel time. The concepts of VOT and VOR involve estimating the magnitude of the benefits gained by saving in travel time and reduction in travel time variability or the penalties incurred by longer travel times and greater travel time variability.[26]

their needs. Table 2 shows the reliability metrics used by several agencies.

Table 2. Reliability metrics used by various transportation agencies.[19]

Agency	Reliability Metrics Used
Georgia Regional Transportation Authority and Georgia Department of Transportation (GDOT)	Buffer index and planning time index
Florida Department of Transportation (FDOT)	Buffer index and on-time arrival
Southern California Association of Governments (SCAG)	Buffer index
Washington State Department of Transportation (WSDOT)	95th percentile travel time
Maryland State Highway Administration (MDSHA)	Travel time index and planning time index

VALUE OF RELIABILITY

Recently, the valuation of travel time reliability in a benefit-cost analysis of transportation projects has been gaining attention. Some U.S. and international research projects have been initiated to provide guidance on how an agency can include the value of reliability (VOR) in a benefit-cost analysis when making congestion reduction-related project investment decisions.[27–33]

Most benefit-cost studies of mobility solutions require the monetary value of travel time (VOT) and the monetary VOR. Understanding VOT and VOR can inform decisionmakers about the value of potential strategies for improving reliability, such as adding tolled roads or high-occupancy lanes or reducing incident clearance times.

In the trucking industry, shippers and carriers value travel time at $25 to $200 per hour (depending on the product being carried).[2] A recent study in the area of freight transportation found that the VOT ranged from $12.80 to $283 per shipment hour, and the average value was $37 per shipment hour. VOR ranged from $51 to $290 per shipment hour, and the average of the distribution of VOR was $55 per shipment hour.[34,35] This indicates that freight shippers valued travel time reliability 1.5 times as much as travel time savings.

VOR to travelers can be estimated using data from congestion pricing strategies. This includes strategies like tolled roads and managed lanes (e.g., high-occupancy lanes). Such strategies offer reduced travel time and increased reliability to users who are willing to pay. Based on an analysis of congestion pricing data, many studies have reported that drivers value increased travel time reliability more than travel time savings.[36–38] Increased travel time reliability accounted for 68 percent of the benefits of using congestion priced lanes.[38] Another study estimated that users of congestion priced lanes value travel time to be $11.63 per hour, while they value reliability to be $25.45 per hour.[36]

This monetary cost associated with travelers and shipments being late or unreliable arrival time should lead to prioritizing travel time reliability in transportation planning and management. And, the significance of travel time reliability should be taken into account in the appraisal and valuation of infrastructure development projects.

VOR has increased in recent years. More reliable transportation systems are needed to address changes in business, industrial, and personal travel patterns and the emergence of more complex and interrelated scheduled activities (e.g., the just-in-time freight distribution and arrival systems). In 2015, the total weight of freight transported by road in the United States was estimated to be more than 10.8 billion tons and a value of $11.6 trillion.[25] In 2024, the freight figures are projected to increase to a weight of 14.2 billion tons and a value of $18.7 trillion.

To support on-time delivery of freight, a reliable transportation network is critical. For example, for frequent truck drivers who are familiar with the local traffic patterns of a region, information on travel time reliability was found to be a more significant factor in route selection than was historical travel time information.[39] Expanding national and international trade creates greater goods

When moving goods from one end of I-5 to the other, a commercial vehicle operator has to add about **6 hours of buffer time** to ensure on-time delivery with 95 percent confidence.[10]

METHODS FOR MEASURING THE VALUE OF TRAVEL TIME RELIABILITY

Attitudinal survey: Document commuters' perceptions about the relative importance of travel time reliability.

Stated preference survey: Ask respondents how much they value travel time reliability compared to other hypothetical scenarios. (This method represents bias due to respondents not replicating their stated choices as observed in real situations.)

Revealed preference study: Capture behavioral responses concerning the actual choices made by participants to travel time reliability measures. (The advantage of this technique is the reliance on actual choices, e.g., the technique avoids problems associated with stated preferences or a failure to properly consider behavioral constraints.)

volume, further destinations, and increasingly complex and interdependent supply chains. Successful interdependent and interconnected systems require reliable travel times between origins and destinations.

Changing patterns of individuals' employment opportunities, increased income, as well as increased recreational choices have affected passenger miles traveled.[40] Accommodating the busy calendar of an individual demands a more reliable transportation system so that delays in one activity do not affect the next activity. Essentially, road users value travel time reliability for several key reasons:

- Unreliable travel time forces road users to plan for extra time to avoid late arrivals. In economic analysis, the value of the extra time road users plan to avoid late arrivals (VOR) is generally more than the average VOT.
- Given that the VOR is different from VOT, transportation planners have to incorporate the costs of unreliable travel in project planning, programing, and selection processes.
- Reliability becomes an additional factor that influences where, when, and how road users travel.[41] Road users demand and expect a reliable transportation system. For example, given recent advances in communication technologies, the traveling public expects agencies to make traffic data available from a variety of devices so that they can see real-time traffic conditions. They also expect that agencies address traffic disruptions in a timely and efficient manner regardless of who owns the roads.

Travel time reliability is a key factor to the success of the U.S. economy and those who participate in it, including businesses, the traveling public, and local governments. Next, we'll dig a little deeper into the impacts of an unreliable transportation system, which includes negative effects on businesses, the traveling public, and local governments as well as impaired safety and security.

IMPORTANCE OF RELIABILITY ACROSS TRANSPORTATION MODES

On-time arrival of people and freight to their destinations is an important factor in all modes of transportation. Complex global and intermodal logistics chains require minimal disruption to ensure on-time delivery, which makes reliability critical. A recent survey of ocean shippers revealed that *reliability* of waterborne freight is considered to be the *most important factor* in maritime transportation compared to cost, speed, safety, security, and trackability.[42]

Similarly, in air transportation, on-time departures and arrivals are key performance indicators for airline service quality, which determines customer satisfaction and loyalty, market competitiveness, economic benefits, and profitability.[43] Reliability plays a key role in meeting these performance standards.

Why is Reliability Important?

Complex and interrelated supply chains combined with travel needs of the general public require a reliable transportation network.

Unreliability has direct negative impacts to:

BUSINESSES

- Profitability
- Labor costs
- Fuel
- Depreciation

TRAVELING PUBLIC

- Quality of life
- Stress
- Travel delays

LOCAL GOVERNMENTS

- Litigation
- Performance
- Public confidence

Unreliability is Costly

TO BUSINESSES

Businesses rely heavily on transportation systems. If the system is unreliable, it can affect their profitability, labor costs, fuel consumption and emissions, and the wear and tear and depreciation of their vehicles. Let's explore each of these in more detail.

Business Profitability

Unreliable transportation systems cause businesses to incur additional costs due to increases in travel time, travel cost, worker schedule flexibility, and service delivery. Transportation-related goods and services account for more than 10 percent of U.S. gross domestic product (i.e., over $1 trillion in value).(44) Therefore, unreliable transportation systems may impede economic development by diminishing productivity and increasing operation costs of the business (e.g., less freight movement, delayed deliveries, increased fuel consumption, and more vehicles needed to complete the same number of deliveries to ensure they are on time or done by the end of the day, which may mean excess capacity in the fleet when travel is smooth).

Warehouses and distribution centers often require just-in-time processing and delivery of supplies, but unexpected delays threaten business efficiency, diminish rapid inventory replenishment, cause lost sales, and increase inventory management costs. For example, because of delay in delivery of supplies, businesses are forced to increase inventories by as much as 5 to 15 percent depending on location and industry.(45) In the chemical industry, up to one-third of inventory is in transit at any point.(11) Therefore, a decrease in transportation reliability increases wait time, dead freight, and overall production costs in the industry. In addition, due to unreliable transportation systems, firms are less able to ship and receive goods within specified time frames, which directly impacts customer satisfaction and overall profitability of supplying the market.(46)

Unreliability, especially around warehouses and distribution centers, affects access and on-time delivery, which disturbs supply chain management. A survey-based study examined sources of delays in the supply chain of logistics in the United Kingdom and found that delays due to unreliable travel time were responsible for 23 percent of the total delivery delays.(47) This rate can be as high as 34 percent in certain industries. In addition, the study reported that a quarter of sampled managers of logistic companies identified unexpected delays as the main source of unreliable logistic operations.

Due to increasingly unreliable travel times and worsening congestion, logistic and distribution companies are forced to restructure their delivery systems to be competitive in the market. For example, logistic companies attempt to reschedule daytime deliveries to avoid delivery during peak periods and unreliable travel patterns. However, this is often constrained

Annual estimated cost of unreliability on U.S. roads in 2014:(17)

$19,000,000,000

by destination accessibility and customer requirements. In the case of interrelated trips, unexpected delays can have cascading effects. A vehicle delayed by unexpected congestion may have to wait for the next available off-loading slot at a distribution center because it missed its original slot. This can result in amplified effects during subsequent delivery schedules.

The cost of unreliable trip travel times (including the value of lost time, greater vehicle operating costs, increased emissions, etc.) is **incurred by road users**.

Improvements in travel time reliability can lead to increased competitiveness and business productivity resulting from more reliable employee arrival times and access to broader labor markets.[48] This, in turn, has indirect and induced economic benefits. Indirect benefits refer to the increased supplier activities due to a stimulated economy from increased business productivity. Induced economic effects refers to activities related to employees' responding to consumer purchases.

Labor Costs

Market accessibility and transportation reliability directly or indirectly affect the labor costs of businesses. This effect can be in terms of lateness of employees and their decreased productivity due to stress from being caught in unexpected congestion. Increased labor costs affect the structure and profitability of businesses providing goods and services. In addition to costs associated with late deliveries due to unexpected congestion, shippers lose out on labor time of drivers as they sit idle waiting for congestion to dissipate. For example, when moving goods from one end of I-5 (San Diego, CA) to the other end (Blaine, WA), a commercial vehicle operator would have to add approximately 6 hours of buffer time to ensure on-time delivery with 95 percent confidence.[10] The addition of the buffer time directly increases the labor cost of shipping businesses.

A nationwide survey of 1,000 representative employers evaluated the employers' view of traffic-related delays.[49] The study found that unreliable commute times for employees are a concern for 25 percent of the employers. These employers reported that managers regularly complain about lateness of employees due to unexpected delays. About 33 percent of employers view traffic-related delays as a moderate to major problem in their businesses. When only large employers are considered, unreliable commute times for employees are a concern for 38 percent of employers, and about 52 percent of these large employers view traffic delay as a moderate to major problem in their business.[49]

While it is difficult to unambiguously quantify the effect of workers' start-time delays and arrival reliability on business operations, a survey of 1,200 U.S. companies in the construction industry conducted by the Associated General Contractors of America reported that the companies incurred $23 billion in added expenses and losses of 3.7 million days of worker productivity annually due to traffic congestion.[50] In addition, 93 percent of the responding firms reported that congestion affects their operations, and 64 percent reported an annual loss of productivity of at least one day per worker.[51] A portion of these losses were caused by unreliable employee commute time.

Most likely, the increased labor costs due to unreliable travel times are transferred to the consumers of goods and services. A practical example of this is an increase in taxi fares due to unexpected delays. The fare for taxis and other on-demand ride-sharing services are normally calculated based on in-vehicle time, waiting time, and distance of the route in addition to other fees, such as base fare, booking fees, tolls, and surcharges.[52] Therefore, if a trip takes longer than expected due to non-recurrent congestion, the fare increases to compensate for the time of the driver. The unexpected increase in fares can be frustrating to passengers.

Fuel Consumption and Emissions

Unreliable transportation systems cause vehicles to consume more fuel and produce more emissions. A study that compared vehicle emissions in rush-hour (i.e., recurrent) and work zone

U.S. construction companies incurred **$23 billion in added expenses** and **losses of 3.7 million days of worker productivity** annually due to recurrent and non-recurrent delays (i.e., unreliability).[50]

(i.e., non-recurrent) congestion with free-flow conditions found that work zones are associated with the highest fuel consumption rates and the highest carbon dioxide, carbon monoxide, and hydrocarbons emissions.[53]

Non-recurrent traffic congestion due to crashes increases vehicle emissions compared to free-flow conditions. A study that quantified the effect of traffic crashes on vehicle emissions and the quality of air near freeway facilities in South Korea found that communities that were located within a 1-km radius of the crash location were affected by traffic-related air pollution exposure.[54]

Non-recurrent congestion (e.g., incidents and work zones) may initially decrease the instantaneous traffic emissions due to reduced average speed; however, per-vehicle emissions are higher over the duration of the incident compared to free-flow conditions.[55] Under congested and low-speed conditions, per-mile fuel consumption and pollutant emissions are higher compared to free-flow conditions.

An unreliable transportation system that often increases travel time due to unexpected delays increases the exposure risk to pollutants. Emissions from motor vehicles contain pollutants and exposure to pollutants adversely affects health. The health costs of total congestion due to exposure to fine particulate matter and related effects was estimated to be $31 billion (in 2007 dollars) across 83 major cities in the United States, part of which is due to unreliable transportation systems.[56]

Wear and Tear and Depreciation of Vehicles

Unreliable travel times, especially when accompanied by stop-and-go congestion, result in more strain on a vehicle's braking system, engine, and tires as well as increase fuel and oil consumption. This unreliability increases vehicle maintenance and repair costs and accelerates the depreciation of vehicles.

A study of 117 incidents between 2004 and 2006 in Nerang, Australia, estimated the increase in operating costs of vehicles caused by incident-induced delays. The study found that incident-induced delays account for five percent of vehicle operating costs.[57] The study mentioned that an incident occurring in the morning peak hours would result in an increase of total operating costs of the vehicles affected by the incident-induced delay by $21,000 (AUD) over the duration of the incident. This may correspond to substantial financial impacts to road users.

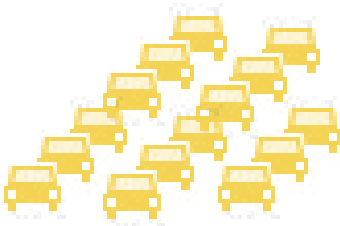
TO THE TRAVELING PUBLIC

The cost in the forms of extra fuel consumption and emissions and additional wear and tear and depreciation of vehicles due to unreliable travel time is certainly also applicable to the traveling public. However, some of the impacts of unreliable travel are unique to the traveling public and warrant special discussion.

Quality of Life and Stress Levels for Drivers

Some studies have linked a secondary effect of travel time reliability to the health and social life of road users. Unpredictable travel times can have adverse effects on worker productivity, such as lateness for work, absenteeism from work, decrease in concentration after an unreliable trip, exhaustion, and poor sleep quality.[5,6]

In a study that examined a large sample of long-distance commuters in Europe in various travel modes, uncertainty of travel time of commute trips was identified as the main source of travel anxiety.[59] Similarly, rail passengers who estimated that their commute would be unpredictable demonstrated greater levels of perceived stress and higher elevations of the stress hormone cortisol.[60] In other words, unreliable travel time was found to increase stress of travelers but not necessarily impact work performance.



Unreliable commute time increases commuting stress.[58]

A study compared the stress levels of car and train commuters in metropolitan New York City who had similar commutes, origins and destinations, and socioeconomic backgrounds.[61] The study found that significantly higher levels of stress and negative mood were shown by car commuters than by train commuters. Further analysis indicated that the increased stress and negative mood associated with car commuters was attributed to greater driving effort due to unpredictable travel time.

Travel time predictability is an important contributor in explaining commuting-related stress. A study that examined the commute and stress levels of 323 participants in the Netherlands found that a lower degree of commute time predictability leads to higher commuting stress.[58] In addition, the study found that travel time is perceived to be less predictable when commute time is longer. A similar study involving 418 participants found that travel time variability had a stronger effect on the strain and symptom measures of the participants.[6]

Delays for Commuter and Personal Travel

An unreliable transportation system unnecessarily increases the travel time of drivers (both commuters and those traveling for personal use), leading to late arrival times. Unexpected delays represent an opportunity cost of time, which could have been spent at work or for leisure.

Based on the 2012 to 2016 American Community Survey, there were a little over 139 million workers commuting, and their average commute time was 26.1 minutes.[62] Given this high number of U.S. commuters, an unreliable transportation system can have far-reaching effects. An average American commuter spends about 42 hours stuck in traffic congestion per year, costing an average of $960 a year and 19 gallons of wasted fuel.[62] Part of the total congestion cost is due to unreliability.

Reduction in travel time and unreliability during congested hours by decreasing delays is highly valued by commuters and improves satisfaction with their commute.[63] On the other hand, if travel time doubles due to unexpected congestion, commuters are likely to be very dissatisfied about their commute.[63] This highlights the importance of reliable transportation systems to commuters.

TO LOCAL GOVERNMENTS

The transportation system provides a critical service to the traveling public. Whether they use roadways, transit, or other forms of travel to get to work or special events, they depend on it to get where they need to go. When the system doesn't deliver on a reasonable expectation of travel time, they lose confidence in the Government's ability to perform this basic service.

Litigation and the Public's Confidence in Government's Ability to Perform a Basic Service

Unreliable travel times during work zone activities or special events have been the cause of litigation between residents and public agencies. An example of this is the construction of the Zoo Interchange in Milwaukee, WI, that resulted in congestion that adversely affected the work commutes of residents.[64] This sparked a lawsuit that was filed by Milwaukee civil rights groups against the Wisconsin Department of Transportation (WisDOT) in 2012. The lawsuit was settled in court-sponsored mediation under the terms that WisDOT provide $13.5 million in transit funding to ease the non-recurring congestion in the region during the construction of the interchange.

Confidence of Transit Users on Public Transportation Services

Long wait times and unreliable travel times of public transportation services are the two most important factors that negatively affect transit users' confidence in public transportation and ridership rate.[65] Transit passengers stated that knowledge of when their bus would arrive and whether it reliably arrives on time are the most important factors affecting their decision to

An average American commuter spends about **42 hours stuck in traffic** per year, costing an average of **$960 and 19 gallons of wasted fuel** per year.[62]

ride transit.[66] Therefore, reliable service and journey time are critical for attracting and retaining transit users.

A survey-based study that investigated the perception of public transportation users of the San Francisco Muni transit system found that the confidence of users in the transit system declines because of delays and unreliability in the transit service.[67]

Providing and maintaining reliable transit service is crucial not only for transit user satisfaction, but it is also important for transit operators. Reliable service improves transit operator efficiency, reduces operating costs, and increases revenues by attracting and retaining users.[68]

Unreliability Impairs Safety

A transportation system that is unreliable can negatively affect safety and security of both road users and non-road users. An unreliable system increases safety risks, affects emergency response, and slows disaster recovery.

INCREASES SAFETY RISKS

Travel time unreliability and crash frequency have a cyclical relationship. Crashes cause travel time to be unreliable as the disabled vehicles block part or all of road lanes, and travel time is increased compared to normal crash-free operations. This, in turn, increases the likelihood of a secondary crash, which, in turn, adversely affects travel time reliability

A recent study examined the relationship between crash frequency and travel time reliability on a 20-mile urban expressway located in Orlando, FL.[69] The study found that unreliable travel conditions pose higher crash risks to motorists (i.e., lower travel time reliability would significantly increase crash frequency). In regard to the effect of unreliability on crash type, unreliable travel time tends to cause more multi-vehicle crashes, especially rear-end and sideswipe crashes, than single-vehicle crashes. The reason is that unreliable travel conditions can promote unexpected driving behaviors and risky interactions between vehicles, thus leading to more multi-vehicle crashes. In addition, the study compared the performance of crash frequency estimation models with and without variables that directly estimate travel time reliability. The results indicate that crash frequency models that included direct travel time reliability measures outperformed the traditional analysis that did not include direct travel time reliability measures. The study recommended incorporating direct measures of travel time reliability for better safety analysis of facilities.

Another safety risk of an unreliable transportation system is the exposure to secondary incidents. Secondary incidents are incidents that would not have occurred unless another incident (a primary incident) occurred earlier and in close proximity. Motorists accustomed to free-flowing traffic may not recognize the queue building up due to a primary incident that occurred earlier in time, and they may end up in a secondary rear-end crash. In addition, rubbernecking and distracted driving while looking at a primary incident scene can lead to secondary incidents. Secondary incidents are estimated to represent about 20 percent of all incidents and about 18 percent of freeway fatalities.[70,71]

Primary incident type, primary incident clearance duration, and time of day are the most significant factors that increase the likelihood of secondary incidents.[53] For each additional minute of primary incident clearance, the likelihood of a secondary crash increases by 2.8 percent, causing a significant safety risk to road users.[72] Clearing secondary incidents can be difficult because first responders are already engaged in clearing the primary incident and are delayed in resolving the secondary incident, which results in additional strain to the incident response staff.

Unreliable travel conditions can promote **risky driver behavior**, which can lead to traffic incidents and secondary crashes.

Unreliable transportation systems also increase the safety risk of first responders, mostly because of secondary incidents. Incidents involving emergency responders often occur as a result of the responder being struck by a passing vehicle while working at a traffic incident scene. For example, a rubbernecking motorist looking at a crash scene strikes a paramedic attending a vehicle crash victim. In 2008, 13 police officers were killed from being struck by vehicles, mostly while directing traffic at incident scenes or attending to traffic stops.[(73)] In 2013, six firefighters were struck and killed by vehicles while responding to roadway crashes and incidents.[(74)]

AFFECTS EMERGENCY RESPONSE

Response time by first responders is one of the most decisive factors that determines mortality rates, healthcare costs, and level of property damage in traffic and other incidents. A survey of first responders registered with the Alabama Department of Public Health found that traffic congestion, on average, delays the response time of first responders by nearly 10 minutes.[(75)] Any unexpected delay in addition to the recurrent delay exacerbates the late arrival of the first responders.

For situations that are life-threatening, delayed response time for first responders due to unreliable travel time can have a detrimental effect, as rapid interventions in the first few minutes can make the greatest difference. Rapid arrival at traffic crash scenes and rapid conveyance to hospitals is critical for victims with life-threatening medical conditions. In the event of cardiac arrest, survival rates decrease by 7 to 10 percent for every minute of delay.[(1)]

Healthcare costs increase due to late arrival when seeking treatment. Delayed patient arrival at hospitals is associated with longer stays in the intensive care units, additional health complications, costly procedures, and longer recovery periods.

For example, hospital treatment costs increase by seven percent for each minute of delay for individuals with medical conditions that decrease oxygen flow to the brain or heart.[76–78]

Similarly, delayed arrival of first responders increases property damage. For example, response times of fire services have a direct correlation with the magnitude of the structural damage of buildings on fire. Building fires are estimated to grow by 20 percent per minute, which results in an average additional damage in the range from $4,000 to $6,000 per minute.[76] Similarly, the monetary increase in damages from fires and emergency medical services due to traffic affecting quick arrival of first responders is estimated to be $130 to $360 million per year in California.[79]

Unreliable transportation systems increase the time it takes first responders to arrive at an incident scene, which poses a significant risk of increased mortality rate, health complications, and property damage.

SLOWS DISASTER RECOVERY

Travel time reliability is also important to consider as it relates to emergencies and disaster recovery. Traffic demand in areas affected by disaster can be significantly higher due to the evacuation and other activities, which increases the likelihood that the transportation infrastructure will be unreliable. Urban areas are becoming more vulnerable to natural disasters (e.g., floods, rising sea levels, hurricanes, and landslides) due to changes in weather patterns and climate. During these emergencies and disasters, rescue routes need to be reliable enough to maximize the effectiveness and efficiency of evacuations as well as mobilize disaster relief resources and operations.

Damage costs increased between **$130 to $360 million** per year in California due to traffic slowing arrival of first responders for fires and emergencies.[79]

Effectiveness of recovery operations from disasters and other national emergencies not only requires the road transportation system to be reliable but also resilient. Infrastructure resilience refers to the ability to reduce the magnitude and duration of destructive events by designing the infrastructure to be robust, resourceful, rapidly recoverable, and adaptive.[80]

In summary, a reliable transportation system is critical to all those who use it. So, how do we create a reliable system? First, we must determine the system's current level of reliability and then take action to improve it. We will explore these topics in the next section.

COSTS OF UNRELIABILITY — BY THE NUMBERS

Unreliability costs represent costs assumed by road users because the trip travel time is unreliable. In a conservative appraisal of unreliability using 2005 data, the annual cost of unreliability in the United States was estimated to be **$10.1 billion** (in 2007 value).[81] The total annual unreliability costs in very large and large urban areas were found to be **$7.31 and $1.47 billion**, respectively, while in medium and small cities, it was **$0.14 and $1.17 billion**, respectively (in 2007 value). The annual total costs of congestion (including the value of additional travel time, reliability, vehicle operating costs, emissions, and mobility) in 2005 were estimated to be **$85.4 billion**.

Unreliability-related costs were estimated to be about **12 percent** of total congestion costs, though it can be higher in larger urban areas. Assuming the proportion of unreliability to the total congestion costs remain the same, the cost of unreliability in 2014 would have been slightly higher than **$19 billion** (depending on a total congestion cost of **$160 billion** as estimated by the *2015 Urban Mobility Scorecard*).[17]

How Do We Create a Reliable Transportation System?

Proven approaches exist to determine current reliability and take action to improve reliability in the transportation system.

Key steps:

DETERMINE CURRENT RELIABILITY

- Collect data
- Track performance

TAKE ACTION TO IMPROVE RELIABILITY

- Improve planning and response to system disruptions
- Actively manage transportation and demand
- Increase capacity
- Change business and organizational processes

Determine Reliability

One of the first steps to understanding the current reliability of a transportation system is to implement a travel time monitoring program, which comprises actions a transportation agency can take to track reliability performance and understand the factors that influence travel time reliability. Reliability monitoring programs also help agencies evaluate progress in making a transportation system more reliable, comparing network reliability of one region with another, and justifying investments that enhance reliability.

Monitoring travel time is the basis for providing credible reliability information to system operators and users. Potential users of travel time reliability monitoring programs include system administrators and their staff, highway system operators, transit system operators, freight service providers, highway system users, transit system users, freight system users, and employers.[(41)] Such information is useful for making better decisions concerning actions they can take to better plan and manage their travel.

A travel time reliability monitoring program has to be able to perform four critical functions. First, it has to measure travel time by fusing information from a variety of sources using statistical analysis. Second, it should be able to evaluate the reliability performance of a given network or link. Third, if a network or link is found to be unreliable, the program should be able to identify the cause of the unreliability and the affected links. This is critical for identifying an effective strategy to correct the unreliability. Finally, it needs to help system operators clearly quantify and visualize the effect of the detected unreliability. These four critical functions will help agencies identify the appropriate actions to be taken to restore system operations or mitigate the effect of the unreliability.[41]

Reliability monitoring systems (in combination with other transportation planning and management strategies) can improve the travel time reliability of a region. Given that system managers have a variety of traffic management strategies at their disposal, they can implement appropriate actions to improve reliability or mitigate the effects of unreliability (e.g., deploy more patrol vehicles). Travel time monitoring systems add a valuable decision-support tool to system managers for practical and efficient traffic management.

Table 3 shows reliability improvements from strategies and treatments that reduce delays (shown in order of most to least effectiveness). The treatments that address occasional delays, such as service patrols and road weather information systems, will specifically improve reliability. Any treatment, however, that reduces delays will benefit reliability as well.

TURNING RELIABILITY DATA INTO USEFUL INFORMATION

The Minnesota Department of Transportation (MnDOT) uses creative visualization techniques to get a complete picture of system-wide reliability performance and to communicate it to stakeholders and road users. MnDOT uses such data to compare different design alternatives to identify a solution that will be the most effective in reducing congestion and unreliability. For example, the agency used reliability data and analysis to evaluate the value of adding a general-purpose lane or adding a managed lane (i.e., high-occupancy lane).[82,83]

Table 3. Evaluation of strategies and treatments that improve travel time reliability.[12]

Reliability Improvement	Strategies and Treatments
Delay reduction of up to 50 percent	► National traffic and road closure information ► Service patrols ► On-scene incident management (e.g., incident responder relationship, high-visibility garments, clear buffer zones, and incident screens) ► Work zone management ► Transportation management centers ► Traffic adaptive signal controls and advanced signal systems ► Electronic toll collection
Delay reduction of up to 20 percent	► Remote verification (e.g., through closed-circuit television cameras) ► Pretrip information by 511, websites, subscription alerts, and radio ► Road weather information systems ► Dynamic message signs ► Geometric design treatments ► Signal retiming and optimization ► Advanced transportation automation systems, signal priority, and automated vehicle location ► Ramp metering and ramp closure ► Congestion pricing (e.g., area wide) ► Managed lanes (e.g., high-occupancy vehicle lanes, high-occupancy toll lanes, and truck-only toll lanes)
Delay reduction of up to 10 percent	► Planned special events management ► Freight shipper congestion information and commercial vehicle operations ► Driver assistance systems ► Traffic-signal preemption at grade crossings
Other improvements	► Driver qualification (e.g., driver training) ► Automated enforcement ► Probe vehicles as a means to provide near real-time travel time estimation ► Geometric design improvements ► Variable speed limits
Unknown benefits to date	► Access management (e.g., driveway location, raised medians, channelization, and frontage roads) ► Changeable lane assignments (e.g., reversible and variable) ► Integrated multi-modal corridors ► Travel alternatives (e.g., ride-share programs, telecommuting, home office, and video conferencing)

Improve Reliability

There are several actions that can be taken to improve travel time reliability. These actions can be grouped based on the similarity of their technical nature or issues addressed. These groups of actions include better management of incidents and other traffic disruptions, capacity additions at bottlenecks, and use of better business and organizational processes to improve reliability. The following sections explore each of these in more detail.

IMPROVE PLANNING AND RESPONSE TO INCIDENTS, ROADWORK, AND SPECIAL EVENTS

Work zones, special events, crashes, and weather are major sources of unreliability. Incident-related congestion and delays can be reduced with incident management strategies that increase incident detection rates and reduce incident clearance time to restore traffic back to normal conditions. Delays due to special events are caused by sudden traffic surges and can be reduced by proactive management and control of traffic, such as traffic rerouting, temporary capacity addition in the direction of major traffic, and control of traffic at road entry and exit points. Advanced work zone management reduces the effects of work zones by managing the scheduling and duration of work zones and adequately controlling traffic near the work zones. Similarly, a road weather program can play a significant role in mitigating the safety and mobility effects of adverse weather on traffic operations and providing accurate and relevant weather information to travelers. Detailed discussions of advanced incident, work zone management, special event, and weather strategies are presented in the following sections.

TRAINING TRAFFIC INCIDENT RESPONDERS

Training first responders to safely, effectively, and efficiently respond to incidents can significantly improve reliability. A coordinated incident management plan minimizes incident-induced delays, reduces the likelihood of secondary incidents, and also improves the safety of responders.

State transportation departments are realizing that effective incident management requires collaboration among responding agencies (e.g., police, firefighters, medical personnel, towing companies, and others). Many have already started providing tailored, interactive, and hands-on training to traffic-incident responders.

More and more responders are trained every year.[84] This training includes train-the-trainer sessions as well as in-person and web-based training.

The Maryland State Highway Administration (MDSHA), the Utah Department of Transportation (UDOT), and the Colorado Department of Transportation are among the many State transportation departments already training first responders.[85] MDSHA has hired a full-time traffic incident management program manager dedicated to providing training to responders. The Tennessee Department of Transportation has integrated the incident response training into their law enforcement training academy. UDOT is integrating the incident response training into their State Fire Academy training.[86]

Traffic Incident Management Services

Traffic incident management services refer to rapid and efficient removal of debris, roadkill, stalled vehicles, and vehicles involved in crashes, as well as detection of incidents. It also refers to coordination of agencies involved in clearing the incident, such as the fire department, police department, paramedic services, and towing companies. The benefit of rapid and coordinated incident management is that unexpected incident-induced delays are minimized, and injured people are treated more quickly. Rapid incident response also reduces the occurrence of secondary incidents resulting from traffic disturbances due to primary incidents.

Along the busy shipping corridor of I-710 leading from the ports of Long Beach, CA, and Los Angeles, CA, rapid incident management services have helped improve travel time reliability.[44] Considering a 30-minute free-flow trip, the typical average delay on this route was reduced from 8 to 5 minutes due to rapid and coordinated incident management. Similarly, the travel time on the worst days was reduced by 9 minutes.

A time-consuming component of traffic incident management is tediously measuring tire marks as well as locations of debris and pavement marks at crash scenes. Technologies are available to expedite this process. Photogrammetry is one way to get precise measurements from photographs. For example, Indiana uses photogrammetry-based crash reconstruction. It allows police and crash reconstruction personnel to map a crash scene faster than traditional methods, which rely on field measurements that must be taken while lanes are blocked. Indiana State Police reported that traditional crash reconstruction takes on average 2 hours and 46 minutes, while photogrammetry-based crash reconstruction takes only 59 minutes on average. This use of photogrammetry translates to an average of 1 hour and 47 minutes saved per road closure scene.[44]

Work Zone Management

Work zone management strategies that reduce work zone impacts and generate time and cost savings are crucial for improving travel time reliability. About 24 percent of non-recurring traffic delays are attributed to work zones. Effective work zone management can reduce work zone-related delays by 50 to 55 percent, which can create an opportunity to improve travel time reliability.[12]

Techniques that reduce the impact of work zones include monitoring traffic and making adjustments to traffic control; providing traveler information about work zone locations, delays, and possible alternate routes before and during trips; and effectively planning and coordinating work zones. Examples of these techniques include the following:

- **Management of work zone traffic:** Traffic conditions at and upstream of work zone locations are better managed if drivers are given information so that they have a better perception of the work zone and how traffic is managed around it. This can be achieved by utilizing queue warning and speed management techniques to enhance safety and reduce traffic delays at work zones.
- **Planning and coordination of work zone activities:** Sharing information on short- and long-term work zone activities with multiple local and regional agencies creates an opportunity to engage stakeholders, develop an optimal schedule and sequence for work zones, combine multiple projects in a corridor, and coordinate construction work among agencies.[87] These techniques expedite work zone completion and minimize lane closures and total delay to road users. They also help construction crews with getting materials to the work site.

Special Event Management

Special events (e.g., street closures for parades and high travel demand at stadiums during sporting matches) are a source of delays and unreliability as they suddenly increase traffic demand and diminish roadway capacity. Delays due to special events affect not only individuals traveling to attend the event but also those who are using the adjoining roadways in the vicinity of the event.

About 24 percent of non-recurring traffic delays, which create unreliability, are attributed to work zones.

Tips for Handling Key Challenges

Incidents

- Promptly remove vehicles and debris
- Coordinate fire, police, paramedic, and towing
- Use technology to map crash sites more quickly

Work Zones

- Use traffic management tools and technology, such as queue warning and speed management
- Plan and coordinate with local and regional agencies
- Inform travelers of work zone locations and possible delays

Events

- Plan ahead
- Reroute traffic
- Add temporary lanes
- Control traffic entry and exit points
- Share real-time information with travelers

Weather

- Use road weather information systems (travelers and operations)
- Clear roads (before, during, and after)

In Los Angeles County, it is estimated that approximately 1,000 planned special events happen each year and are attended by millions of people.[88] When not managed adequately, such high numbers of special events can be a significant source of delay in both urban and rural areas.

Because planned events are scheduled ahead of time, public agencies can obtain information on the location, time, duration, and expected demand from the events. As a result, there is an opportunity to successfully manage the traffic before and during the events to minimize delays and unreliability. Specifically, the effect of such events on delays can be reduced by proactively managing and controlling traffic through tactics such as rerouting traffic, adding temporary lanes in the direction of major traffic, controlling traffic entry and exit points, and sharing real-time information with drivers.

Road Weather Information Systems

Travel time reliability is affected by the existence and intensity of adverse weather conditions, such as precipitation, snow, wind, fog, and sun glare. In addition to disruption of traffic flow, adverse weather can cause damage to infrastructure assets, increase weather-related crashes, and interrupt emergency services. The most severe weather events (e.g., heavy rainfall that causes flooding, severe wind that topples trees, and snow ice) have the possibility of causing complete road closures.

To cope with the effects of adverse weather on reliability, advanced weather detection and response strategies can be deployed. Road weather information systems develop and implement techniques to maintain safety, mobility, and reliability during adverse weather conditions. This is achieved by disseminating information to road users and integrating weather with traffic operations and maintenance procedures. Adequate road-clearing efforts before, during, and after adverse weather events can restore roads to full capacity or near capacity. The statewide reduction in user costs due to a weather responsive traveler information system in Michigan was estimated to be 25 to 67 percent.[89]

ACTIVELY MANAGE TRANSPORTATION AND DEMAND

Active Transportation and Demand Management (ATDM) is the dynamic and real-time management of transportation demand and supply by influencing traveler behavior. ATDM has three components: (1) active traffic management, (2) active demand management, and (3) active parking management.

Active Traffic Management

Active traffic management is the dynamic management of traffic based on combinations of historic, real-time, and predicted traffic conditions. It refers to improvements in transportation system operations by applying traffic management strategies to maintain and improve highway level of service during peak and off-peak hours. As opposed to only responsive traffic management strategies (reacting to traffic conditions), active traffic management is both responsive and proactive (planning according to anticipated traffic conditions). It can include advanced traffic management strategies and traveler information systems that dynamically manage recurrent and non-recurrent congestion. Some of the most common active traffic management strategies are as follows:

- **Adaptive traffic lights:** Adjusts the timing of traffic lights to accommodate the real-time traffic in the intersection.
- **Variable speed limits:** Adjusts speed limits for a segment based on real-time traffic and weather conditions.
- **Adaptive ramp metering:** Dynamically controls the rate of vehicles entering the freeway through the use of traffic signals on freeway on-ramps that are based on real-time conditions of the main line traffic.
- **Queue warning:** Provides information concerning the presence of downstream stop-and-go conditions via dynamic message signs to prepare drivers for emergency braking.

Common active traffic management strategies include:

- Adaptive traffic lights
- Variable speed limits
- Adaptive ramp metering
- Queue warning
- Dynamic en-route information systems

- **Dynamic en-route information systems:** Provides travelers with mobility- and safety-related information (e.g., route guidance and other advisory functions).

Integrated corridor management can be viewed as an application of these strategies. It is a joint management of transportation operations within and between corridors that offers an opportunity to operate and improve traffic conditions in the entire system. In addition, emerging connected and automated vehicle technologies offer a new opportunity for improving traffic management and operations.

Active Demand Management

Active demand management refers to strategies that influence individual travel behavior by providing options to reduce the number of vehicles on a regional transportation network during peak hours. It attempts to reduce congestion and improve travel time reliability by managing the demand side of the transportation equation. The goal is to reduce the strain on traffic operations by maximizing the people-moving capability of the transportation system while reducing the number of vehicles on the network. Some examples of demand management are encouraging road users to shift from using single occupancy vehicles to shared modes of transportation (carpooling, car sharing, and public transit systems), influencing the time of travel and the need to travel, and giving incentives to travel during off-peak hours and discourage travel during peak hours (congestion pricing). Active demand management leads to improved air quality, reduced energy consumption, efficient road capacity usage, and greater traffic mobility. Some of the strategies involving active demand management include the following:[90]

- **Dynamic ridesharing:** Arranges shared rides with short notice for on-time pick up of travelers using advanced communication technology (e.g., smart phones and social networks).
- **Managed lanes:** Dynamically changes the qualification of vehicles to use a particular lane (e.g., restricting single occupancy vehicles from using high-occupancy vehicle lanes).

Active demand management includes:

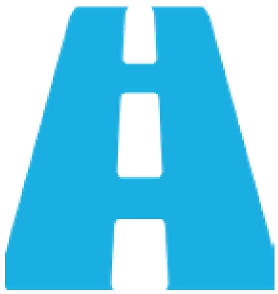
- Dynamic ridesharing
- Managed lanes
- Dynamic pricing
- Dynamic routing
- Dynamic transit capacity assignment
- On-demand transit
- Predictive traveler information

- **Dynamic pricing:** Charges users in certain lanes or roads based on real-time level of congestion.
- **Dynamic routing:** Directs road users to use alternative roads that are less congested.
- **Dynamic transit capacity assignment:** Reorganizes the scheduling and assignment of public transit operations in response to the real-time and predicted travel demand.
- **On-demand transit:** Provides flexible routes and schedules so that users can customize their transit trips as an incentive to avoid using personal modes of travel.
- **Predictive traveler information:** Provides pretrip and en-route information to road users based on real-time and historical traffic data.
- **Other:** Includes strategies that employers and service providers implement to distribute peak-hour traffic (e.g., employer programs for telework and variable work hours and commuter incentives by transit providers).

Active Parking Management

Active parking management refers to optimizing the operations of parking facilities through dynamic management and influencing the behavior of travelers. Since limited parking spaces can be the source of unreliable transportation systems, particularly in city centers with curb parking spaces, active parking management can potentially improve trip reliability.[91,92] Active parking management uses strategies like dynamic parking pricing, dynamic parking reservation, dynamic way-finding, and dynamic parking capacity. Circling for parking causes congestion, so helping drivers find open parking spaces and effectively pricing parking so that spaces open up more often at busy times can reduce congestion and help drivers arrive at their destination in a more timely manner. Effectively pricing parking near offices and shops may also help balance demand between different travel modes.

Limited parking availability can be a source of unreliability, especially in city centers with curb parking.



Facilities that operate at or near capacity can quickly become unreliable and are prone to excessive delays from even slight disruptions in traffic flow.

INCREASE CAPACITY

Uncongested facilities have better reliability, even during minor traffic disruptions, as the extra traffic can be easily absorbed by the available capacity. However, with increases in congestion levels, facilities that operate at capacity or near capacity become quickly unreliable and are prone to excessive delays due to slight disruptions in traffic flow. Therefore, in some cases, adding capacity is the best approach to improving both congestion and reliability.

Capacity addition refers to improvements in the road capacity so that more traffic is accommodated by the facility. Capacity addition is a treatment that is focused on a corridor level and can range from simple repainting of pavement markings to more extensive lane additions. Facilities where capacity has been added exhibit less sensitivity to reliability problems.

Capacity can be added at strategic locations where traffic flow breakdown is frequently observed and congestion is severe. Bottleneck locations are good candidates for capacity additions, as they often result in significant improvement in travel time reliability. Capacity addition strategies include link additions, lane additions, roadway widening, access management, pavement resurfacing, lane delineation treatments, and improved geometric alignment.[12]

Considerations for capacity additions, especially major construction projects, include the cost and timeline, impacts to traffic and local communities, and the possibility that increased capacity may lead to induced congestion (e.g., some drivers shifting from other roads, other times of day, or other modes to the newly expanded road).

In some cases, TSMO can be used as an alternative to adding capacity by instead improving mobility and reliability of existing facilities, which can be implemented in a relatively short period of time and at a fraction of the cost than for capacity addition.

This creates an opportunity for agencies to invest in other areas. In cases where capacity addition is needed, TSMO can be used as a complementary strategy to increase the effectiveness of a capacity addition for a longer-lasting solution to mobility and reliability problems and superior performance.

CHANGE ORGANIZATIONAL, INSTITUTIONAL, AND BUSINESS PROCESSES

There are many techniques that can be implemented additionally or as a complement to the three previous approaches. For example, improving travel time reliability may require an integrated business process. Integrating business processes to improve reliability involves defining specific reliability goals, understanding the existing business processes, identifying activities that need to be changed, monitoring outcomes against reliability goals, and implementing and institutionalizing the process. It can also foster coordination among public agencies and stakeholders that are seeking to improve travel time reliability. Reengineering business processes to improve reliability requires direct intervention with various traffic planning and management strategies, such as traffic incident management, work zone management, planned special event management, road weather management, and traffic control system management.

In the context of integrating business processes for travel time reliability, the following obstacles should be addressed:[93]

- State and local transportation departments are historically focused on construction and maintenance and are less operations focused and performance-driven.
- Given that travel time reliability was recently introduced as a performance metric, it may not get much attention in the business processes of transportation agencies.
- The stakeholders that contribute to or are affected by reliability business processes usually do not have the same motivations, expectations, and approaches to implementing changes.

INTEGRATING RELIABILITY IN THE TRANSPORTATION PLANNING AND MANAGEMENT PROCESSES

Traditionally, average delay and level of service have been used as performance measures for transportation planning and management. These measures do not indicate the variability of travel time. However, some agencies have started incorporating travel time reliability as an additional performance measure in their planning and management process.[28] This entails incorporating the benefits of travel time reliability in benefit-cost analyses for project prioritization.

The Virginia Department of Transportation has integrated travel time reliability into its planning and project selection process. Similarly, the Florida Department of Transportation is incorporating operations and travel time reliability into its planning process.[86] The Maryland State Highway Administration has developed a framework for including the value of travel time reliability in the project evaluation, prioritization, and implementation process.[27]

Address key obstacles, including:

- Help State and local transportation departments be performance-driven
- Incorporate travel time reliability metrics in project prioritization
- Engage key stakeholders in identifying and implementing business process changes that improve reliability

Other examples of techniques include the organizational and institutional approaches to enhancing reliability. Many of the strategies that enhance travel time reliability are focused on improvement in highway operations and traffic management. However, this can be successful only if the strategies are complemented by efficient collaboration and coordination among the divisions within an agency and other key public agencies. Effective traffic management at work zones, incidents, and adverse weather conditions requires effective collaboration among multiple organizations that perform the various functions of the system (e.g., traffic management center operators, transit service providers, police departments, fire divisions, emergency medical services, construction firms, maintenance crews, debris clearance crews, safety service patrols, weather information services, and towing companies). Therefore, improvement in travel time reliability should consider a systemic approach to successfully execute programs and activities. FHWA offers capability maturity frameworks on these and other topics to aid agencies in assessing their situation and improving their performance.[94]

Institutional approaches should be considered in improving highway operations and travel time reliability. These types of approaches mainly address non-technical features of an agency.[95] Non-technical features include the existing culture, leadership, priorities, staffing, resources, relationships, and interactions of an agency. For example, effective work zone management requires an "interrelated sequence of planning, systems engineering, resource allocation, procurement, project development and implementation, procedural coordination, and so forth."[95] Successful execution of all these components depends on having a supportive institutional setting. The institutional architecture of an agency consists of more than its organization, including leadership, legal authorization, organized responsibilities, staff capabilities, available resources, and working partnerships.

A supportive institutional architecture with the following six key elements is needed to improve transportation system management and operations and enhance travel time reliability:[96]

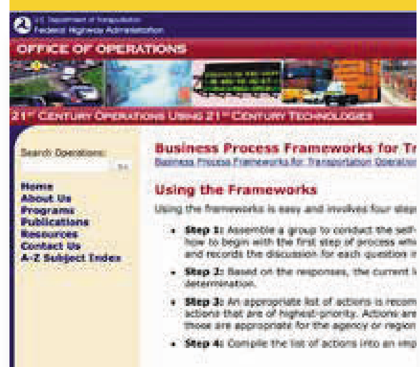
1. **Business process:** Refers to a formal scoping, planning, programming, and budgeting process to achieve a reliable transportation system. Restructuring business processes to improve reliability requires intervention with various agency divisions. This also includes improving the technical and administrative activities of transportation agencies and institutionalizing the process. Improved reliability business processes start with setting reliability goals and constantly monitoring and evaluating performance outcomes at various agency divisions.
2. **Systems and technology:** Defines the approach to building a reliable transportation system by developing system architecture, standards, interoperability, standardization, and documentation to improve transportation reliability. Standard specifications of reliability metrics, objectives, and goals focus the efforts of different agencies on a common outcome.
3. **Performance measurement:** Determines the metrics, data sources, and data analysis techniques to be used for measuring and evaluating reliability. Tracking reliability data can provide useful information to quantify system performance, identify opportunities to improve system operations, and promote quantifiable accomplishments.
4. **Culture:** Refers to the values, assumptions, and priorities of an agency. Lack of commitment to advance mobility, level of service, customer and stakeholder support, and accountability lead to inefficient traffic operations and management. Undertaking educational programs on travel time reliability and its importance to road users can significantly change the culture and leadership of an agency.
5. **Organization and workforce:** Seeks to improve the structure of a transportation agency and improve its workforce capability, professional development, and retention. Construction and maintenance projects may have previously been given significant attention, while traffic management and other functions were left fragmented and understaffed with limited capabilities to improve reliability. Well-trained staff with clearly defined responsibility, accountability, and performance incentives with respect to reliability are required.

TSMO FRAMEWORKS

TSMO is a set of strategies that focus on operational improvements that can maintain and restore performance of the existing transportation system. Agencies can use the following six frameworks to assess and upgrade their TSMO:

- Traffic Incident Management
- Traffic Management
- Work Zone Management
- Traffic Signal Management
- Road Weather Management
- Planned Special Events

Learn more at **https://ops.fhwa.dot.gov/tsmoframeworktool**.



There are **six key elements** to improve TSMO and enhance reliability:

BUSINESS PROCESSES

SYSTEMS AND TECHNOLOGY

PERFORMANCE MEASUREMENT

CULTURE

ORGANIZATION AND WORKFORCE

COLLABORATION

6. **Collaboration:** Refers to improving the relationship and communication between stakeholders, partners (e.g., public agencies, local governments, and metropolitan planning organizations), and the private sector. Lack of clearly defined roles and responsibilities for these groups has an adverse effect on addressing congestion and reliability improvements. Consolidated and stable partnerships always benefit reliability. This can be achieved by agreeing on the operational roles and responsibilities of stakeholders, identifying opportunities for joint operational activities, developing procedures for minimal disruptions, and developing public–private partnerships.

Examples of institutional best practices that State transportation departments have implemented include the following:[90]

- Strong and transparent commitment to operational improvements by developing goals, objectives, and strategies in line with the enactment of the Federal transportation legislation, *Moving Ahead for Progress in the 21st Century Act*.[23]
- Public–private partnership for prompt clearance of incidents as demonstrated by both the FDOT Rapid Incident Scene Clearance and GDOT Towing and Recovery Incentive programs.
- Development of unique contractor requirements for effective work zone traffic control as demonstrated by the Oregon Department of Transportation.
- I-95 Corridor Coalition's Operations Academy that provides a 2-week training to middle and upper transportation department managers on transportation management and operations.

The matrix on the following page presents some possible reliability-related problems, solutions, and suggested reports with practical guidance for State transportation departments. Additional resources with useful TSMO insights for addressing reliability-related issues include the following:

- FHWA primer: *Improving Business Processes for More Effective Transportation Systems Management and Operations*.[97]
- FHWA primer: *Creating an Effective Program to Advance Transportation System Management and Operations Primer*.[98]
- American Association of State and Highway Transportation Officials' TSMO Web-based publications: **http://www.aashtotsmoguidance.org**.[99]

Table 4. Potential reliability problems, solutions, and resources.

Problem	Possible Solution	Report No.
Reliability is not considered a highway performance measure	▶ View reliability as an additional highway performance measure ▶ Initiate reliability monitoring programs and turn reliability data into useful information	S2-L02-RR-1 S2-L03-RR-1 S2-L05-RR-3
Reliability benefits are not incorporated in project appraisal	▶ Consider reliability's benefits in the project prioritization process (e.g., consistent travel time, reduced secondary crashes, reduced emissions, and others)	S2-L05-RR-3 S2-L11-RR-1 S2-L35B-RW-1
Reliability is not integrated into the business process of the transportation agency	▶ Define reliability goals and identify activities that need to be changed to achieve the goals ▶ Monitor outcomes against reliability goals	S2-L01-RR-1 S2-L01-RR-2
Understanding of operational strategies and treatments to improve reliability is limited	▶ Identify the strengths, weaknesses, threats, and opportunities of key operational strategies and strategies for improving travel time reliability	S2-L11-RR-1 S2-L03-RR-1 S2-L07-RR-1
Organizational and institutional approaches for improving reliability are not considered	▶ Assess the existing culture, leadership, priorities, staffing, resources, relationships, and interactions of the agency to improve reliability ▶ Improve coordination between public and private stakeholders	S2-L06-RR-1
Existing real-time travel information initiatives lack reliability information	▶ Develop a process to provide reliability information to travelers	S2-L14-RW-1 S2-L14-RW-2

All reports listed in this table are available online at **http://www.trb.org/StrategicHighwayResearchProgram2SHRP2/Pages/Reliability_Projects_302.aspx**.

WHAT CAN I DO?

USDOT Leadership

▶ Prioritize TSMO; allocate resources and coordinate activities to improve reliability

Transportation Planners

▶ Incorporate reliability into planning and quantify the benefits for decisionmakers

First Responders

▶ Establish and follow best practices to safely minimize lanes closed and time to reopen

Transportation Users

▶ Drive carefully and consider alternate routes, modes, and travel times when feasible

Visit the TSMO website for more information: **https://ops.fhwa.dot.gov/tsmo**

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