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TRAVEL-TIME RELIABILITY DATA AND ANALYSIS TOOLS: UTAH PILOT TESTS (SHRP2 L38 IAP ROUND 7, INCLUDING L02, L05, L08)

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Final Report
March 2020

RESEARCH
Keeping Utah Moving
Utah Department of Transportation - Research Division
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16. Abstract
Travel-time reliability (TTR), which significantly influences people's travel experience and costs, is an important indicator in evaluating the performance of the transportation system, especially the freeway network. To evaluate TTR of transportation systems and incorporate TTR into the planning and programming process, the SHRP2 program previously completed a series of research projects and produced multiple products. In this project, we have conducted pilot tests on products developed via multiple SHRP2 projects, including L02, L05, and L08. The L02 project developed a holistic method with statistical probability functions of travel time as the TTR measure to build highway performance evaluation and monitoring systems. The L05 project proposed a guideline of incorporating TTR into the planning and programming process for project managers and other decision makers. In addition, the L08 project developed a TTR analysis tool that incorporated non-recurrent congestion into the Highway Capacity Manual (HCM) procedure. All the products have been tested to address the local issues in Utah: the holistic method from L02 and the reliability analysis tool developed in L08 have been applied to analyze TTR on an interstate freeway corridor during the peak period; and the L05 project prioritization process has been applied to evaluate the priority of current statewide transportation improvement programs in Utah. The results have been carefully analyzed to evaluate the adoptability of these products. We have also developed multiple tools and approaches to make the products user-friendly and better their assistance to transportation agencies.

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SHRP2, Travel-Time Reliability, Planning, Traffic Operation, Highway Capacity

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UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BTI	Buffer Time Index
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
PTI	Planning Time Index
SHRP2	Strategic Highway Research Program 2
TRB	Transportation Research Board
TTI	Travel Time Index
TTR	Travel-Time Reliability
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

Travel-time reliability (TTR), which significantly influences people's travel experience and costs, is an important indicator in evaluating the performance of the transportation system, especially the freeway network. To evaluate TTR of transportation systems and incorporate the TTR into the planning and programming process, the Strategic Highway Research Program 2 (SHRP2) previously completed a series of research projects, such as L02, L05, and L08, which have developed multiple products to address the TTR issues. However, the effectiveness and usability of these products are still subject to testing. To this end, in this project, we have conducted pilot tests on products developed via SHRP2 L02, L05, and L08. The products have been applied to address local traffic issues in Utah, and the results have been carefully analyzed to evaluate the adoptability of the products.

The L02 project developed a holistic method using statistical probability functions of travel time as the TTR measure to build highway performance evaluation and monitoring systems. To evaluate the L02 method, a TTR analysis on the I-15 freeway corridor in Salt Lake City, Utah, with both the L02 measure and the Utah Department of Transportation's (UDOT's) current TTR measures has been conducted. Based on the comparison results, it is observed that the roadway segments on the I-15 freeway corridor demonstrate varying performance patterns in terms of TTR and such pattern changes over time. Incidents appear to contribute more to unreliability than adverse weather in Utah. The two measures produce very consistent results in the TTR assessment and unreliability sources identification. Also, the cross-validation process between the two methods can help UDOT evaluate the threshold for their quadrant-based TTR measure.

The L05 project proposed a guideline of incorporating TTR into the planning and programming process for project managers and other decision makers. To evaluate its adoptability, the guideline has been merged with Utah's current project prioritization system and showcased with an example of prioritizing freeway improvement projects on I-15 in Utah. The results demonstrate good consistency with UDOT's judgments on the project prioritization.

The L08 project developed a TTR analysis tool that incorporated non-recurrent congestion into the Highway Capacity Manual (HCM) procedure. The TTR analysis tool consists of three components: data depository, scenario generator, and computational engine. We developed a series of tools to facilitate the implementation of L08 computational engine, including an automatic segmentation tool, a seed file generator, and travel demand calibration methods. The segmentation tool can automatically divide long corridors into short segments based on the HCM segmentation rules and visualize the segmentation results for users to review and correct. The seed file generator can automatically generate a seed file to be fed into the L08 computational engine based on the segmentation results. Each seed file contains more than 70 features for each segment. To calibrate the traffic demand, the research team developed two approaches: the Annual Average Daily Traffic (AADT)-based approach estimates traffic demands based on the daily traffic profile and the demand distribution; while the volume-based approach estimates demands by matching the modeled vs. actual speed profiles. A case study of applying the L08 tool to evaluate the peak period reliability on I-15 has been demonstrated. The results of TTR analysis show that, although the L08 tool might not reproduce the exact reliability condition at individual locations, its overall reliability trend prediction is satisfactory.

1.0 INTRODUCTION

Travel-time reliability (TTR), which significantly influences people's travel experience and costs, is an important indicator in evaluating the performance of the transportation system, especially the freeway network. To evaluate TTR of transportation systems and incorporate the TTR into the planning and programming process, TRB, AASHTO, and FHWA through the Strategic Highway Research Program 2 (SHRP2) previously completed a series of research projects, such as L02, L05, and L08, which have developed multiple products to address the TTR issues. However, the effectiveness and usability of these products are still subject to testing. To this end, in this project, we have conducted pilot tests on products developed by SHRP2 L02, L05, and L08. FHWA also sponsored the SHRP2 Implementation Assistance Program (IAP), through several rounds of highlighting SHRP2 products and offering funding, for transportation agencies to implement the SHRP2 tools in their projects and operations. This Utah study was funded by one of the rounds of funding assistance for the L38 bundle which included the L02, L05, and L08 products. The products have been applied to address local traffic issues in Utah, and the results have been carefully analyzed to evaluate the adoptability of the products. The objectives of this study include:

1. Further validate the reliability analysis and diagnosis that are currently conducted at the Utah Department of Transportation (UDOT) based on the testing results for SHRP2 L02, L05 and L08; and

2. Provide meaningful interpretation of reliability measures based on the heterogeneous data sources that can be easily used by agencies and decision makers, which can lead to the investment decisions based on cost-effective solutions.

The L02 project developed a holistic method using statistical probability functions of travel time as the TTR measure to build highway performance evaluation and monitoring systems. The L05 project proposed a guideline of incorporating TTR into the planning and programming process to be used by project managers and other decision makers. The L08 project developed a TTR analysis tool that incorporated non-recurrent congestion into the Highway Capacity Manual (HCM) procedure. In this report, we provide a detailed description of pilot tests on each product with local planning or operational issues and the evaluation of the product's adoptability in Utah.

There are five chapters in this report, including this introduction, a pilot test on the L02 product, a pilot test on the L05 product, a pilot test on the L08 product, and conclusions. In each pilot test, we provide detailed information including the research method, data collection, analysis, and findings.

<u>2.0 PILOT TEST ON SHRP2 L02</u>

TTR, as a key measurement of highway performance, is also a desired piece of information for travelers. The definition of TTR can vary depending on the targeted audiences/users. For example, public agencies that are concerned about the consistency of freeway performance may define TTR as the probability that trips are completed within a specified period of time (*1*). Yet travelers and shippers who repeatedly travel along the same routes may consider TTR as the range of travel times for their commute trips (*2*). Based on the various definitions, researchers proposed and tested a series of TTR measures over the past decade, including Buffer Index (BI), Planning Time Index (PTI), Travel Time Index (TTI), just to name a few, to quantify or describe TTR for roadway networks or corridors (*3*, *4*). These measures can be easily applied due to the computational simplicity, as they are directly calculated from the mean, variance, or a percentile of historical travel times.

However, in practical cases, these measures could demonstrate inconsistent performance across networks or corridors, incurring debatable results of reliability analysis (*5*). A roadway segment determined as reliable by one measure can be diagnosed as unreliable by a different measure. Another issue with these single value reliability measures is that they fail to single out the contributions of non-recurrent congestion factors to roadway unreliability. To provide guidance to TTR analysis, the SHRP2 L02 project developed a holistic method using probability density functions (PDFs) and cumulative density functions (CDFs) to describe reliability. List et al. (*6*) showcased the L02 product by applying it in building a TTR monitoring system for several states. The method takes non-recurrent congestion factors into consideration and is able to identify the cause and location of unreliability, demonstrating its advantages over other single value measures (*7–9*). However, very few studies have been conducted to assess the effectiveness of reliability analysis with this method. In this pilot test, we focus on examining the adaptability of the TTR measures proposed by the SHRP2 L02 project and UDOT, cross-validating the two suites of measures, and calibrating the critical values in the UDOT TTR measures. The objectives of this pilot test include:

1. Apply the TTR measures proposed by L02 and UDOT to evaluate reliability on the I-15 freeway corridor in Salt Lake City, Utah, using probe data. The highly unreliable segments on the corridor as well as the causes for unreliability will be identified;

2. Cross-validate the two suites of TTR measures by comparing the results of reliability assessment and unreliability source identification; and
3. Adjust the critical values in the TTR measure proposed by UDOT based on cross-validation results.

The rest of this chapter is organized as follows. The next section briefly reviews previous efforts on TTR measurements. Then, the TTR monitoring system developed in SHRP2 L02, the probe data, and the reliability measure currently used by UDOT will be introduced. Using the I-15 corridor in Salt Lake City, Utah, as a case study, the section to follow will demonstrate the result of applying the SHRP2 L02 measure. The next section will compare the results of L02 and UDOT TTR measures for cross-validation. The final section provides concluding remarks and findings.

2.1 Literature Review

As a critical issue in traffic operation, freeway TTR has been intensively studied. At the beginning, researchers focused on the performance of single value TTR measures and aimed to identify the best-fitted measures for different networks or corridors (*5*, *10*–*12*). Van Lint et al. (*5*) evaluated various TTR measures such as standard deviation, buffer time, tardy trip, width of travel time distribution, and skew of travel time distribution using empirical data. They recommended the skew of travel time distribution. Pu (*10*) explored the mathematical relationship between several TTR measures and numerically tested them with assumed travel time distribution. He found that coefficient of variation is the best proxy for other measures since it is easy to calculate and has the same varying direction (increasing or decreasing) as other measures. Yazici et al. (*11*) conducted TTR analysis with multiple reliability measures using taxi GPS data in New York City and found that those measures produce very different reliability judgments. All these studies found that the TTR analysis on one segment with multiple measures may yield different results, indicating the inconsistent performance of reliability measures.

To enhance the accuracy of reliability analysis, significant effort has been made into improving the existing measures and developing new methods to quantify TTR. One approach to improve reliability measurement is to refine the model of travel time distribution (*13*–*18*). Lei et al. (*13*) implemented shockwave theory into the probability-based TTR measures and generated six different travel time distributions based on roadway level of service. Compared with the models which simply assume travel time being normally distributed, their proposed model achieved better estimation accuracy. Yang and Wu (*14*) conducted TTR analysis with mixture models of travel time distributions, and found that TTR measures are insensitive to the selection of distribution family. Barkley et al. (*15*) incorporated non-recurrent events into multistate models of travel time. Alvarez and Hadi (*16*) conducted TTR analysis on general purpose lanes and high-occupancy-toll (HOT) lanes, separately. They found that these measures yield different continuity and sensitivity for these two types of lanes. By adjusting the models of travel time distributions, especially in Barkley et al. (*15*), the non-recurrent factors can be incorporated into TTR measures, which represents an important improvement in reliability analysis.

Another approach for improving reliability measures is to apply a modeling process to construct travel time distribution (*19*–*21*). Mauro et al. (*20*) simulated a series of traffic scenarios with random events based on the speed and vehicular density, and with the simulated flow and speed, the travel time unreliability is evaluated. Tu et al. (*21*) constructed a macroscopic travel-time reliability diagram (MRD) to describe the relationship between travel-time reliability and average density. The diagram was tested in multiple networks to identify critical vehicle density, below which the vehicle density has little impact on TTR. Compared with the approach of refining travel time distribution models, the simulation or modeling process is computationally complicated. However, it increases the frequency of non-recurrent events, providing sufficient information for TTR estimation. Note that for either approach, very few studies have been conducted on the measurement validation.

With TTR properly measured, researchers could focus on diagnosis of travel time unreliability causes (*22*–*25*). Kwon et al. (*22*) applied an empirical corridor-level method to divide the contributions of multiple non-recurrent events, such as weather, incidents, work zone, and special events on travel time variation and found that incidents have the highest contribution among non-recurrent events. Caceres et al. (*26*) proposed a probabilistic model for estimating route travel time variation with consideration of weather and incidents. They found that adverse weather except snow has minor impacts on traffic during non-peak period but causes great travel time variation during peak period.

2.2 Methodology

The SHRP2 L02 project provided guidance on building a travel-time reliability monitoring system (TTRMS) on top of the current traffic management system. The TTRMS consists of four components: measuring travel time, characterizing reliability, identifying unreliability sources, and understanding the impacts of these sources. Accurate travel time measurement is the foundation for TTR analysis, and highly relies on the quality of the detection system. In L02, PDFs and CDFs are applied to characterize reliability under a particular operating regime – defined via a combination of congestion levels and non-recurrent events. Unreliability can be caused by both endogenous and exogenous factors, including demand variation, incident, weather, special events, infrastructure failures, and performance of complementary and competing transportation modes. With the TTRMS, operators can understand how unreliability is generated and make decisions to mitigate its impacts.

In this pilot test, travel time information is retrieved from HERE traffic data, which is collected from multiple sources, such as in-vehicle devices, smartphones, road sensors, and connected vehicles. Compared with loop detector data which requires sensors installed on the roadway, probe data does not rely on roadway infrastructures, providing more comprehensive coverage of the network (*27*). Another benefit of using probe data is its accurate estimation of travel time, especially when the loop detector data is sparse (*28*).

Travel time observations, once retrieved, are classified into multiple regimes, based on the congestion level and occurrence of non-recurrent events. To observe the variation of travel time distribution, the PDFs and CDFs of travel time under each regime are visualized. By comparing the PDFs or CDFs across regimes, the operators are able to identify the unreliability sources and estimate the contribution of each source. For example, to create the travel time CDF of incident regime, we will identify all scenarios with incident on the segment during the study interval. Then we will draw the CDF curve of travel time in these scenarios. This CDF curve represents the performance of the segment in terms of travel time under the impacts of incident. To diagnose the unreliability sources, multiple regimes, such as incident, adverse weather, and work zone, will be created and their corresponding CDF curves will be constructed together with the one under normal operating condition. By comparing these curves, we can assess the TTR on the segment and identify the major unreliability sources. Detailed explanation of TTR evaluation and unreliability source identification will be given in the *Case Study* section.

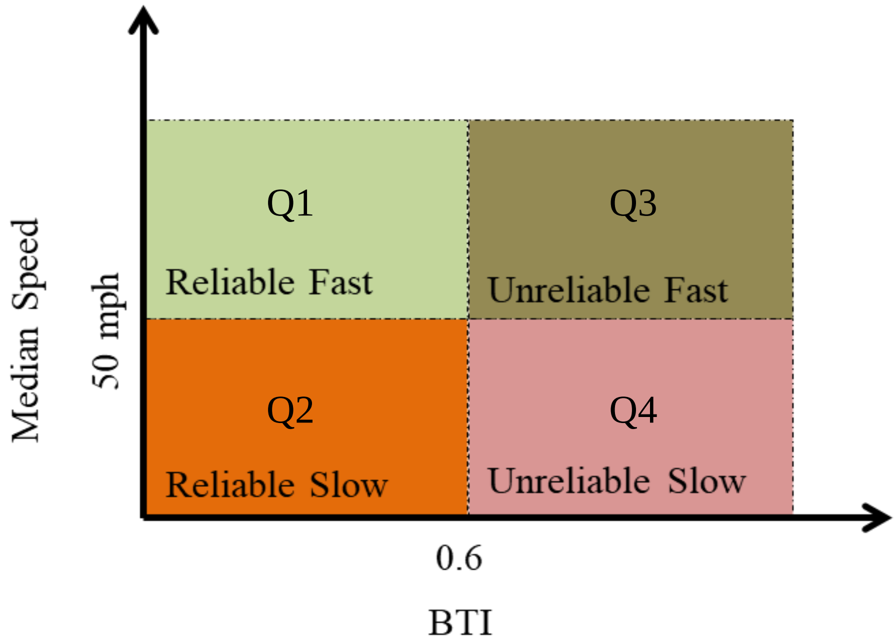


Figure 2.1 Illustration of the Quadrant-Based TTR Measure Currently Used by the UDOT

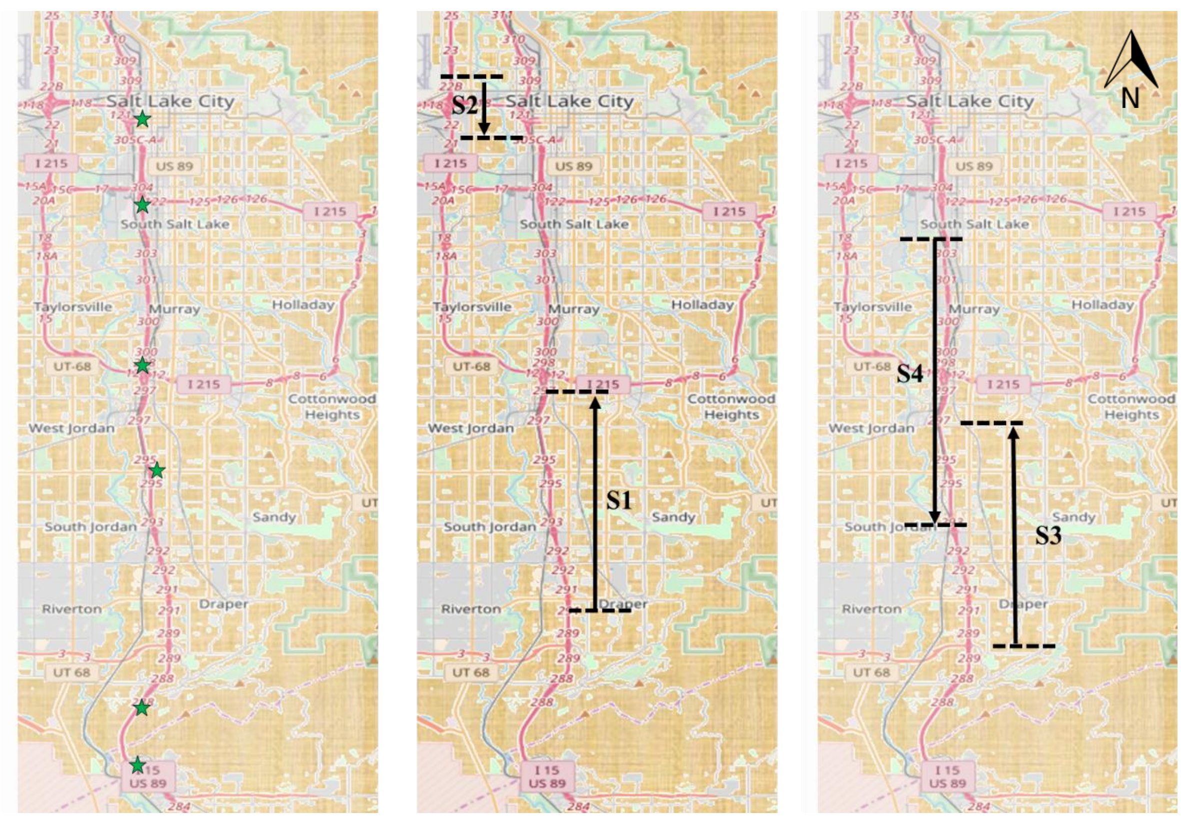
UDOT has established a freeway performance monitoring system to improve the decision-making process for traffic operation. In the system, a new quadrant-based TTR measure considering both travel speed and extra travel time needed to be on-time has been applied. The freeway corridor is broken down into short segments (approximately 1 mile each). For each segment, two attributes are calculated based on the historical traffic data: median speed and buffer time index (BTI). BTI is calculated as the extra time that travelers must add to their average travel time when planning trips to ensure on-time arrival. In the current TTR configuration adopted by UDOT, when the median speed is below 50 mph, a segment is considered slow; otherwise, fast. A segment is considered unreliable if BTI is greater than 0.6, meaning that a person has to add 60% more of the travel time in order to arrive on time 95% of the time. Based on the values of these attributes, freeway segments are classified into four categories: reliably fast (Q1), reliably slow (Q2), unreliably fast (Q3), and unreliably slow (Q4).

Figure 2.1 illustrates the quadrants. Each quadrant represents a unique pattern of reliability and the cause for unreliability. As Tu et al. (*21*) mentioned, there are two major unreliability sources: demand variation and supply (capacity) variation. Among the four categories, Q1 represents the most desirable traffic conditions: high speed and low travel time variation. Q4 represents the worst traffic conditions: low speed and long buffer time. Segments in Q4 are considered under the impacts of both unreliability sources: demand variation reflected by the highly varying traffic volumes and non-recurrent congestion factors that cause supply variation. Segments that fall within Q2 and Q3 are suffering unreliable traffic conditions, but not as bad as Q4. For segments in Q3, traffic moves at high speed but suffers highly fluctuating travel time, implying that non-recurrent factors often cause severe increase in total congestion. Segments in Q2 have low travel time variation and low speed, so the non-recurrent congestion is negligible or at least not significant compared with recurrent congestion. In summary, the quadrants represent various reliability patterns. All the thresholds in defining the regimes are determined via robust sensitivity analysis.

2.3 Case Study

In this pilot test, we have conducted TTR analysis on I-15 freeway segments in Salt Lake City, Utah, using measures from SHRP2 L02 project and the UDOT performance monitoring system. The studied I-15 corridor in Salt Lake City spans 25 miles long between MP 285 and MP 310. Since it is a long corridor, travel time variation could be averaged out if TTR is analyzed over the entire corridor. As a result, four segments, empirically suffering very congested traffic condition during peak periods, were selected for analysis. During morning peak period (from 6 AM to 10 AM), we selected the northbound segment between 13200 S and 7500 S and the southbound segment between South Temple ST and 1300 S. During evening peak period (from 4 PM to 8 PM), the northbound segment located between 12300 S and West Center ST, and the southbound segment located between 3300 S and 10600 S were used for analysis.

HERE data on I-15 was collected for the entire year of 2016, including travel time and speed on the selected segments. The data was extracted at 5-minute granularity from non-holiday weekdays. In List et al. (*6*), 5-minute granularity is suggested since the 15-minute analysis interval used in the Highway Capacity Manual (HCM) might not fully capture the fluctuation in traffic condition. In terms of non-recurrent events, we choose incident and adverse weather in our analysis, which induce the most frequent and severe non-recurrent impacts (*29*). The incident records, which are collected from police reports, include various attributes of the incidents, such as location, start time, clearance time, severity, and incident type. In 2016, there were 2,899 incidents that happened on the I-15 corridor in Salt Lake City. In our study segment, there were a total of 2,081 incidents. Weather data is obtained from the MesoWest project, including temperature, relative humidity, wind speed, precipitation, and other weather parameters (*30*). The MesoWest project collects the current weather condition and provides access to archived weather observations across the country. There are 6 stations along I-15 in Salt Lake City, recording the weather data every 10 minutes. The locations of the four study segments and weather stations are illustrated in Figure 2.2. During the year of 2016, the six stations identified 5,879 precipitation records. Table 2.1 summarizes the information of each I-15 segment and the frequency of non-recurrent events.



(a) (b) (c)

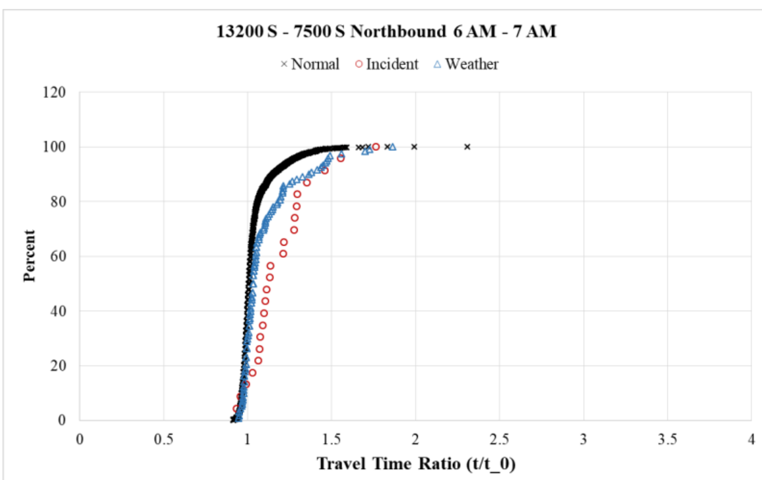
Figure 2.2 Illustrations of Weather Stations and the I-15 Freeway Segments: (a) Weather Stations, (b) Segments for Morning Peak Period, and (c) Segments for Evening Peak Period

Table 2.1 I-15 Freeway Segments for TTR Analysis

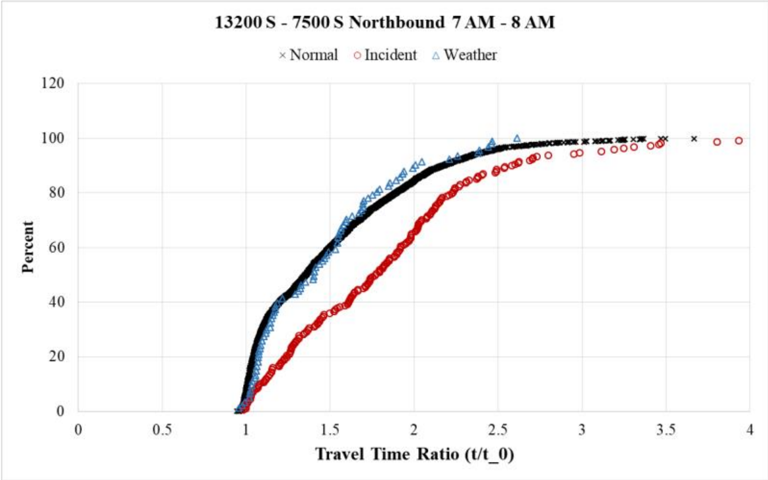
	Morning		Evening	
Segment	S1: 13200 S -7500 S	S2: South Temple ST – 1300 S	S3: 12300S - West Center ST	S4: 3300 S- 10600 S
Direction	Northbound	Southbound	Northbound	Southbound
Distance (mile)	7.2	2.9	5.7	9.6
Number of peak period scenarios	11,952			
Number of incident scenarios	255	882	1,889	2,112
Number of adverse weather scenarios	233	404	254	251

TTR analysis was conducted for the selected segments during morning and evening peak periods. Each peak period spans 4 hours, during which traffic conditions may change significantly. It was further broken down into one-hour intervals for traffic pattern comparison. List et al. (*6*) suggested that CDFs are more helpful than PDFs for reliability comparison; our L02 analysis therefore uses CDF.

Figure 2.3 shows the CDFs of travel time on segment S1 between 13200 S and 7500 S from 6:00 AM to 10:00 AM. To make the CDFs between different segments comparable, the travel time of each segment t has been normalized by the free flow travel time t_0. In Figure 2.3 (a), it is observed that the CDF curve of normal traffic condition from 6 AM to7 AM has a very steep slope. Almost all trips are completed within twice of the free flow travel time, indicating smooth traffic on the segment. After 7 AM (Figure 2.3 (b)-(c)), the CDF curves of normal condition slant horizontally. Around 20% of trips spent more than twice of the free flow travel time. The traffic condition recovered after 9 AM (Figure 2.3 (d)). From the temporal shifts of CDF curves of normal traffic condition, we can observe that the *actual* morning peak period for S1 occurs between 7 AM to 9 AM. The CDF curves of incident regime are consistently below the curves of normal condition, indicating the negative impacts of incidents on travel time. The CDF curves of adverse weather regime show that the adverse weather has mixed impacts on traffic. Between 6 AM and 7 AM (Figure 2.3 (a)), the travel time during adverse weather is always longer than the one under normal condition at the same percentile. After 7 AM (Figure 2.3 (b)-(d)), compared with normal condition, the adverse weather curves start with longer travel time, initially overlap with the normal condition curves, but eventually outperform the normal condition. This phenomenon can be caused by several reasons: the first one stems from the definition of adverse weather in our study. Scenarios in adverse weather regime are identified based on precipitation. Scenarios with drizzle rain and thunderstorm, which could incur very different impacts on traffic, are all classified into the same regime. In the Salt Lake City area, a considerable number of scenarios in the adverse weather regime are of light precipitation. There is no pronounced difference in traffic condition between these scenarios and the ones under normal traffic condition. This explains the overlap between the two CDF curves. Another reason lies in the methodology itself. By using the statistical probability functions, it is easy to observe travel time distribution. Yet for some less frequently observed regimes, where sample size is limited, the constructed CDFs are easily influenced by individual cases, providing biased results. This explains why travel time of adverse weather regime is shorter than the normal condition at upper percentile.



(a)



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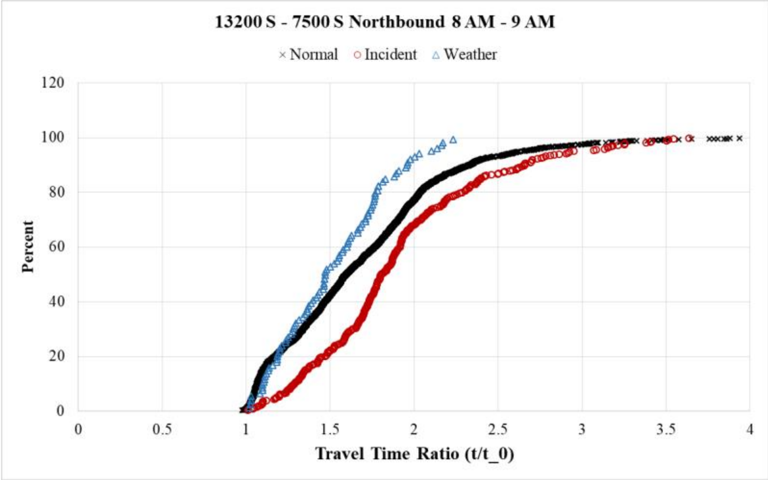
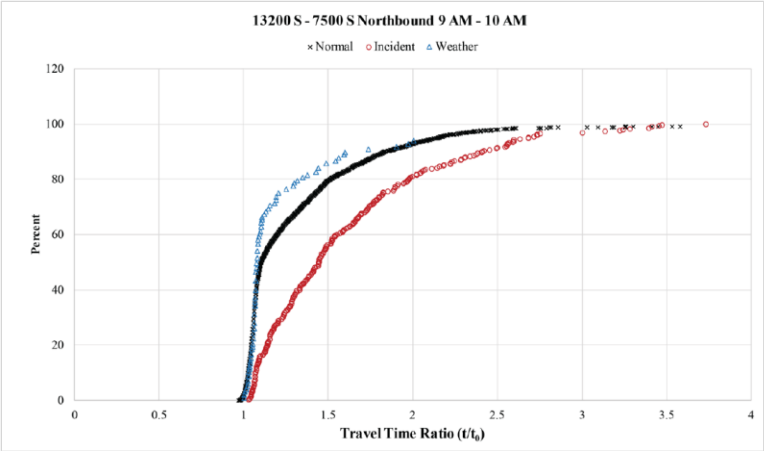


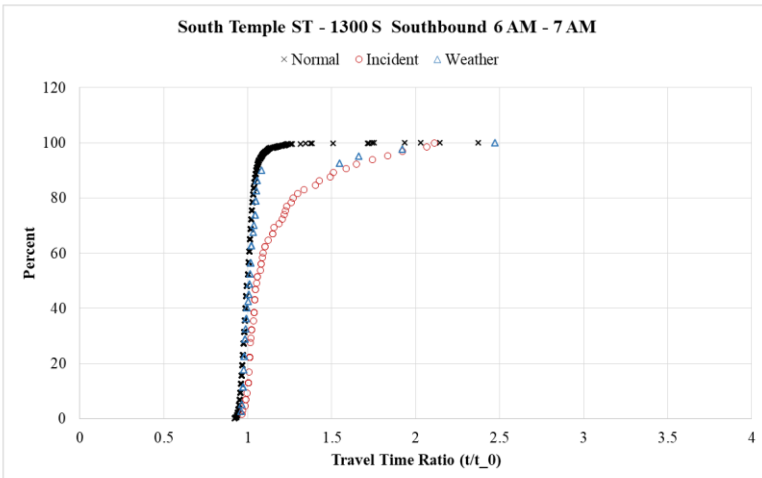
(c)



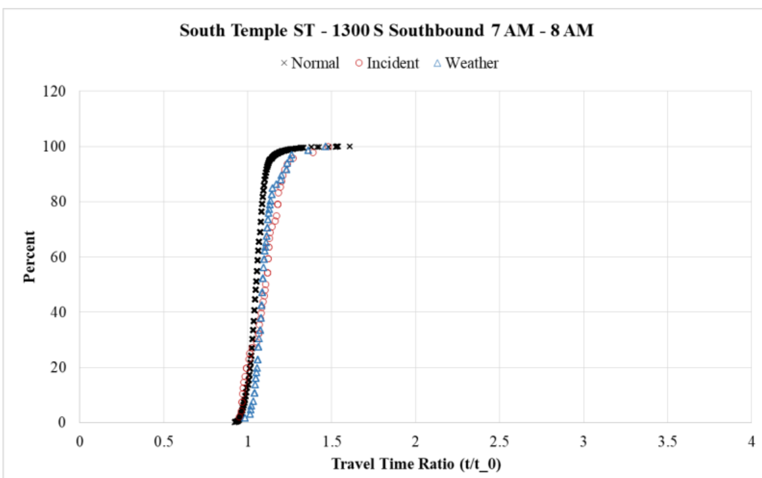
(d)

Figure 2.3 CDFs of Normalized Travel Time t/t_0 on S1 during Morning Peak Period: (a) 6:00-7:00 AM, (b) 7:00-8:00 AM, (c) 8:00 – 9:00 AM, and (d) 9:00 – 10:00 AM

Figure 2.4 shows the CDFs of travel time on S2 from 6:00 AM to 10:00 AM. Although we empirically selected congested segments during peak period, according to the TTR analysis results, traffic condition on S2 is not as bad as S1. Traffic under normal condition is quite consistent and smooth for the entire morning peak period. Travel time slightly increases after 8:00 AM (Figure 2.4 (c)-(d)), and the CDF curves for normal condition show long tails, indicating that extremely long travel time cases happened during this period.



(a)



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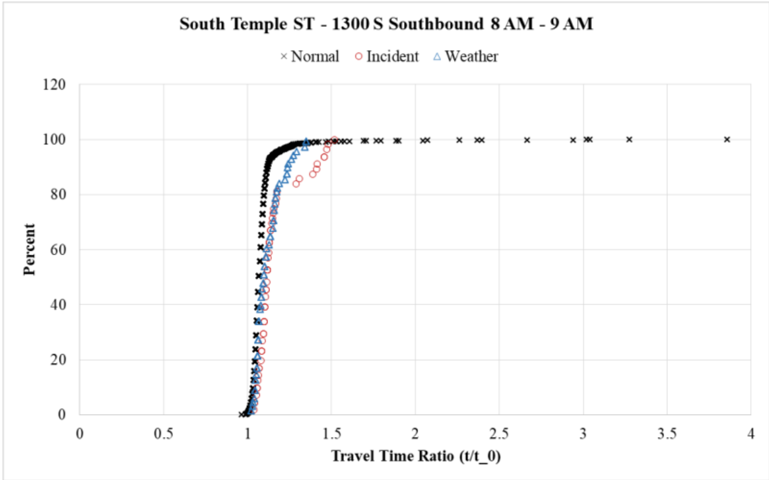

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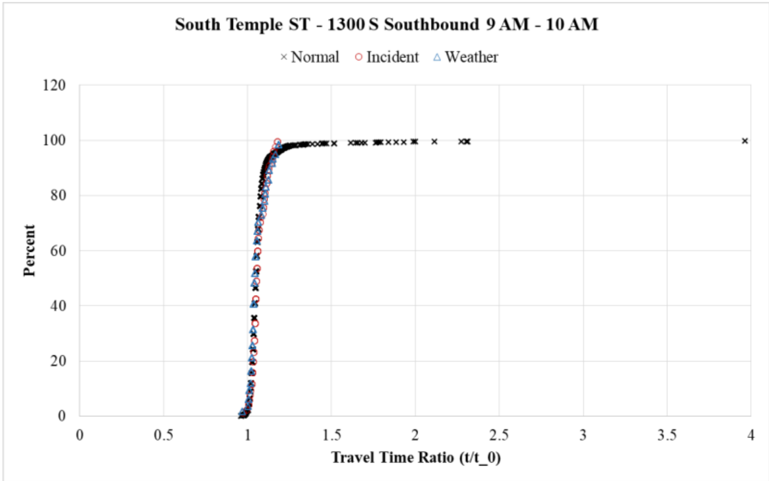
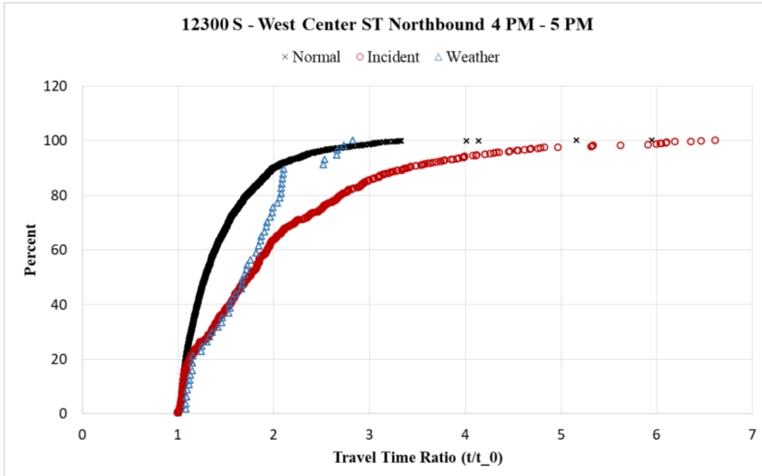


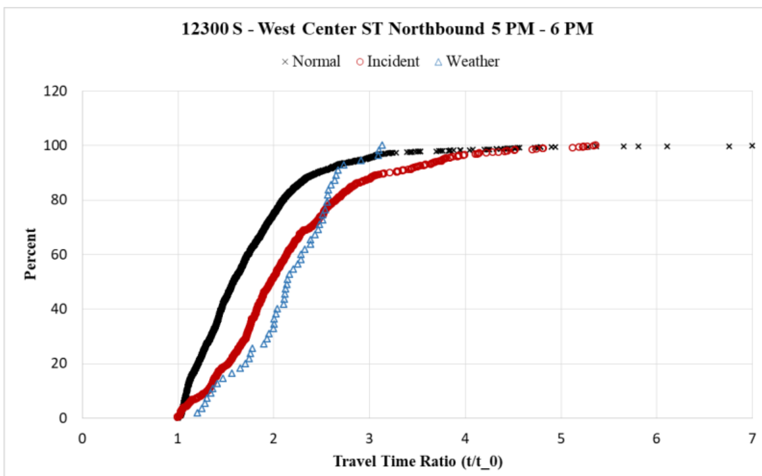
(d)

Figure 2.4 CDFs of Normalized Travel Time t/t_0 on S2 during Morning Peak Period: (a) 6:00 -7:00 AM, (b) 7:00 -8:00 AM, (c) 8:00 – 9:00 AM, and (d) 9:00 AM -10:00 AM

Figure 2.5 shows the CDFs of travel time on S3 during evening peak period. By comparing the curves for normal condition, it is observed that peak period for segment S3 starts as early as 4 PM and ends by 7 PM, and the worst congestion happens between 5 PM and 6 PM (Figure 2.5(b)). The curves for incident regime are consistently below the curves for normal condition, demonstrating the conspicuous impacts of incidents in terms of travel time. Different from S1 and S2, adverse weather is also a major contributor to the unreliability between 4 PM to 6 PM on S3 (Figure 2.5(a)-(b)). The substantial gaps between the curves of normal condition and adverse weather indicate that precipitation between 4 PM to 6 PM can significantly increase the travel time on S3. Especially between 5 PM to 6 PM, it generally increases the travel time by half of the free flow travel time.



(a)



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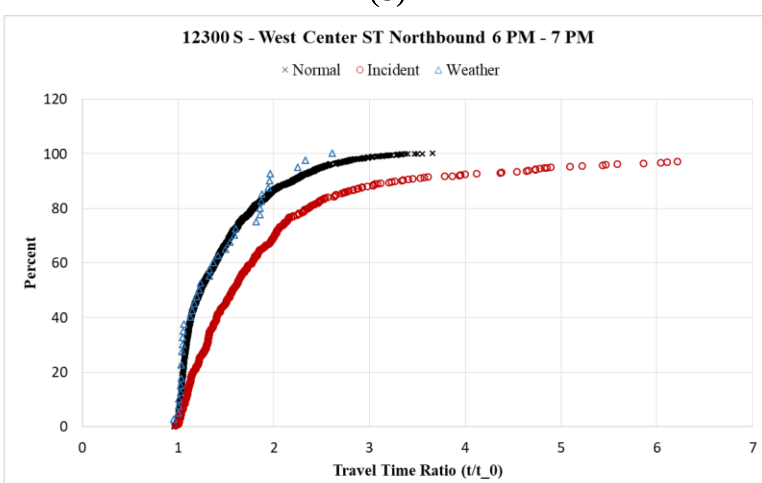

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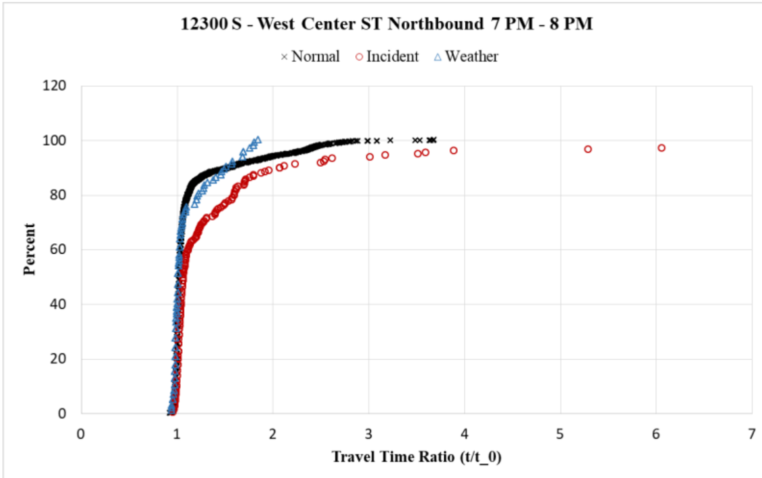
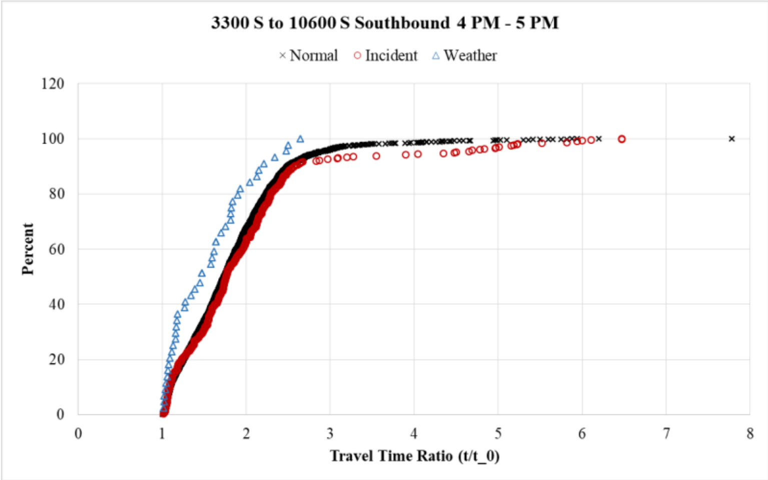


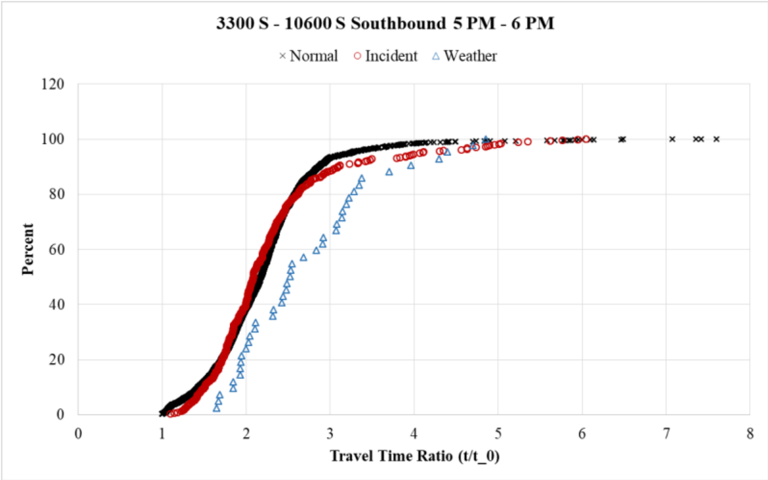
(d)

Figure 2.5 CDFs of Normalized Travel Time t/t_0 on S3 during Evening Peak Period: (a) 4:00 - 5:00 PM, (b) 5:00 - 6:00 PM, (c) 6:00 PM to 7:00 PM, and (d) 7:00 PM to 8:00 PM

Figure 2.6 shows the CDFs of travel time on S4 during evening peak period. Figure 2.6 (a)-(c) demonstrate very skewed CDF curves under normal condition, indicating that peak period on S4 starts from 4 PM and ends by 7 PM. But during evening peak period, the gaps between the travel time distributions of normal condition and incident regime are quite narrow. It means that the travel time remains the same or slightly increases due to incident on S4. Therefore, we can speculate that incident is not a major source for unreliability on S4 during evening peak period. In Figure 2.6(d), from 7 PM to 8 PM, the CDF curve of normal condition shows that travel time starts to decrease. By comparing the travel time distributions of incident regime over time, it is observed that the distributions from 4 PM to 7 PM are similar. After 7 PM, the upper 50 percent of travel time remains the same, yet the lower 50 percent of travel time significantly drops. This coincides with the temporal traffic pattern: after 7 PM, as traffic congestion is gradually relieved, less severe incidents can be relatively easily dismissed and would not cause much negative impacts. Yet severe incidents, which could potentially block multiple lanes, still may increase travel time significantly on the segment. It also explains the turning point on the CDF curve of incident regime in Figure 2.6(d).


3300 S to 10600 S Southbound 4 PM - 5 PM
× Normal ○ Incident △ Weather
Percent
Travel Time Ratio (t/t_0)

(a)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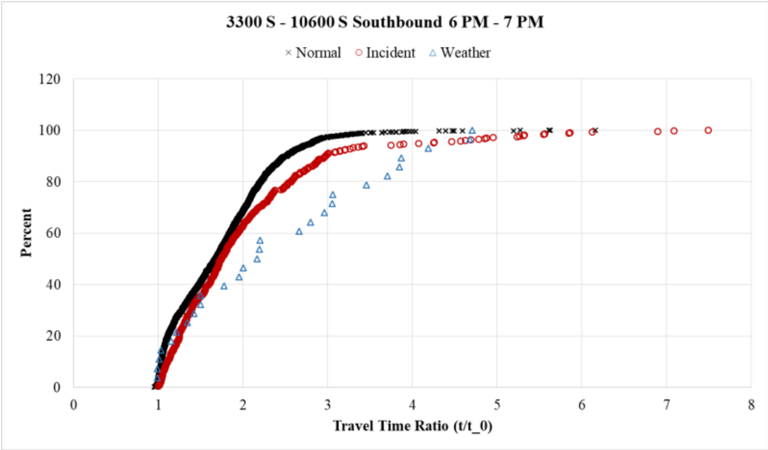
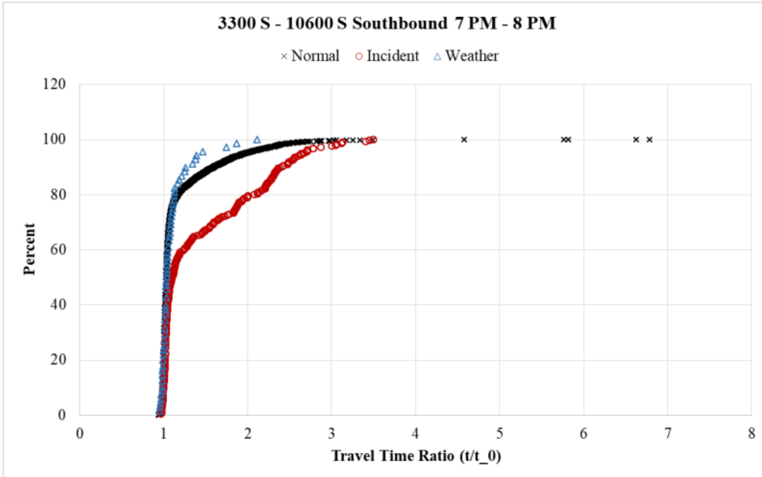
× Normal ○ Incident △ Weather
Percent
Travel Time Ratio (t/t_0)

(b)


3300 S - 10600 S Southbound 6 PM - 7 PM
× Normal ○ Incident △ Weather
Percent
Travel Time Ratio (t/t_0)

(c)



(d)

Figure 2.6 CDFs of Normalized Travel Time t/t_0 on S4 during Evening Peak Period: (a) 4:00 - 5:00 PM, (b) 5:00 - 6:00 PM, (c) 6:00 - 7:00 PM, and (d) 7:00 - 8:00 PM

In summary, travel time distributions on the selected segments during peak periods show different reliability patterns, and from these patterns, we can speculate the varying unreliability sources. In the next section, we compare these results with the output of quadrant-based TTR measure to cross-validate each other.

2.4 Analysis: Cross-Validation

To conduct a comprehensive cross-validation, besides the assessment presented in the previous section, we extend the analysis to the study segments during other peak periods, namely, evening peak period for S1 and S2, and morning peak period for S3 and S4. The peak periods are still broken down in one-hour interval. Both SHRP2 L02 and UDOT measures have been applied. In Figure 2.7, we mapped the traffic condition of each segment during each one-hour interval by BTI and median speed to determine which quadrant they belong to. Each point in Figure 2.7 represents the hourly performance of one segment.

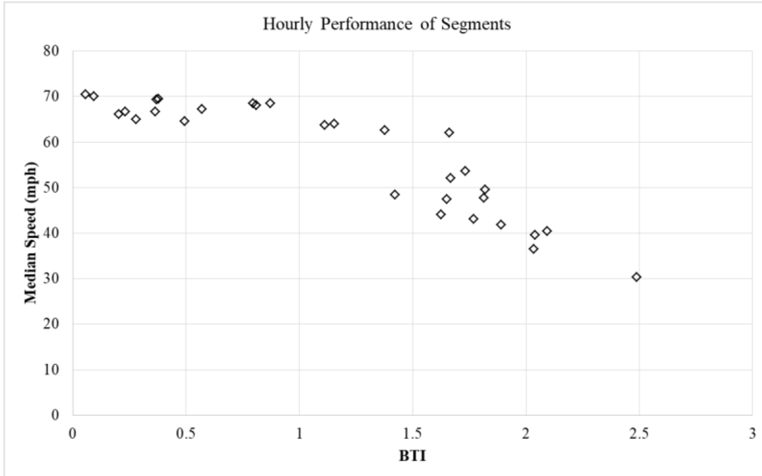
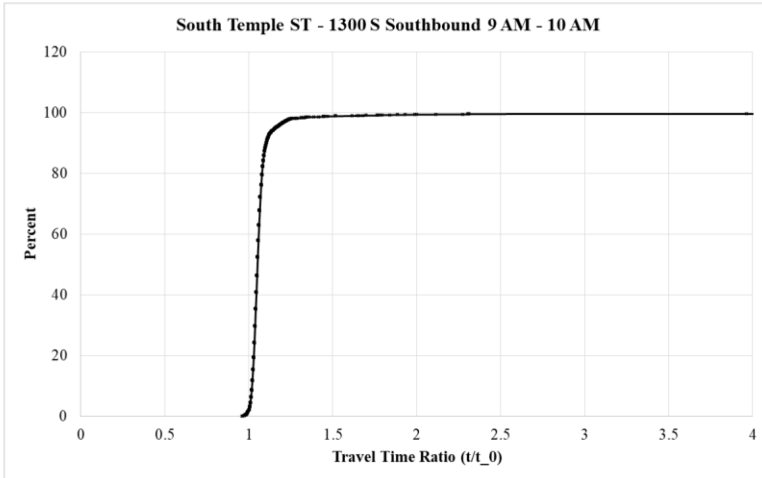


Figure 2.7 TTR Analysis Results of UDOT Quadrant-Based Measure

One important guideline for evaluating reliability with the L02 TTR measure is the shape of CDF curve. To quantitatively describe CDF curves, we identified two typical distributions of travel time illustrated in Figure 8. By comparing these distributions, we decided to use the difference between 20 percentile and 80 percentile travel time (referred as ΔT) as the parameter to describe the two distributions. When ΔT is below half of the free flow travel time, the CDF curve resembles the curve in Figure 2.8(a), indicating that it follows the reliable pattern. Otherwise, it resembles the curve in Figure 2.8(b) and follows unreliable pattern. Based on the value of ΔT, all the observations are classified into the categories of reliable and unreliable. Then we marked each observation in the quadrant domain by its category, illustrated in Figure 2.9. It is observed that almost all the reliable observations cluster in the area from the center to the top left area, which represents the desired and smooth traffic condition. The unreliable observations cluster in the area from the center to the bottom right of the domain, representing the undesired traffic condition. It is therefore concluded that the two suites of measures are consistent in terms of reliability assessment under normal traffic condition.



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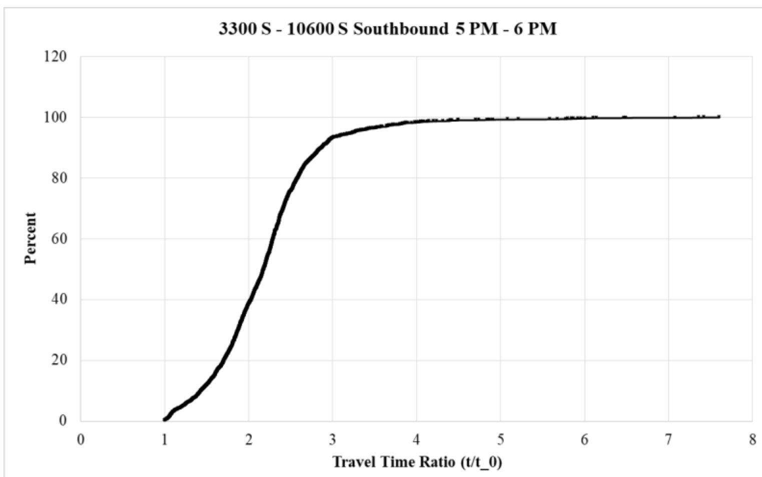


(b)

Figure 2.8 Examples of CDF Curves: (a) Reliable, (b) Unreliable

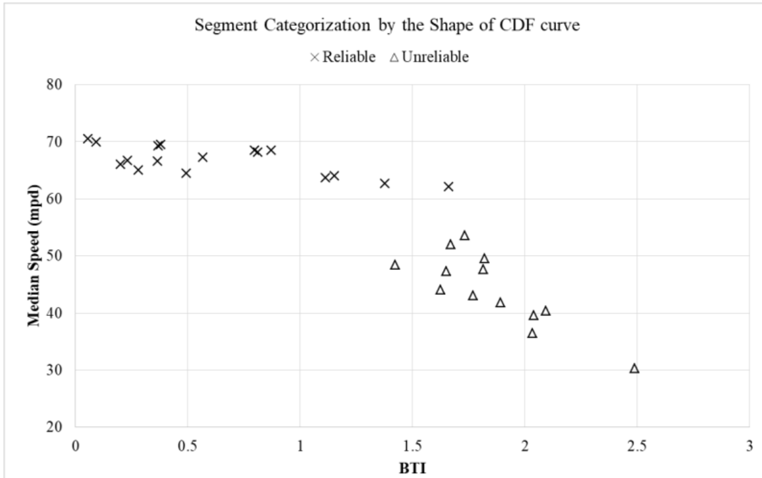


Figure 2.9 Reliable and Unreliable Observations in terms of Travel Time Distribution under Normal Condition

The most significant advantage of both measures comparing with single value TTR measures is that they are able to identify unreliability sources. In the previous analysis, it is concluded that incident is the major unreliability source for most scenarios. So to cross validate both measures in terms of unreliability source identification, we will categorize the outputs of L02 measure based on the gap between the normalized travel time distributions of normal condition and incident regime, namely, the difference between the expected values of the two distributions. The gap is illustrated in Figure 2.10. The area of the gap is calculated as:

$$A_{gap} = A_{Incident} - A_{Normal}$$

$$= \frac{1}{2}\Sigma_{i=1}^{m}(t_i + t_{i+1})(P_{t+1} - P_t) - \frac{1}{2}\Sigma_{i=1}^{n}(t_i{}' + t_{i+1}{}')(P_{t+1}{}' - P_t{}') \quad (2.1)$$

where m is the number of points in incident CDF curve, n is the number of points in the normal condition CDF curve, t and P are the normalized travel time and corresponding probability in the incident curve, and t' and P' are the normalized travel time and probability in the normal condition curve.

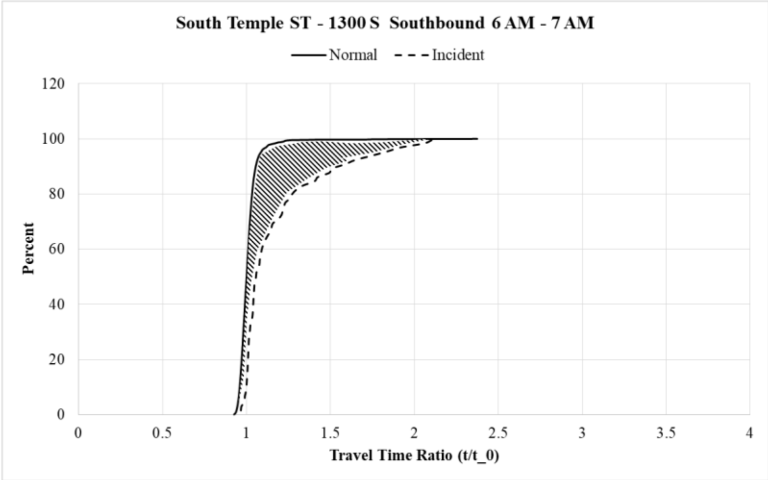


Figure 2.10 Illustration of Difference between the Expected Values of Normalized Travel Time Distributions

Figure 2.11 categorizes the segments by the gap area, which is also the travel time difference between under normal and incident conditions. The color of the dot represents the extra travel time caused by incidents. The darker it is implies there are higher impacts on travel time from incident. Note that in the figure, the color gets darker in the direction from bottom left to top right of the domain (trend marked in the figure), which is consistent with the direction from Q2 to Q3. As mentioned earlier, Q2 and Q3 imply different unreliability sources: unreliability on road segment in Q2 is mainly caused by the demand variation (traffic flux), while for road segment in Q3, it is caused by the supply variation (non-recurrent factors). From Q2 to Q3, the contribution of non-recurrent factors on travel time unreliability increases. The color changes represent the growing impacts of incidents on traffic based on the SHRP2 L02 measure. It is therefore concluded that the two measures again demonstrate consistency in terms of unreliability source identification.

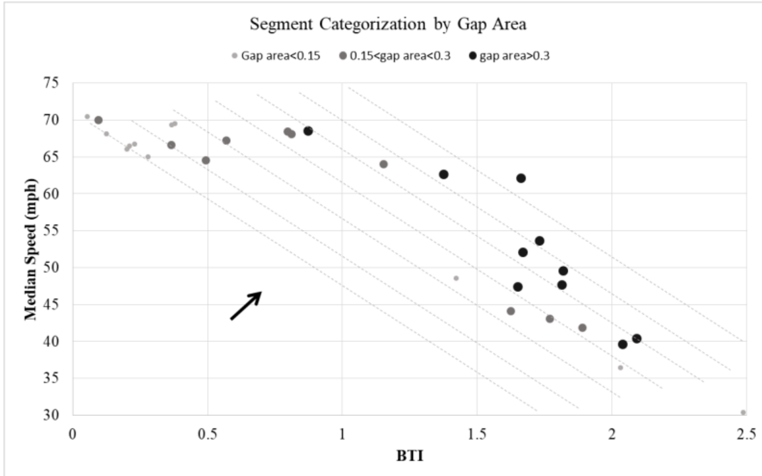


Figure 2.11 Observations Distribution in terms of Incident-Contributed Unreliability

When UDOT utilizes the quadrant-based TTR measure, the quadrants are divided at critical median speed of 50 mph and critical BTI of 0.6. However, as observed in Figure 2.10 and Figure 2.11, the reliable and unreliable observations are distinguished at BTI = 1.3 and speed = 60 mph. The cross validation therefore can help examine and adjust the critical values for the quadrant-based measure.

2.5 Summary

In this pilot test, we conducted TTR analysis on I-15 freeway corridor in Salt Lake City, Utah, using probe data. Two TTR methods are applied to the study corridor for cross validation. The first TTR measure is proposed by SHRP2 L02 project, suggesting the use of statistical probability functions of travel time in different regimes to evaluate roadway reliability and identify the unreliability sources. The second measure is currently adopted by UDOT, which categorizes segments based on median speed and BTI to construct a quadrant-based domain and to identify the reliability pattern of each segment. Based on the comparison, interesting patterns are emerged. First of all, roadway segments on I-15 freeway corridor demonstrate varying performance pattern in terms of travel-time reliability and such pattern changes over time. Between incident and adverse weather, incident contributes more to unreliability as the non-recurrent factor to most segments. Second, the two measures produce consistent results in terms of TTR assessment and unreliability sources identification. Third, the cross-validation process can help UDOT evaluate thresholds for the quadrant-based TTR measure. Future efforts of the study will focus on applying simulation or modeling approach to construct statistical probability functions and cross-validating the measures at the network level.

3.0 PILOT TEST ON SHRP2 L05

One primary challenge in estimating TTR is its random nature, which is mainly caused by non-recurrent factors, including incident, adverse weather, work zone, special event, etc. Non-recurrent congestion impairs the performance of transportation system and lowers its reliability by decreasing the probability that a trip can be successfully made within a certain time period. Although many aspects such as safety, environmental impacts, and economy are critical for transportation agencies to consider when selecting transportation improvement projects, TTR is certainly an important indicator during the project prioritization process. In order to assist DOTs and local transportation agencies streamline project prioritization process, the SHRP2 L05 program developed a systematic guideline on how to incorporate TTR into the process. The products of L05 program include a detailed guideline, a technical reference, and a summary of case studies. These products explain the methodological framework and provide elaborated examples to the agencies.

The objective of this pilot test is to evaluate the products of SHRP2 L05 program and seek for the feasibility of applying them into the project planning and prioritization process in the state of Utah. We started by selecting several transportation capacity projects in our Transportation Investment Fund (TIF), and applied the L05 methodology to assess their priority. The evaluation results were compared with UDOT's current plan, which was determined via the existing prioritization process. This chapter will be organized as follows: L05 product briefing, project prioritization process in Utah, description of the candidate transportation capacity projects, and application results of the SHRP2 L05 guideline.

3.1 L05 Products Briefing

The products of L05 program include three components: 1. A detailed explanatory guideline for project managers and other decision makers on how to incorporate the reliability into their current planning or programming processes. 2. A technical reference including methods and tools for reliability estimation, reliability analysis, and benefit-cost analysis, which provide technical support for analysts and engineers in applying the guideline. 3. A case study report with examples of the guideline being adopted by transportation agencies, which serves as the validation of the guideline. In this section, we will explain each of these steps of incorporating reliability into the decision-making process for project prioritization in SHRP2 L05.

3.1.1 Guideline

3.1.1.1 Reliability

In previous studies (*31*), reliability is defined as the level of consistency in travel condition over time. There are two common interpretations of TTR that researchers and engineers currently use to measure travel consistency: the first one considers TTR as the probability that a trip can be accomplished within a certain time period; and the second one treats TTR as the extra time that travelers must add to their travel time to ensure they could arrive on time. Based on the two interpretations, multiple measurements of TTR were developed, including planning time index, buffer time index, standard deviation, semi-standard deviation, failure measure, and misery index. Table 3.1 describes the calculation of each measurement.

Table 3.1 Examples of TTR Measurements

Measurement	Definition	Description
Planning Time Index (PTI)	$\frac{95th\ Percentile\ TT}{Freeflow\ TT}$	The extra time required to arrive at a destination on time 95% of the time
Buffer Time Index (BTI)	$\frac{95th\ Percentile\ of\ TT - Average\ TT}{Average\ TT}$	The extra time required to arrive at a destination on time 95% of the time, compared with average or median travel time
Standard Deviation	$\sqrt{\frac{1}{n}\Sigma_{i=1}^{N}(TT_i - Average\ TT)^2}$	The variation of travel time compared with the average
Semi-Standard Deviation	$\sqrt{\frac{1}{n}\Sigma_{i=1}^{N}(TT_i - Freeflow\ TT)^2}$	The variation of travel time compared with the free flow
Failure Measure	$\frac{Trips\ with\ TT < 1.1 * Median}{Total\ Trips}$	The percentages of trips arriving on time
Misery	$\frac{Average\ of\ Highest\ 5\ Percent\ TT}{Freeflow\ TT}$	How much longer it takes to travel on the worst 5% of all trips

Although all these are widely adopted measurements of TTR, each of them can only reveal a portion of information on travel time distribution. Therefore, the guideline suggests that agencies conduct experiments to identify the combination of measures to best describe the travel time distribution on any specific roadway segment.

With properly chosen TTR measures, it further requires a significant amount of travel time data to estimate TTR on a specific road segment. In an ideal situation, the travel time data can be retrieved from a variety of sources, such as traditional travel monitoring sensors, ITS sensors, and instrumented vehicles. Data can also be purchased from third party vendors, such as INRIX, and NAVTEQ. With these data, agencies can develop TTR monitoring system to monitor, assess, and communicate reliability to end users. However, in cases where the access to such data is limited, agencies need to develop their own model to estimate or forecast reliability. Two types of methods are suggested in the guidelines to address the limited data issue: sketch-planning methods, and model post-processing methods. The sketch-planning methods use available data such as travel time, volumes, etc., as inputs, assume very simple relationship between reliability and these features. The methods require less computational resources than other methods, so it produces compromised results. The model post-processing methods use travel demand model to generate network demand data and apply customized analysis routines to generate specific estimates of travel-time reliability. Other sophisticated tools, such as simulation, and multiresolution methods, can also fulfill the purpose of estimating TTR but require much more resources. A comparison among the methods is available in Table 3.2.

Table 3.2 Overview of Analysis Tools and Methods for Calculating Reliability

Tool/Method	Strengths	Weaknesses
Sketch-Planning Methods	• Easy and fast analysis • Use generally available data • Can be used in data-poor environments where other tools and data are unavailable	• Limited reliability metrics • Based on assumption of average condition • Generally applied to aggregated conditions • Do not explicitly capture reliability because they are based on static conditions
Model Postprocessing Method	• Based on local data from the established regional model • Overcomes some of the limitations in using travel demand models for estimating reliability • More robust than simple sketch-planning methods	• Requires an underlying regional travel demand model (or simulation model) • Can be time-consuming to integrate the methods with the regional travel model • Limited reliability metrics • Requires multiple model runs to assess variations in demand

Simulation or multiresolution methods	• Provides the most robust forecast of travel time variability under all the expected travel conditions • Combining travel demand models with simulation models provides most accurate assessment of long- and short- term impacts on reliability • Typically provides the greatest opportunity to assess operational improvements	• Requires that underlying regional travel demand model and simulation model are available • Time- and resource-intensive to develop the models and conduct analysis • Assessment of underlying causes of congestion requires accurate performance data collected over a long time period • Requires multiple model runs for each scenario • Significant cost to set up, calibrate, and complete analysis
Monitoring and management tools and methods	• Typically easy and fast analysis once system is developed • Based on real-world data • Ability to assess real-time conditions • Ability to assess historical trends • Ability to compare influencing factors and actual traffic conditions retroactively	• Analysis capability limited by data availability and quality of underlying data • Development costs may be moderate to high • Not capable of testing future strategies to address congestion

Once the TTR is estimated, another challenge is to communicate reliability performance to the public and stakeholders. Since TTR measures the variability of travel time, it is always focused on specific issues, such as time periods, travel patterns, roadway type, and users. Also, traveler's understanding of TTR measurements at corridor-level and system-level are very different. Therefore, agencies oftentimes need to identify their key issues and find proper ways to communicate TTR. For example, the public might not know what PTI represents and the meaning behind it. To effectively communicate corridor-level TTR to the public, agencies can translate PTI into good/fair/poor categories and determine PTI thresholds for categorization. To inform the public of the system-level of reliability, agencies can combine data from multiple corridors to form a singular number. For example, they can use weighted average of the reliability measure from each corridor.

3.1.1.2 Incorporating Reliability into Policy Statement

The SHRP2 L05 guideline explains the process of incorporating reliability into policy statement by answering three questions:

1. What is the appropriate level to incorporate reliability into an agency's policy statements?
2. How can an agency's goal and objectives be tailored to include reliability in a way that matters to system users?
3. What are the chief causes of poor reliability in a state or region?

To answer the first question, the guideline provides five levels for incorporating reliability: vision, mission, goals, objectives, and policies/strategies/actions. The level to incorporate reliability is decided by multiple factors, including the significance of reliability issues faced by the state or region, resource availability, and agency's previous investment experience. Vision or mission level means that reliability is a top or at least a major issue for the agency. Once reliability is incorporated into vision or mission statements, the agency needs to collaborate with appropriate stakeholders focusing on reliability. One example of incorporating reliability into vision/mission level is from Massachusetts DOT whose mission was "deliver excellent customer service to people who travel in the Commonwealth, and to provide our nation's safest and most reliable transportation system in a way that strengthens our economy and quality of life."

To incorporate reliability at the level of goals or objectives, agency needs to understand the issues in their transportation system and closely examine the performance measures to ensure that they are related to the issues. To identify the goals and objectives, agency needs to work with key stakeholders and provide them with the correct type of information, such as existing reliability, and predicted reliability trends. For example, for the 2060 Florida Transportation plan, the Florida DOT convened a group focused on improving economic competitiveness, which included members from Florida Trucking Association, economic development agencies, business associations, MPOs, and several businesses. The group suggested an objective of "increasing the efficiency and reliability of travel for people and freight", which was incorporated into the plan under the goal of "improving mobility and connectivity for people and freight".

To incorporate reliability at the level of policies/strategies/actions, agency needs to collect data from multiple complementary planning efforts, such as CMPs, operation plans, corridor plans, transit plans, and other similar efforts. These data can provide significant amount of details on the reliability issues, which can be used by the agency to set specific goal or objectives. One example for incorporating reliability into complementary planning efforts is from Florida DOT District 4 Transportation Systems Management and Operations (TSM&O), who included reliability among their objectives: "achieve peak period travel-time reliability on critical arterial segments in the TSM&O network."

3.1.1.3 Evaluating Reliability Need and Deficiencies

To fulfill the goal of incorporating reliability into policy statements, it is important to understand the extent of reliability deficiencies and needs. The first step to identify the deficiencies and needs is to determine the reliability thresholds: the points at which a segment is considered to have good, fair, or poor reliability. Segments or trips whose performance is below the threshold of being reliable are considered reliability deficiency. Reliability need is defined as the total cost to improve deficiencies to an acceptable level.

The SHRP2 L05 guideline recommends an iterative approach to determine the reliability thresholds. With this approach, agency initially sets preliminary thresholds and evaluates the reliability performance of target system or corridor. Then they discuss the preliminary results with stakeholder to examine if the performance matches the stakeholder's understanding of reliability deficiencies. If there is a gap between the analysis results and stakeholder's understanding, agency will adjust the thresholds until an agreement is reached. When they make decisions in term of reliability thresholds, multiple factors need to be considered, including users, time period, roadway types, and geography. Another approach to identify the corridor reliability thresholds is to use data from a similar corridor to establish acceptable thresholds.

Although reliability thresholds can be defined, the expectations of acceptable travel-time reliability may vary. It is thus still challenging to assess reliability need. The L05 guideline provides three approaches to estimate the needs: 1. Identifying needs at the corridor or segment level; 2. Using a performance-based approach to estimate program needs; and 3. Using incremental benefit-cost to estimate program needs.

To identify the reliability need of a specific corridor, L05 guideline suggests a strategy toolbox, which lists a series of strategies that may improve the corridor TTR via increasing capacity, reducing demand, or improving traffic operation. Characteristics of each strategy are considered in determining the needs, including relevant situations to apply the strategy, capital and operating costs, expected benefits and political support, and its capability of being bundled with other projects.

For system level reliability improvement, the focus of identify reliability needs shifts from project to funding. One suggested approach to quantitatively estimate the system level reliability benefits is to establish the relationship between costs of investments and reliability improvement. Another approach to estimate system level reliability need is to construct performance curve with incremental benefit cost (IBC) ratio, which is defined as the ratio between benefit increment and cost increment. By observing the curve, system level reliability need is estimated.

3.1.1.4 Incorporating reliability into investment decision

There are three levels that reliability measures can be incorporated into the project investment decision making process: program trade-offs, project prioritization, and project alternative selection. Program trade-off refers to funding allocation between programs. With estimated reliability performance measures, agencies can evaluate how much emphasis to be applied on the operations and management programs. Currently there are no widely adopted methods to set program funding level since most programs are funded based on federal and state funding requirements and historical practice. With properly measured reliability, agencies can identify the appropriate level of funding for the program which can best meet the various needs of users.

For project prioritization, reliability performance measurement can be used along with other measures to identify a preferred list of projects to be implemented, e.g., using reliability performance measurement in a cost-effectiveness analysis or an econometric analysis. In project alternative selection, reliability performance should be considered alongside other measurements, which helps ensure that the selected alternative addresses the full set of concerns.

3.1.2 Technical Reference

In the previous section we have introduced the four categories of reliability analysis tools, so in this section, we will explain in detail the general procedure and applications of each category.

3.1.2.1 Sketch Planning Tools

The sketch planning method was adopted in SHRP2 L03 program, which developed statistically derived reliability equations based on empirical data. In L03 program, it is assumed that reliability metrics can be effectively predicted from the overall mean travel time index, which includes all of the sources of possible variations in travel time. Figure 3.1 shows the relationship between an example reliability metric and overall mean travel time index in L03 program.

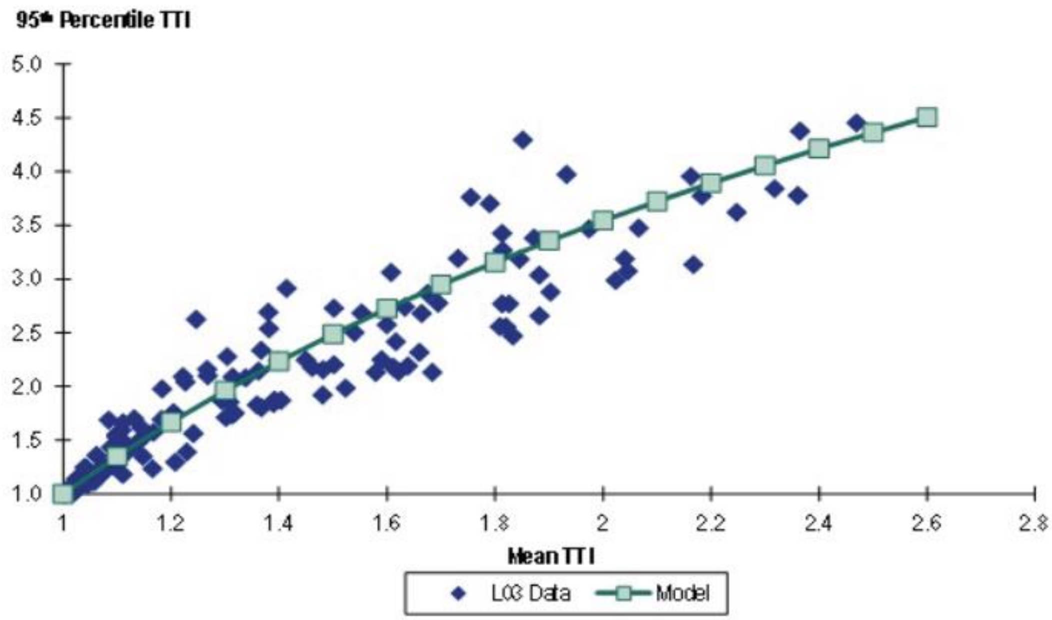


Figure 3.1 Relationship between 95th Percentile TTI and Mean TTI

The sketch-planning tool was also used in SHRP2 L07 program Evaluating Cost-Effectiveness of Highway Design Features. SHRP2 L07 program aimed at evaluating capacity improvements caused by highway treatments, such as drivable shoulders, runaway truck ramps, variable message, etc. A user-friendly tool was developed to produce multiple reliability measurements, including PTI, BTI, 50th percentile, skew statistic, and misery index. Figure 3.2 shows the interface of the L07 tool.

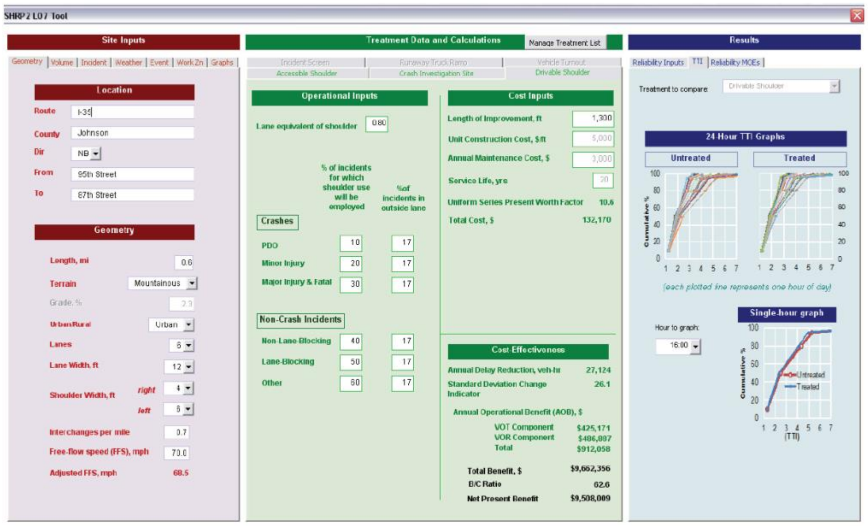


Figure 3.2 L07 Tool User Interface

The advantage of sketch-planning methods is that they may be applied in a data-poor environment with limited operational data. To apply the methods, segment free-flow speed, distance, and average travel time data are required. Due to the limited operational data, the average travel time can be estimated in three ways: 1. Collected in the field, 2. Extracted from a model, 3. Estimated using segment volume and capacity. The outputs of sketch-planning methods are usually BTI or PTI for corridor or network.

3.1.2.2 Post-Processing Tools

Post-processing tools are developed due to the limitations of travel demand models, such as limited application in previous transportation system, and their ability to analyze reliability. Therefore, transportation agencies developed several post-processing tools and methods to conduct reliability analysis with established travel demand models. Examples of post-processing tools and methods include the tools developed by FHWA, the Florida DOT, and Southeast Michigan Council of Governments (SEMCOG).

The model post-processing tool developed by FHWA is named as ITS Deployment Analysis System (IDAS), which pulls in data from a regional planning model to perform analysis on the relative benefits and costs. Figure 3.3 shows the user interface of IDAS. The IDAS was one of the first tools that specifically incorporate an analysis of reliability. It considers incident-related delay as the unreliable source in the reliability analysis. The tool utilizes a series of lookup tables containing the anticipated amount of incident-related delay on a particular freeway link to calculate the network-level or link-level reliability.

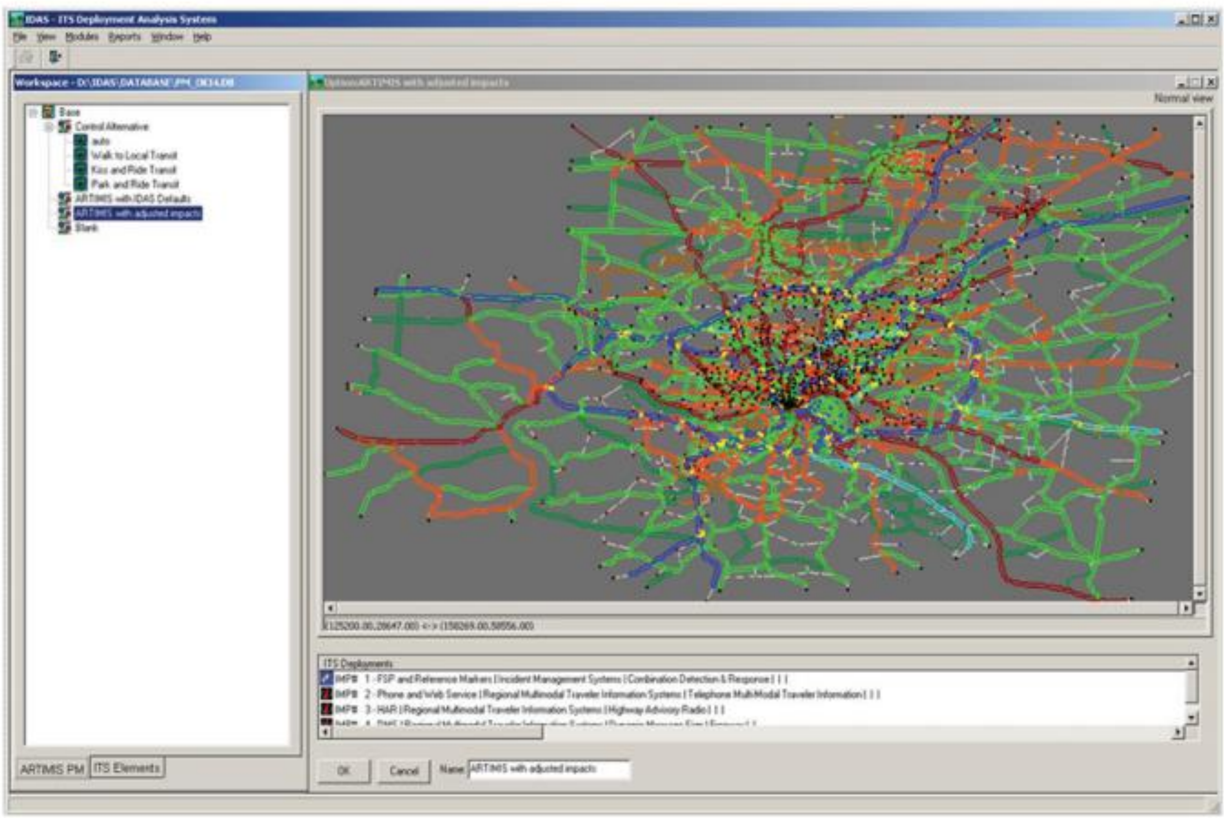


Figure 3.3 IDAS User Interface

Although IDAS only considers incident-induced delay as the non-recurrent source of unreliability, it is still possible to structure an analysis to calculate the delay from weather or construction. By applying a multi-scenario approach, the traffic condition that would occur for each day with similar weather or construction activity can be estimated. Based on IDAS, the Florida DOT modified the approach with its standard travel demand structure in state. The new tool was name as Florida ITS Evaluation tool or FITSEval.

3.1.2.3 Simulation/Multiresolution Tools

Simulation or multiresolution methods provide more robust analysis of traffic performance under varying conditions, including both non-recurrent events and short-term traveler behavioral changes. They can provide very detailed performance metrics, especially the performance at particular time period. Therefore, simulation models are considered a powerful tool for reliability analysis and strategy decision-making in reducing non-recurrent congestion.

However, simulation models can be complicated since it usually combines less discrete models in a multiresolution approach. For example, a typical simulation model includes a regional travel demand model as the less discrete one and microscopic simulation model as the more discrete one. So it is challenging to develop and calibrate the simulation models. US DOT Integrated Corridor Management (ICM) program developed a multi-scenario method when conducting a comprehensive analysis of ICM benefits at several pilot sites, including San Diego, Dallas, and Minneapolis-Saint Paul. To conduct the analysis, each site integrated their regional travel demand model with a simulation model for a specific corridor where the ICM deployments to be implemented. Both long-term and short-term impacts were evaluated as well as the system performance under adverse weather and incident condition. They identified the three major causes for variability: demand, incident, and weather. The portion of influence from each cause was estimated and probability of a combination of three causes at certain severity was calculated based on the archived data. Then the distribution of the model runs was assigned according to the likelihood of particular scenario occurring. With all the model runs being finished, the results of runs are combined to estimate travel time, delay, and travel-time reliability. Figure 3.4 shows an example distribution of the three causes at varying severities based on the archived data in Dallas, Texas in 2007.

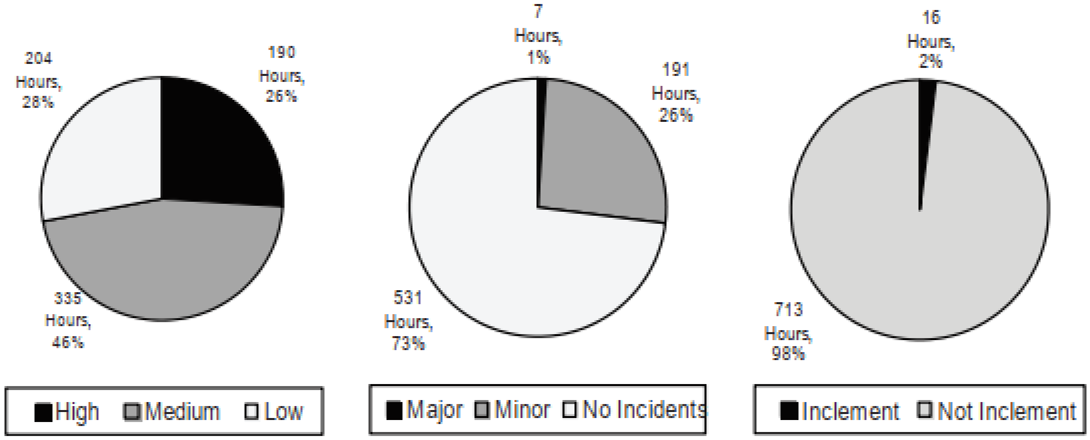


Figure 3.4 Distribution of Demand, Incident, and Weather at Varying Severities

Multiple resources are required in the calibration process, including high-detailed roadway geometry, traffic signal timings, discrete data on travel speed and volume, and distributions of scenario likelihood if multi-scenario approach is applied. Due to the complex calibration process and huge amount of required data the simulation models are usually applied to corridors and the expansion of the analysis to any larger network would require significantly more resources.

3.1.2.4 Monitoring and Management Tools

Monitoring and management tools and methods are different from the aforementioned methods since they focused on providing analysis of both real-time and archived traffic data. A number of agencies have developed or are in the process of developing monitoring and management tools. For example, the Los Angeles County Metropolitan Transit Authority (LAMTA) is developing an arterial performance and reliability measurement system using data from traffic control devices and transit automatic vehicle location (AVL) systems.

The monitoring and management tool can be used for accessing archives, comparing trends, reporting performance measures, creating dashboards, and creating historical data for planning and operation modeling. To effectively fulfill these functions, the tool should have two components: a back-end data repository and a front-end user interface.

Currently, a list of monitoring and management tools have been developed, including the National ITS Architecture, the Archived Data Management System Data Model, the ASTM 2259-03a Standard Guide for Archiving and Retrieving ITS Generated Data. Data plays an important role in these tools and data quality, data management and fusion, and data fidelity significantly influence their performance of the tools. Caltrans Performance Measuring System (PeMS) is using several ways to ensure the quality of data: by location, time, and cause of error. The system can show the percentages of "good" and "bad" data and the types of errors encountered for bad data. After data from different sources is reviewed for quality assurance, they are combined into one seamless network of database. Then the robustness of the database is evaluated. Finally, the intended audience will determine the geographic scale and level of detail provided in analysis and reporting.

Since all the tools and methods have their own advantages and limitations, the selection of reliability analysis tool is challenging. The technical reference provides a five-step tool selection framework for agencies to choose proper reliability analysis tool, which are:

1. Plan reliability analysis
2. Filter by input requirement
3. Identify resource availability
4. Apply scoring
5. Review and reality check

The framework provides the general process that can be used in identifying and developing a methodology appropriate to the needs of a particular analysis. Since specific influencing factors exist in particular analysis, the practitioners need to consider all of these factors simultaneously.

3.1.3 Examples

To validate the project prioritization guideline, the L05 program report has included seven case studies, which are listed in Table 3.3.

Table 3.3 L05 Case Study Summary

Case Study	Objectives	Key Findings/Lessons
Colorado DOT	Conduct a before-and-after analysis and benefit study of a pilot traffic operations project being conducted by Colorado DOT in Denver. One of the key themes of SHRP2 L05 and other efforts is an attempt to main-stream operations planning within the broader planning process. This validation case study identified methods to better achieve that objective	Documents the process for conducting an arterial before-and-after analysis with emphasis on travel-time reliability; Benefits of operational strategies in improving travel-time reliability; Steps to incorporating reliability performance measures into the LRTP at CDOT. The finding validate the operational planning phase of the planning process
Florida DOT	Documents FDOT's efforts to incorporate travel-time reliability into their planning the programming process, including incorporating reliability into their short range decision support tool (strategic investment tool) and modeling techniques for predicting the impact of projects on reliability	Incorporating reliability into the programming process is a challenge due to lack of specific funding categories and challenges due to statutory requirements regarding the types of projects that can be funded. The case study documented many success factors for incorporating reliability into the planning and programming process. The findings validate the programming phase of the planning process
Knoxville, TN MPO	Demonstrate how reliability can be incorporated into the ITS operations element of the region's upcoming LRTP and assist MPO staff in incorporating reliability performance measures in plan development, project identification, and project prioritization processes.	Developed a reliability objective for inclusion in the Congestion Management Process; Calculated reliability performance measures along freeways and incident prone locations; Developed a method for incorporating reliability into the project selection process. The findings validate tools for quantifying travel-time reliability using somewhat less sophisticated modeling and other tools
LAMATA (Los Angeles)	Document the development of an arterial performance	Recommends approach for using alternative data sources to

	monitoring system, which will be used to prioritize arterial operations projects for funding	support an arterial performance monitoring system. Preliminary findings suggest that multi-modal reliability measures can be calculated from alternative data sources, although data source consistency is critical
NCTCOG (Dallas-Fort Worth)	Identify best practices on how other MPOs are incorporating reliability into their Congestion Management Process and provide recommendations on how NCTCOG can incorporate reliability into their planning process	Only a limited number of MPOs have incorporated reliability into their CMP. Success factors include having robust amounts and sources of traffic data, using corridor-level measures and effective reporting graphics, defining reliability in a way that can be easily understood by multiple audiences, and having a performance measurement working group with agency staff, technical and policy board members, local stakeholders, and the public
SEMCOG (Detroit)	Identify reliability performance measures for highway operation and develop a method to incorporate reliability into SEMCOG's performance-based program trade-off process	Reliability can be incorporated into the trade-off process and may affect the results of prioritization process; the selected corridors can be very representative in the regional analysis; reliability can be assessed with limited access of data. The findings validate incorporation of reliability into a program-level trade-off analysis
Washington State DOT	Incorporate reliability into identifying deficiencies and investment in a corridor	Establishes a methodology for examining reliability deficiencies for WSDOT corridor studies

3.2 Project Prioritization System in Utah

Currently, the Utah's Transportation Vision (UVision) framework is adopted by UDOT for long-range transportation planning at local, regional, and state levels. The framework was co-developed by UDOT, Utah Transportation Commission, and the state's Metropolitan Planning Organizations (MPO). The objectives of the framework are to accomplish four goals of maintaining a high quality of life - good health, better mobility, strong economy, and connected communities. According to the funding sources, projects are divided into two categories in the framework: Transportation Investment Fund (TIF) and Transit Transportation Investment Fund (TTIF). TIF can be used to fund highway capacity projects as well as stand-alone active transportation projects, and TTIF can be used to fund capital transit projects as well as first/last mile projects. Four decision support tools were developed accordingly to fulfill each individual goal: TIF- Highway, TIF-Active, TTIF- Transit, and TTIF- First/Last Mile. Each decision tool uses the same structure for project prioritization and produces separate outcome areas. Several key criteria are developed for each decision tool through stakeholder engagement. Each criterion is weighted in the framework. By comparing the weighted criteria, agency can prioritize projects and allocate budgets. In this section, we will introduce the criteria in each decision support tool, especially the criterion related to TTR. Table 3.4 summarizes the weighting system of criterion in TIF highway.

Table 3.4 TIF- Highway Model Weighting System

Good health: 25%	**Strong economy:20%**	**Better mobility:40%**	**Connected communities:15%**
Safety: 60%	Accessibility: 35%	Travel time:55%	Connectivities:35%
Public health:20%	Transport costs: 20%	Throughput: 30%	Land use and community:35%
Environment:20%	Economic development: 45%	Risk and resiliency:15%	Integrated system: 30%

Better mobility (40%) is considered as the most important goal in prioritizing projects on highway improvement and travel time. In the framework, TTR is measured with two widely adopted measurements: Travel Time Index (TTI) and Buffer Time Index (BTI). TTI is calculated as the ratio between the measured travel time during congestion to the travel time at free-flow condition. BTI is calculated as the ratio between extra travel time a driver would have to budget to be 95 percent sure of arriving on time and the average travel time. Reliability is scored differently for non-freeway and freeway projects on a scale of 0 to 3 points. The reliability thresholds are shown in Table 3.5. Travel time is retrieved from UDOT Traffic Operations Center's HERE probe data collected during peak hours. Figure 3.5 shows the distribution of criterion weight in TIF-Highway model.

Table 3.5 Reliability Thresholds in TIF- Highway Model

Freeway			
Points	Classification	TTI	BTI
0	Fast & Reliable	<=1.4	<=0.6
2	Fast & Unreliable	<=1.4	>0.6
1	Slow & Reliable	>1.4	<=0.6
3	Slow & Unreliable	>1.4	>0.6
Non-Freeway			
0	Fast & Reliable	<=1.4	<=0.9
2	Fast & Unreliable	<=1.4	>0.9
1	Slow & Reliable	>1.4	<=0.9
3	Slow & Unreliable	>1.4	>0.9

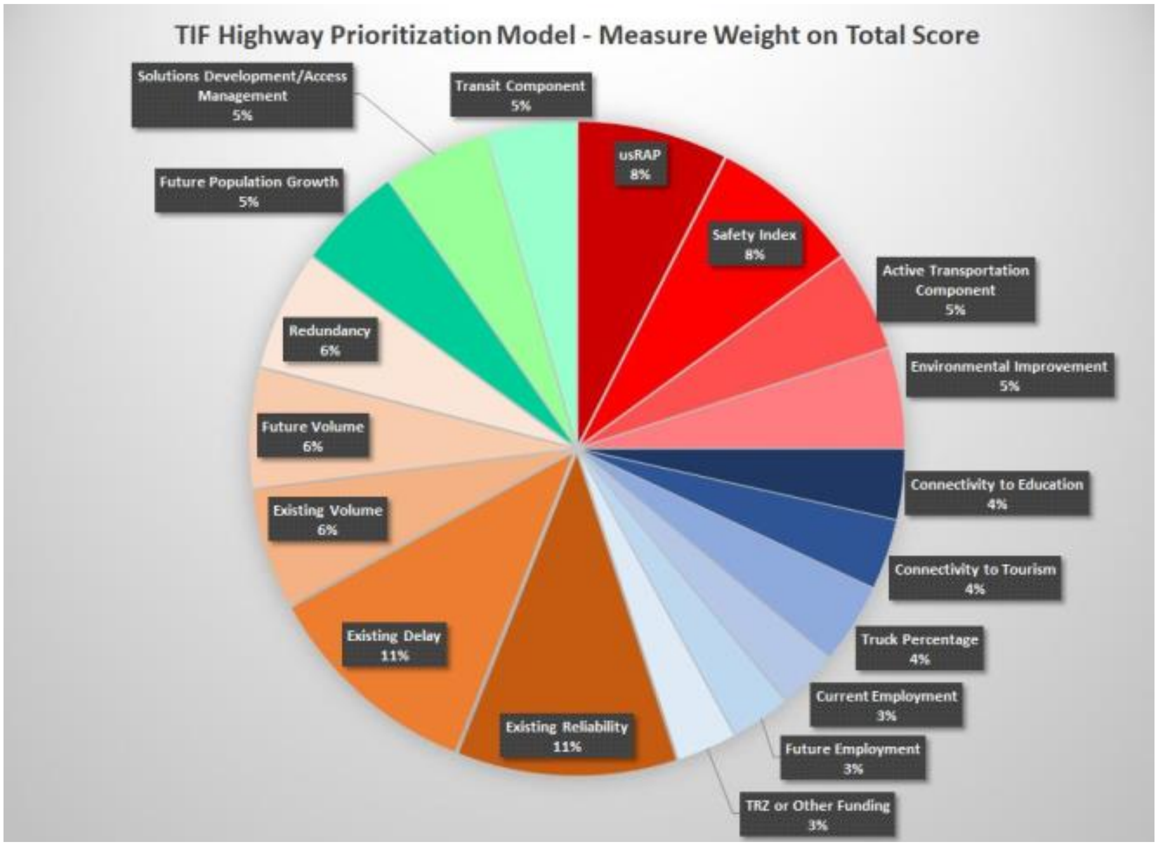


Figure 3.5 Weight Distribution in TIF-Highway Model

Table 3.6 shows the weighting system in the TTIF-Transit model. Better mobility is still considered as the most important goal in project programming. The importance of travel time and reliability slightly decreases to 50% within better mobility. In the TTIF-Transit model, all projects are aiming at public transit improvement. Therefore, projects are scored based on the number of reliability related components included in the project concepts. The components may include, but are not limited to:

- Provides exclusive right-of-way or independent fixed guideway;
- Includes transit signal prioritization or queue jump technology;
- Designed for 15 min headways or less; and
- Demonstrates maintenance improvements or fleet reliability improvements.

Projects with each component above receive 1 point, and projects without reliability components receive 0 points. A maximum of 5 points are available in the measure. Figure 3.6 illustrates the weight distribution in TTIF- Transit model. It is observed that reliability related component has the highest weight compared with other criteria, which is 20% of the final measure.

Table 3.6 TTIF- Transit model Weighting System

Good health: 25%	Strong economy:20%	Better mobility:40%	Connected communities:15%
Safety: 35%	Accessibility: 45%	Travel time:50%	Connectivities:50%
Public health:20%	Transport costs: 20%	Throughput: 40%	Land use and community:35%
Environment:45%	Economic development: 40%	Risk and resiliency:10%	Integrated system: 15%

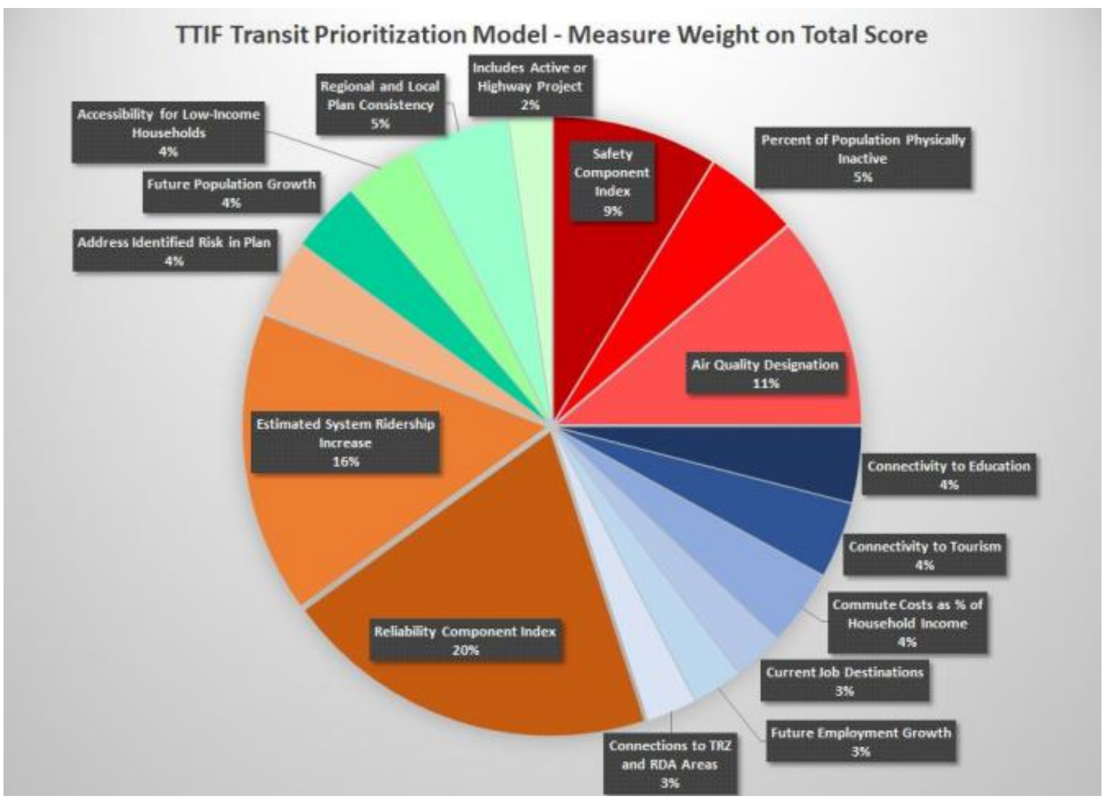


Figure 3.6 Weight Distribution in TTIF- Transit Model

Table 3.7 shows the weighting system in TIF- Active Transportation model and TTIF-First/Last Mile model.

Table 3.7 Weighting System in TIF- Active Transportation Model and TTIF- First/Last Mile Model

Good health: 25%	Strong economy:20%	Better mobility:40%	Connected communities:15%
Safety: 60%	Accessibility: 40%	Travel time:30%	Connectivities:60%
Public health:20%	Transport costs: 40%	Throughput: 45%	Land use and community:25%
Environment:30%	Economic development: 20%	Risk and resiliency:25%	Integrated system: 15%

In both TIF-Active Transportation and TTIF- First/Last Mile models, the reliability improvement of projects are scored based on their highest level of improvements. The scoring system is as follows:

- 4 points: new dedicated used, separated travel lanes
- 3 points: direct access or improved connections to destinations at project termini
- 2 points: elimination of crossings, over/underpasses, intersection improvements, bike/ped signal features, etc.
- 1 point: direct connections into existing long-distance ped/bike network.

Figure 3.7 shows the weight distribution of criteria. Although the weights of TTR decreases compared with previous two models, they still have the highest weight among all criteria.

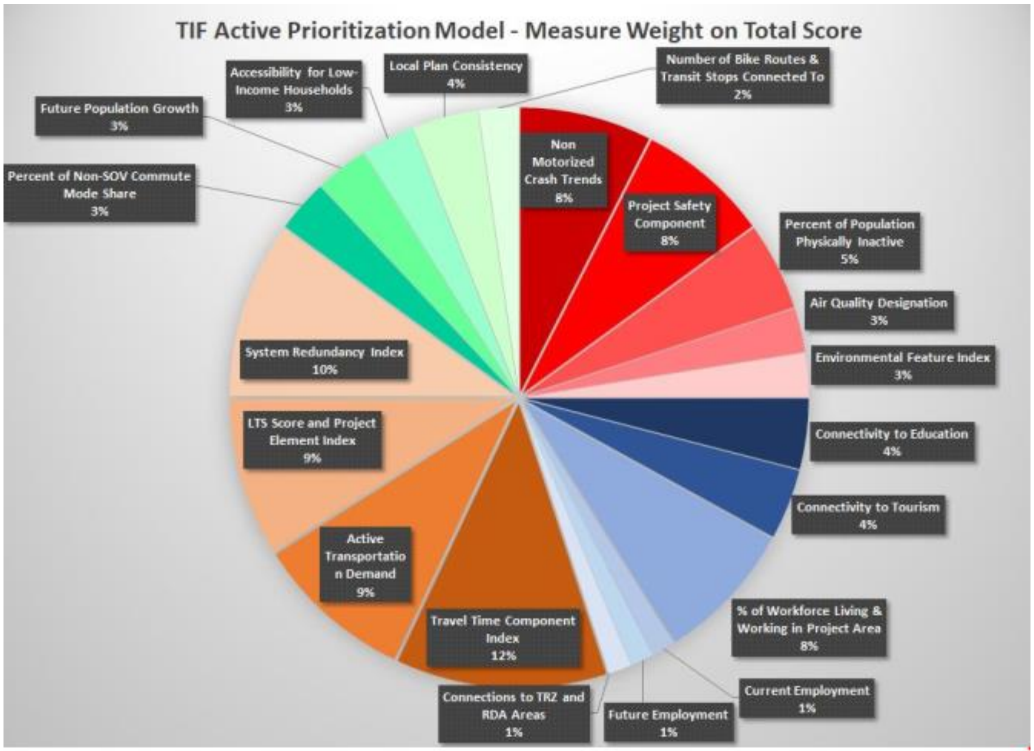


Figure 3.7 Weight Distribution in TIF-Active Model and TTIF- First/Last Mile Model

3.3 Case Study in Utah

Since the SHRP2 L05 program has been proven effective in multiple case studies, we are evaluating the adaptability of the L05 guideline with project prioritization process in the state of Utah. Five projects aiming at improving the freeway capacity of Interstate 15 in Utah have been selected as candidate projects for applying the L05 guideline. The prioritization results were compared with the outcomes of UDOT's decision-making process within the UVision framework. In this section, we will provide a brief introduction of the example projects and showcase the evaluation results of L05 guideline. Five projects are selected as the example projects in the evaluation process, they are:

- P1: I-15 Widening MP 10 to 13 + Milepost 11 Interchange (Region 4)
- P2: I-15 Lane Widening from MP 6-8 (Region 4)
- P3: I-15 Freeway, US-6 to Salt Lake County Operational Improvements (Managed Motorways) (Region 3)

- P4: I-15; NB Widen one lane, SLC/Davis County Line to 2500 So. (Region 1)
- P5: I-15 Managed Lanes - Salt Lake County to Davis County Line (Managed Motorways) (Region 2)

3.3.1 P1: I-15 Widening MP 10 to 13 + Milepost 11 Interchange (Region 4)

Figure 3.8 shows the location of the I-15 widening project between MP 10 and 13, which includes building a new interchange at Main St (MP 11). The objective of the project is to enhance the mobility and safety of the transportation system in Washington City's primary business district. According a preliminary study on the traffic condition between MP 10 and 13 along I-15, by 2040 the queue length at Exit 10 is projected to exceed 4,000 feet northbound and 2,400 feet southbound. It would result in spillback beyond the physical boundary of the ramp and into the I-15 mainline travel lanes. Both the Exit 10 intersection and Green Spring Drive/Telegraph Street intersection are projected to operate at failing conditions. To increase the roadway capacity and reduce congestion in the future, six build alternatives have been proposed, including widening Green Spring Drive/3050 East from five lanes to seven lanes, adding a dedicated right-turn lane for southbound Green Spring Drive at Buena Vista Boulevard, widening telegraph Street/Green Spring Drive intersection, widening Telegraph Street from five lanes to seven lanes, widening/improving Telegraph Street/750 West intersection, and installing raised median along portions of Telegraph Street and Green Spring Drive/3050 East.

Figure 3.8 Location of I-15 Widening MP 10 to 13 + Milepost 11 Interchange Project

3.3.2 P2: I-15 Lane Widening from MP 6-8 (Region 4)

The freeway-widening project on I-15 between MP 6 and 8 was proposed to address the projected 2040 travel demand on the I-15 corridor between MP 0 and MP 16. According to I-15 South Environmental Assessment, by the year of 2040, the population growth, traffic volume growth, and high volumes of freight traffic would bring significant amount of congestion to the I-15 corridor between MP 0 and MP 16. Therefore, a multi-phase construction plan was proposed. The project of I-15 lane widening (MP 6- 8) is in the second phase of the construction plan, which will add general-purpose lanes between Brigham Road and St. George Boulevard. Figure 3.9 illustrates the location of the project.

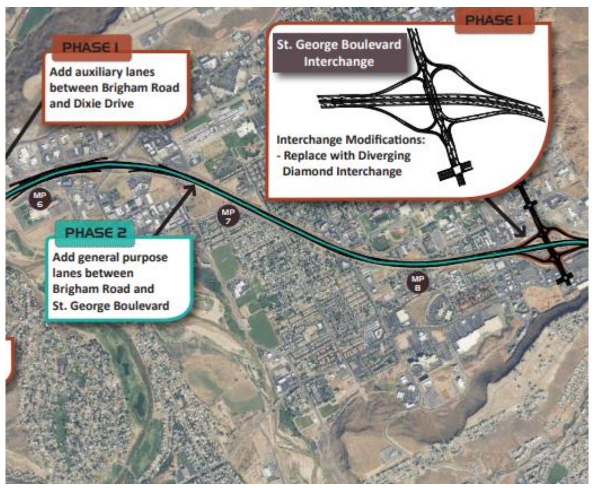


Figure 3.9 Location of I-15 Lane Widening from MP 6 to 8

3.3.3 P3: I-15 Freeway, US-6 to Salt Lake County Operational Improvements (Managed Motorways) (Region 3)

The location of project I-15 Freeway US-6 to Salt Lake County Operational Improvements is illustrated in Figure 3.10, which is from MP 257.7 to MP 285.9.

Figure 3.10 Location of I-15 Freeway, US-6 to Salt Lake County Operational Improvements

3.3.4 P4: I-15; NB Widen one lane, SLC/Davis County Line to 2500 So. (Region 1)

The I-15 NB widening project between SLC/Davis county line to 2500 South is located between MP 10 to MP 13, illustrated in Figure 3.11.

Figure 3.11 Location of I-15 NB Widen One Lane SLC/Davis County Line to 2500 South

3.3.5 P5: I-15 Managed Lanes - Salt Lake County to Davis County Line (Managed Motorways) (Region 2)

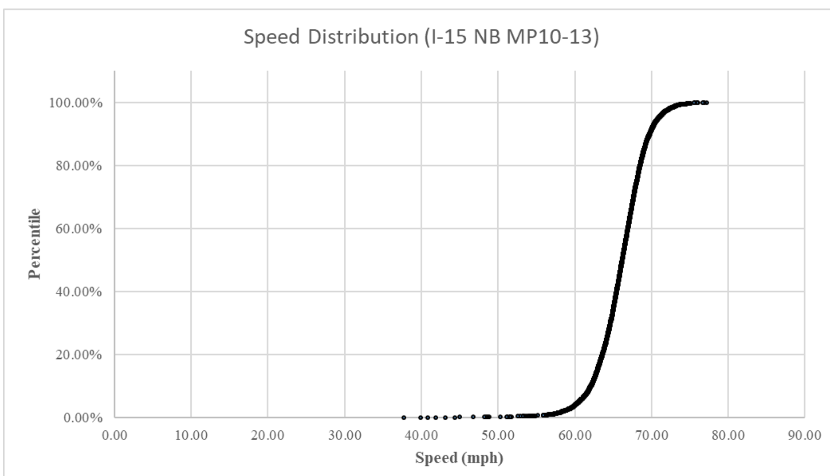
The location of I-15 Managed Lanes project starts at MP 285.9 and ends at MP 312, as illustrated in Figure 3.12.

Figure 3.12 Location of I-15 Managed Lanes –Salt Lake County to Davis County Line

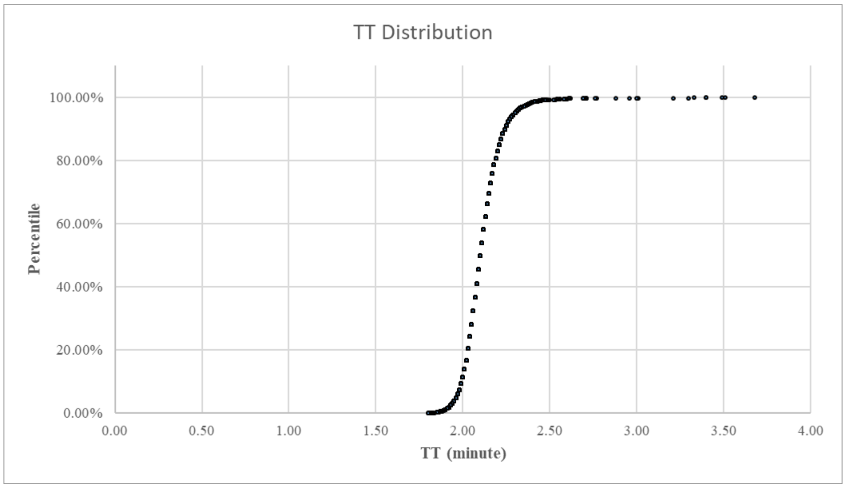
3.4 Result Analysis

Since all the projects proposed are on I-15, falling into the model of TIF- Highway, we have adopted the weighting system in Table 3.4 and its corresponding thresholds. In UVision framework TIF-Highway model, the TTR measurement is developed based on two widely used reliability measurements: TTI, and BTI. Rather than simply dividing the freeway performance into good/fair/poor, the UVision framework divided the freeway performance in terms of reliability into four categories: fast and reliable, slow and reliable, fast and unreliable, and slow and unreliable. Compared with the single-value reliability measurements, such as BTI, or 95th percentile travel time, which only reflects one dimension of the travel time portfolio, the UVision reliability regime reveals fuller information of travel time distribution and even identifies the sources for unreliability. Segments that fall into the category of fast and reliable, have the most desirable traffic condition, requiring very little operational or constructional improvements. Those that fall into the category of slow and unreliable have the least desirable traffic condition, which is caused by both recurrent and non-recurrent congestions. Segments in the rest two categories are suffering unreliable traffic condition, but not as bad as the slow and unreliable category. On the segments in the fast and unreliable category, traffic moves at high speed but suffers highly fluctuating travel time, implying that non-recurrent factors often cause severe increase in total congestion. Segments in slow and reliable category have low travel time variation and low speed, so the non-recurrent congestion is negligible, or at least not as significant compared with recurrent congestion.

To calculate travel-time reliability, we have retrieved the speed and travel time data of 2018 on the target segments from UDOT's iPEMS (https://udot3p.iteris-pems.com/). The data was aggregated at 15-minute granularity. Figure 3.13 through Figure 3.17 show the afternoon peak period (16:00-20:00) speed and travel time distributions along the I-15 corridor for each project. It is observed that during evening peak hours, the median speeds on all the corridors are between 65 mph and 70 mph.

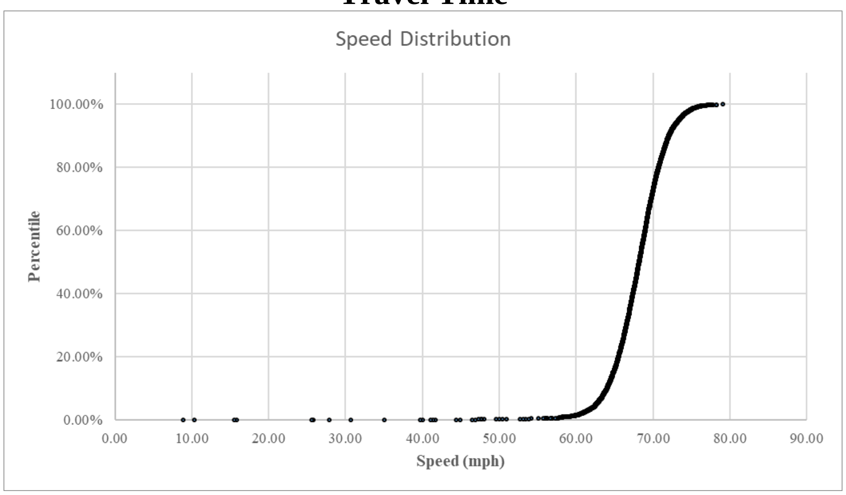


(a)

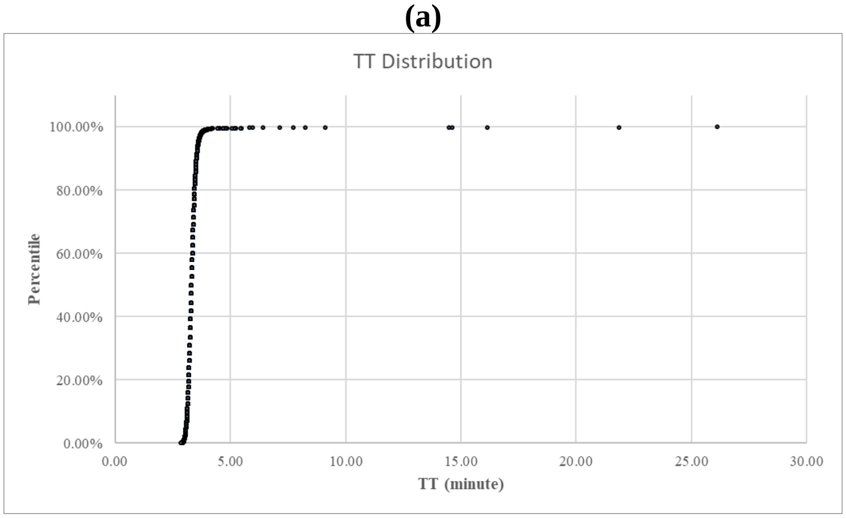


(b)

Figure 3.13 Speed and Travel Time Distribution on I-15 NB MP 10-13 (P1): (a) speed (b) Travel Time

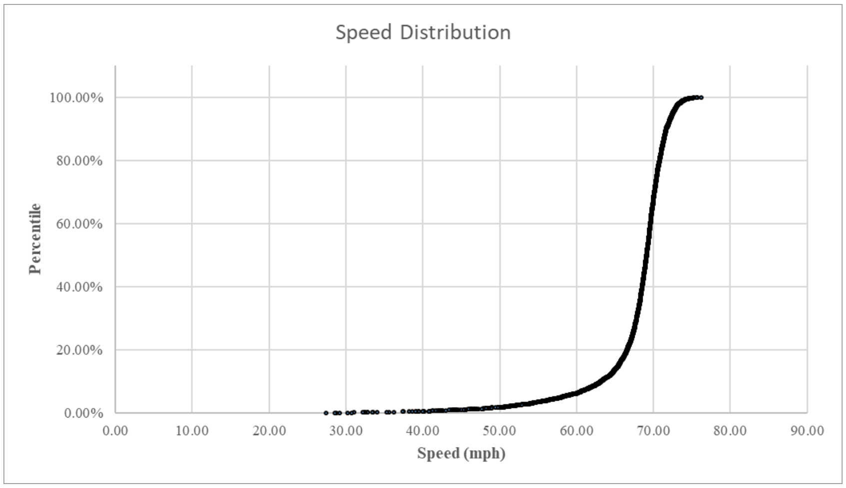


(a)

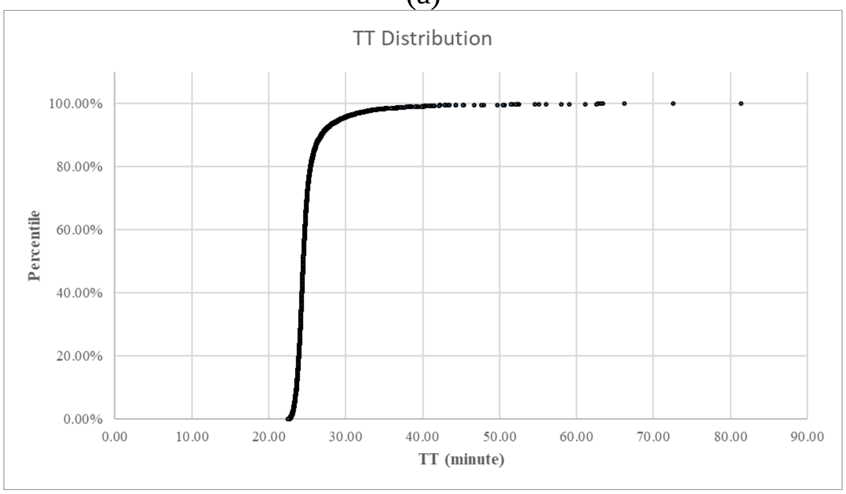


(b)

Figure 3.14 Speed and Travel Time Distribution on I-15 NB MP 6-8 (P2): (a) speed (b) Travel Time

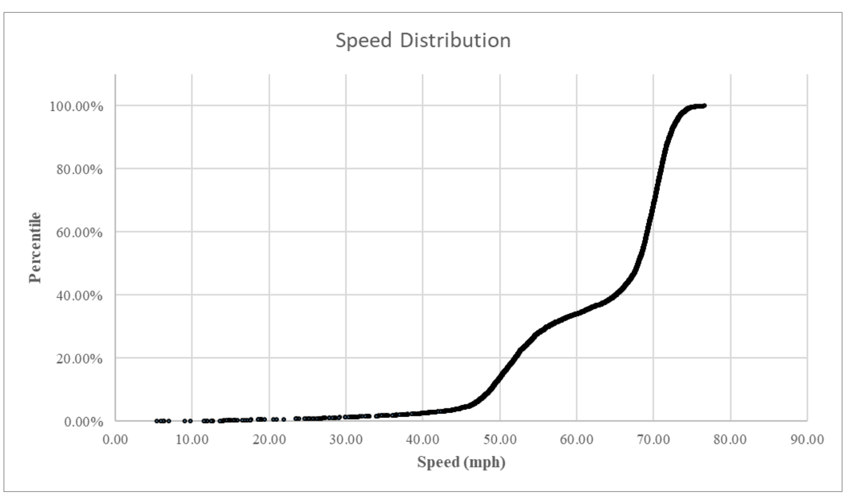


(a)

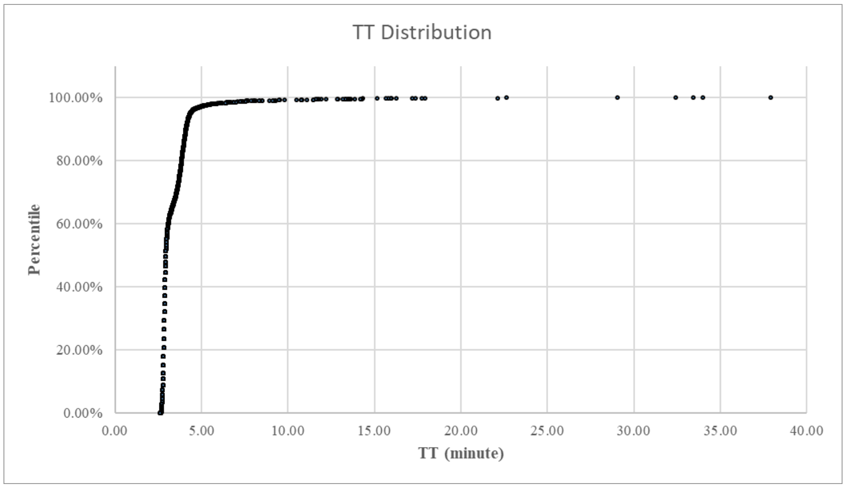


(b)

Figure 3.15 Speed and Travel Time Distributions on I-15 NB from US-6 to Salt Lake County (P3): (a) speed (b) Travel Time

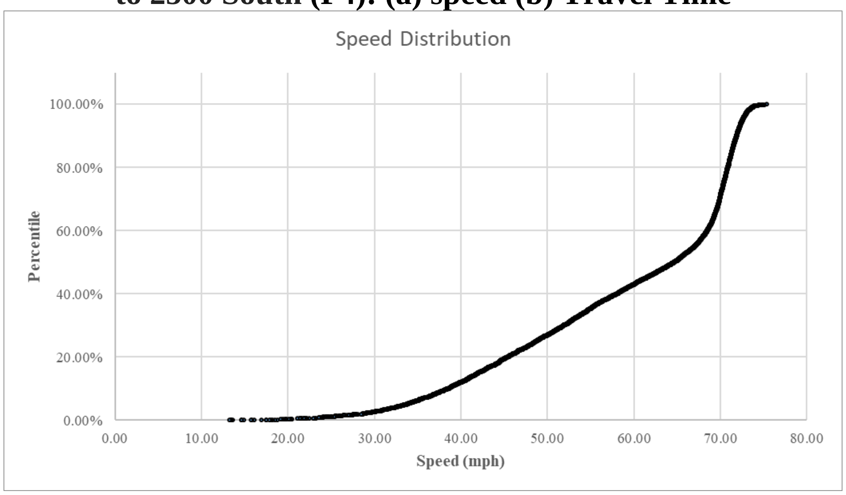


(a)

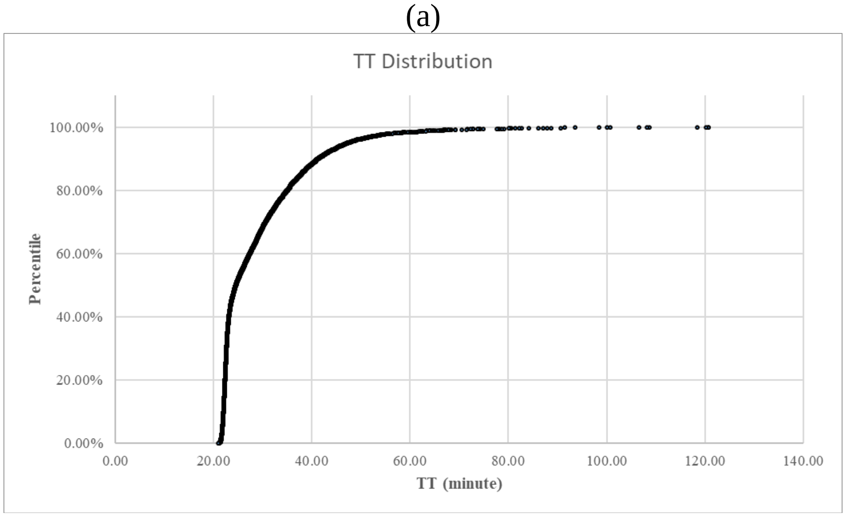


(b)

Figure 3.16 Speed and Travel Time Distributions on I-15 NB from SLC/Davis County Line to 2500 South (P4): (a) speed (b) Travel Time



(a)



(b)

Figure 3.17 Speed and Travel Time Distributions on I-15 Managed Lanes from Salt Lake County to Davis County Line (P5): (a) speed (b) Travel Time

To prioritize these projects, we applied UDOT's reliability regime to the candidate projects. Both BTI and TTI in 2018 have been calculated for each study segment. BTI on each corridor is calculated as:

$$BTI = \frac{95th\ percentile\ travel\ time - average\ travel\ time}{average\ travel\ time}$$

TTI is calculated as:

$$TTI = \frac{peak\ hour\ travel\ time}{free - flow\ travel\ time}$$

The values of reliability measurements for each project are shown in Table 3.8. Among the five projects, the peak period traffic conditions of P1 and P2 are fast and reliable, which is the most desirable. P4 and P5 currently suffer slow and unreliable traffic, which is the most undesirable condition. The traffic condition of P3 highly depends on the fast/slow and reliable/unreliable thresholds. In this pilot test, the thresholds are empirically decided as $TTI = 1.0$ and $BTI = 15\%$. Such thresholds may change correspond to different study periods. For example, in this test, we have considered 16:00-20:00 as peak period. Yet UDOT usually assesses evening peak hour as occurs between 17:00-18:00, which may be the most congested hour within 16:00 -20:00. With different time periods, the BTI and TTI benchmark can vary. This explains why UDOT's current threshold in distinguishing fast and slow regimes of TTI = 1.4 is higher than our threshold of TTI = 1.0. Also, since the peak period in our analysis is longer than UDOT's and it contains time period with relatively less severe congestion, the travel time distribution is much smoother, so our BTI threshold is much lower than UDOT's. Figure 3.18 illustrates the reliability comparison between the five projects.

Table 3.8 Reliability Evaluation for UDOT's Projects

Project	TTI	BTI (%)	Description
P1	0.948	9.05	Fast and reliable
P2	0.943	9.09	Fast and reliable
P3	0.996	19.36	Fast and unreliable
P4	1.089	47.62	Slow and unreliable
P5	1.175	92.62	Slow and unreliable

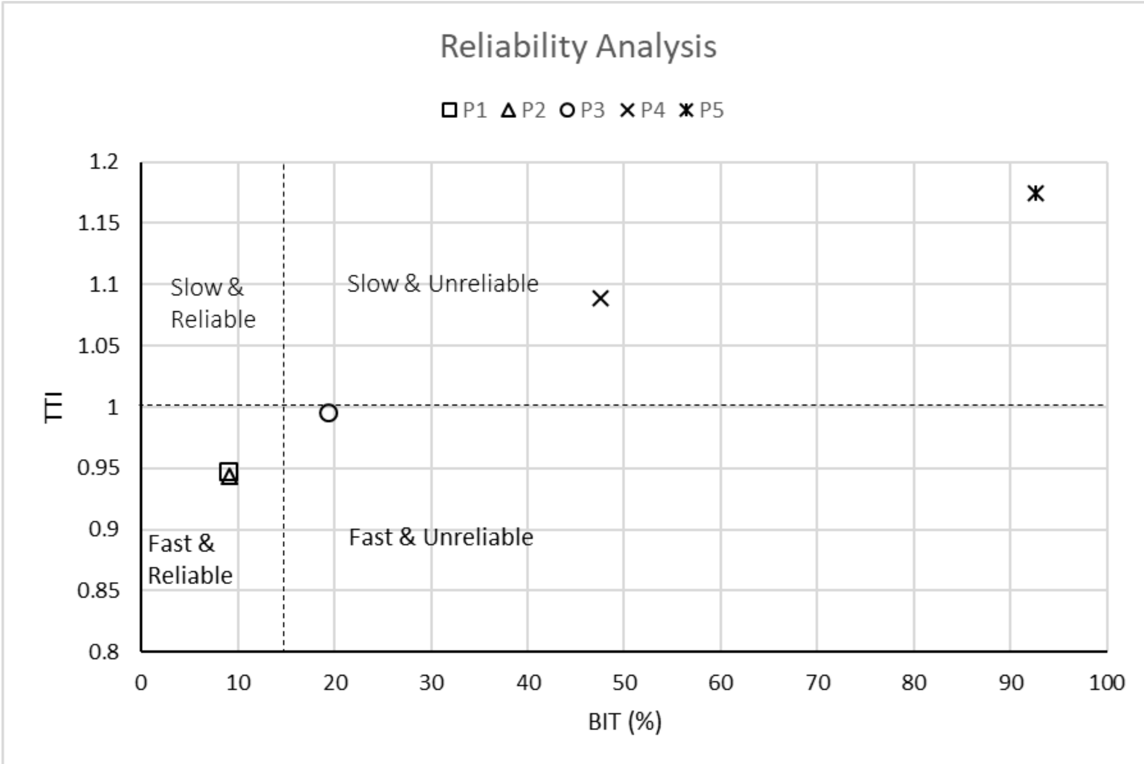


Figure 3.18 Reliability Analysis Results of the Five Projects

3.5 Summary

In this pilot test, a guideline of incorporating reliability into project prioritization process has been evaluated and showcased with an example of prioritizing freeway improvement projects on I-15 in the state of Utah. The guideline was developed by SHRP2 L05 project. It has been applied to a series of previous projects and followed by the project prioritization rules in many states. Reliability assessment, which is part of UDOT's project prioritization process, has been applied to five highway capacity improvement projects along the Interstate 15. Reliability deficiency at the site of each project is identified and can be considered in the project funding allocation process.

4.0 PILOT TEST ON SHRP2 L08

4.1 Introduction

The SHRP2 Project L08 has two objectives: the first objective is to incorporate non-recurrent congestion into the Highway Capacity Manual (HCM) procedure, and the second objective is to expand the time horizon of reliability analysis to an expanded period of weeks or even months. For freeway facilities and urban streets, L08 developed separated methodologies to evaluate the reliability. In this section, we will give a brief introduction of both methodologies and a detailed explanation on the freeway facility methodology.

4.1.1 Freeway Facility Methodology

The freeway facility methodology was adapted from previous macroscopic analysis computational engine FREEVAL, and more components have been added. There are three primary components in the freeway facilities methodology: a data depository, a scenario generator, and a core computational procedure (FREEVAL-RL). Figure 4.1 shows the relationship between the three components. The non-recurrent congestion is incorporated into the model by the freeway scenario generator (FSG), which assigns initial probabilities to a number of base scenarios. The base scenario probability is expressed as the fraction of time a particular combination of events occurred during the study period. The non-recurrent congestion sources include weather, incidents, work zones, and special events. The scenario generator provides sufficient sets of operational scenarios that a corridor may experience during reliability reporting period. In data depository, data specific to the freeway facility need to be collected, including all segment geometrics, free-flow speeds, lane patterns, and segment types. The demand data can be either directly measured for a sample of days from field sensor or estimated from AADT and time-based factors. The core component FREEVAL-RL engine has been significantly revised from the FREEVAL engine.

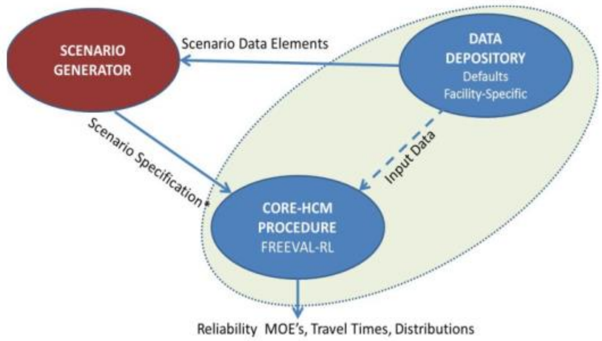


Figure 4.1 Freeway Facility Methodology Components and Their Relationship

With required data properly collected, FREEVAL-RL engine can run the input files as each file represents one scenario. The variation across scenarios result from three types of adjustment factors: demand variability, capacity variability, and free-flow speed variability. The demand variability refers to the demand variation in terms of time. The capacity variability is resulted from non-recurrent congestion, such as weather, incidents, work zone, and special events. The free-flow speed variability is caused by the weather condition. Each variability is expressed as an adjustment factor, which is applied to the base scenario. Compared with the FREEVAL engine, there are several major enhancements on FREEVAL-RL: 1. A method to incorporate free-flow speed and capacity adjustments has been developed; 2. FREEVAL-RL specifies a queue discharge rate less than the uninterrupted flow capacity; 3. FREEVAL-RL reports additional reliability-based outputs.

4.1.2 Urban Street Methodology

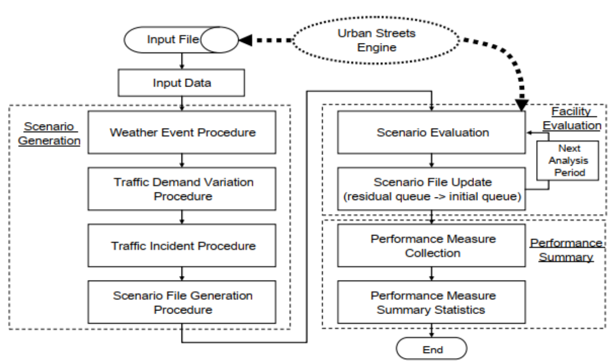


Figure 4.2 Workflow of the Urban Street Methodology

Figure 4.2 shows the workflow and components of the urban street methodology. There are three components in urban street methodology, including scenario generation, facility evaluation, and performance summary. Each component represents one stage in the workflow. The HCM 2010 urban street performance computational engine developed in previous research efforts was used to generate the input files for the new methodology. The input files are used to describe the traffic demand, geometry, and signal timing conditions for each intersection and segment on the urban street facility for one analysis period. Therefore, for reliability analysis, at least two input files are required: one represents the base condition without any work zone or special events, and another file describe conditions when a work zone or special event is present. Once the input files are created, the data needed for reliability methodology are identified. Compared with the freeway facilities, the urban street methodology requires more data. Table 4.1 lists all the input data required for urban street methodology.

Table 4.1 Input Data of Urban Street Methodology

Category	Variable	Description
General	Nearest city	One of 284 U.S. cities and territories whose climatic conditions are summarized periodically by the National Climatic Data Center (www.ncdc.noaa.gov)
	Functional class	Functional class of subject urban street facility
Input file	Date of traffic count	Basis of traffic volumes in base file. Can be either 1. Traffic counts measured in the field (enter the date of the count) or 2. Planning estimates of volume during the average day of week and month of year (do not enter a date)
	Starting hour of the count	Hour of the day that the traffic counts were measured or, if based on planning estimates, hour of the day to which the estimates apply
	Basis of traffic counts in the alternative input files	Basis of traffic volumes in alternative file. Can be either 1. Adjusted traffic counts from base file (enter the date of the count) or 2. Planning estimates of volume when the work zone or special event is present (do not enter a date)
Time period	Analysis period	Duration of analysis period (0.25 h or 1.0 h)
	Study period	Starting hour of study period and its duration in hours
	Reliability reporting period	Starting date of reliability reporting period and its duration in days
	Alternative file operating period	Starting date of work zone or special event and its duration in days
	Days of week considered	Days of week considered in reliability reporting period
Crash	Segment crash frequency	The segment-related crash frequency for each segment, including all severities. The value entered represents the long-run average number of crashes each year when work zones and special events are not present. It is adjusted appropriately if the reliability reporting period is not 1 year in duration.
	Intersection crash frequency	Same as for segments but based on intersection-related crashes
	Crash frequency adjustment factors	This factor is multiplied by the segment or intersection crash frequency. The product represents the long-run crash frequency if the work zone or special event were in operation for 1 year.

The scenario generation stage consists of four sequential procedures: the first procedure predicts weather event data, time, type, and duration; the second procedure identifies the appropriate traffic volume adjustment factors for each date and time during the study period; the third procedure predicts incident event data, time, and duration; and the fourth procedure uses the results from the preceding three procedures to develop one urban street engine input file for each analysis period.

In facility evaluation stage, input files are applied to engines created in the previous stage for evaluation and the analysis results are saved to an output file. The performance measures then can be extracted from the output files and used to revise the input files associated with the next analysis period. It enables that the initial queue input value for the next analysis period is equal to the residual queue output from the current period.

The performance summary stage aims to extract performance measures of interest from the output files. The measures include travel time, travel speed, stop rate, running time, and through delay. These measures are described and evaluated with their average, standard deviation, skewness, median, percentiles (10^{th}, 80^{th}, 85^{th}, and 95^{th}), and number of observations. Compared with freeway facility methodology, which generates scenarios on the basis of the combinational probability, urban street methodology randomly assigns non-recurrent events. So, in freeway facility methodology, some combination may not exist due to their low probability, but may be applicable in urban street methodology, since all events have their random probability. Since our study focuses on the reliability of freeway facilities, in the next section, we will provide a detailed explanation of the freeway facility methodology.

4.1.3 Freeway Facility Methodology Explanation

As mentioned above, there are three sources of unreliability being consider: demand variation, weather, and incident. The scenario generator uses a deterministic approach to model variations, which categorizes different sources of variability into subcategories. For example, weather has been divided into 11 categories, such as non-severe weather, medium rain, snow, etc. The probability of occurrence is created for each category. Most variation factors are considered to be independent, but some factors may be influenced by others. For example, some weather types may influence demand.

To calculate the probability of each scenario, time-wise probabilities of each variability contributor should be known. To define the probabilities of demand variability, the demand pattern in each study period should be studied. The demand pattern has two dimensions: one is the monthly variation and the other one is the weekly variation. Variation is expressed as demand multiplier (DM), which is the ratio of demand for a day-month combination to the AADT. Days with similar DMs are combined into the same pattern. Table 4.2 shows an example demand multiplier table from a case study of I-40 EB and Table 4.3 shows the corresponding demand pattern. In Table 4.3, it is observed that the demand pattern varies by season. In each season, the demands on Monday, Tuesday, and Wednesday are in the same pattern, but Thursday and Friday have unique patterns.

Table 4.2 Example Demand Multiplier Table

Month	Day of Week				
	Monday	Tuesday	Wednesday	Thursday	Friday
January	0.996623	1.027775	1.040394	1.052601	1.081612
February	0.939253	1.010728	1.039214	1.092029	1.140072
March	1.043305	1.069335	1.063524	1.110921	1.171121
April	1.073578	1.087455	1.098238	1.161974	1.215002
May	1.076331	1.106182	1.113955	1.157717	1.210434
June	1.078043	1.085853	1.067470	1.138720	1.180327
July	1.082580	1.070993	1.102512	1.147279	1.184981
August	1.046045	1.052146	1.060371	1.093243	1.164901
September	1.016023	1.024051	1.023625	1.074782	1.152946
October	1.048981	1.045723	1.066986	1.107044	1.160954
November	0.974044	0.999947	1.041211	1.081541	1.070354
December	0.974785	0.956475	0.987019	0.916107	1.007695

With demand pattern table constructed, the probability of demand pattern can be estimated. The probability $P_{DP}(Z)$ is calculated as

$$P_{DP}(Z) = \frac{sum\ of\ minutes\ within\ demand\ pattern\ Z}{sum\ of\ minutes\ in\ research\ period\ P}$$

where Z represents the demand pattern.

Table 4.3 Example Demand Pattern Table

	Monday	Tuesday	Wednesday	Thursday	Friday
January	1	1	1	2	3
February	1	1	1	2	3
March	4	4	4	5	6
April	4	4	4	5	6
May	4	4	4	5	6
June	7	7	7	8	9
July	7	7	7	8	9
August	7	7	7	8	9
September	10	11	11	12	12
October	10	11	11	12	12
November	10	11	11	12	12
December	1	1	1	2	3

The weather variability is calculated for each category of weather events. In HCM, weather events are divided into 16 categories, within which five categories have negligible effect on the performance of freeway facilities. There are thus 11 categories considered in the scenario generator. Similar to demand variability, weather variability is distinguished by month, which enables the users to incorporate the seasonal effects of weather. The probability of weather in each category is calculated as:

$$P_W(i,j) = \frac{sum\ of\ duration\ in\ minutes\ in\ month\ j\ that\ weather\ category\ i\ is\ present}{sum\ of\ study\ period\ duration\ in\ minutes\ in\ month\ j}$$

where i represents the weather category, and j represents the month.

Table 4.4 Example Weather Probability for Case Study on I-40 EB

Month	Weather Categories (based on HCM2010 Chapter 10: Freeway Facilities)										
	Medium Rain (%)	Heavy Rain (%)	Light Snow (%)	Light to Medium Snow (%)	Medium to Heavy Snow (%)	Heavy Snow (%)	Severe Cold (%)	Low Visibility (%)	Very Low Visibility (%)	Minimal Visibility (%)	Normal Weather (%)
January	1.970	0.000	5.911	0.000	0.000	0.000	0.000	0.000	0.000	0.000	92.1182
February	2.717	0.000	0.000	0.000	0.000	0.000	0.000	2.174	0.000	0.000	95.1087
March	0.505	0.000	1.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	98.4848
April	0.000	0.543	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	99.4565
May	1.951	1.951	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	96.0976
June	0.505	0.505	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	98.9899
July	0.500	0.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	99.0000
August	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	100.0000
September	4.255	0.532	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	95.2128
October	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	100.0000
November	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	100.0000
December	0.000	0.000	7.805	0.488	0.000	0.000	0.000	0.000	0.000	0.000	91.7073

Incidents are divided into six categories based on their severity on capacity impacts, which are no incident, shoulder closure, one-lane closure, two-lane closure, three-lane closure, and four-lane closure. The probability of each incident category is calculated as

$$P_{Inc}(i,j) = \frac{sum\ of\ all\ durations\ in\ minutes\ in\ month\ j\ that\ incident\ type\ i\ is\ present}{sum\ of\ all\ durations\ in\ minutes\ in\ month\ j}$$

In cases where local incident data are not available for the facility, it is recommended to use either local crash rates or crash rate predicted from HERS model together with an incident-to-crash ratio to estimate the probabilities. Table 4.5 shows an example incident probability table from a case study of I-40 EB.

Table 4.5 Example Incident Probabilities (Case Study of I-40 EB)

Month	Probability of Different Incident Types					
	No Incident (%)	Shoulder Closure (%)	One-Lane Closure (%)	Two-Lane Closure (%)	Three-Lane Closure (%)	Four-Lane Closure (%)
January	66.42	23.30	7.06	1.79	1.43	0.00
February	66.36	23.34	7.08	1.79	1.43	0.00
March	65.10	24.18	7.36	1.87	1.49	0.00
April	63.79	25.05	7.66	1.94	1.56	0.00
May	63.87	25.00	7.64	1.94	1.55	0.00
June	64.53	24.56	7.49	1.90	1.52	0.00
July	64.10	24.85	7.59	1.93	1.54	0.00
August	65.30	24.04	7.32	1.86	1.48	0.00
September	65.97	23.60	7.17	1.82	1.45	0.00

October	65.04	24.22	7.38	1.87	1.50	0.00
November	66.79	23.05	6.98	1.77	1.41	0.00
December	68.56	21.86	6.59	1.67	1.33	0.00

With the estimated probabilities of demand, weather, and incident, the scenario probability can be computed. Both weather and incident probabilities are characterized by month, but the probability of demand pattern is very likely by season. So, the probabilities of weather and incidents are aggregated across the demand pattern. The joint probability of a demand pattern and weather/incident combination is calculated as

$$P_w^{DP}(u,i) = \frac{\Sigma_{j\in DP} P_W(i,j) \times N_{DP}(u,j)}{\Sigma_{j\in DP} N_{DP}(u,j)}$$

where j refers to a month, u refers to a demand pattern, and i refers to a weather or incident type. For example, with the above example probabilities of demand pattern, weather, and incident from the case study of I-40 EB, the probability of medium rain (weather type = 1) and one-lane closure (incident event = 3) on Thursdays in Spring season (demand pattern = 5) is calculated as:

$$P_{Base}(demand\ pattern = 5, W = 1, Inc = 3) = P_{DP}(5) \times P_W^{DP}(5,1) \times P_{Inc}^{DP}(5,1)$$

where $P_W^{DP}(5,1) = \frac{\Sigma_{j=3}^{5} P_W(1,j) \times N_{DP}(5,j)}{\Sigma_{j=3}^{5} N_{DP}(5,j)} = \frac{0.00505\times4+0\times5+0.01951\times4}{13} = 0.756\%$

So $P_{Base}(DP = 5, W = 1, Inc = 3) = 0.0498 \times 0.00756 \times 0.007561 = 4.561 \times 10^{-5}$

4.2 Methods and Tools

To evaluate the adoptability of L08 products, the freeway facility methodology has been implemented in this pilot test. The latest version of computational engine is named FREEVAL+. To automate the process of constructing the FREEVAL+ model and reduce potential errors in creating FREEVAL+ seed files, we have developed a series of tools and methods to generate the input files for FREEVAL+. There are three major components in the tool suite:

1. A segmentation tool that automatically divides the freeway corridor into segments based on the geometric features and visualizes the segments;
2. A seed file generator, creating files that can be directly read by the FREEVAL+ engine to construct a corridor model; and
3. Travel demand calibration process which helps users fill in the demand information to the corridor model created by the previous component.

The tools have been applied to a case study to generate FREEVAL+ models for I-15 freeway corridor. In this section, we will introduce the tools developed in our effort.

4.2.1 Segmentation Tool

The current version of FREEVAL+ computational engine provides a map-based platform where users can create segments by manually pinning the start point and end point of segment on the map. The user-friendly interface of this map-based platform is illustrated in Figure 4.3. Compared with previous versions where users need to provide the exact length of each segment to construct the model, this latest version allows them to create segments simultaneously while observing the geometric features of the freeway corridors. Although the platform offers users immediate access to the segments and geometric features, it still has certain disadvantages: 1. the exact length is not available in the map-based platform, so it is difficult to create ramp or weaving segments, which are defined based on distance between geometric features. Without precise length, it is impossible to decide the locations where a new ramp or weaving segment begins. 2. According to the HCM, a new segment should be initiated in several occasions: on-ramp, off-ramp, managed lane access, and/or weaving section. Since users need to create segments manually on the map, it is convenient only when the conducted reliability analysis is for a short freeway corridor or long corridor with very few changes in geometric features.

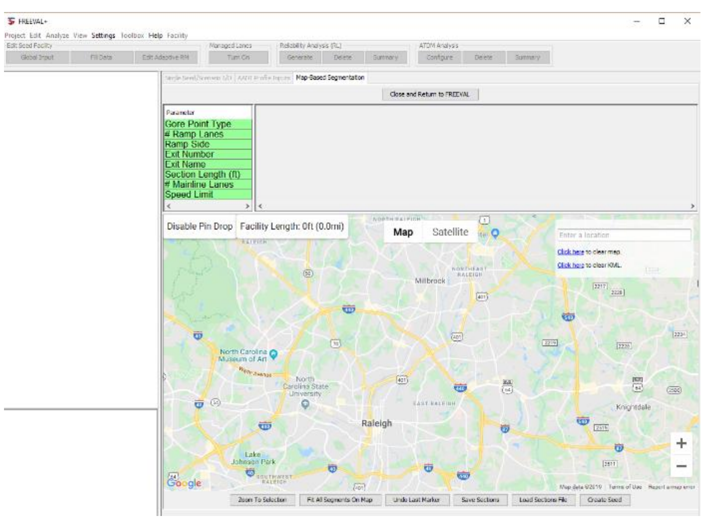


Figure 4.3 Interface of Map-based Segmentation Tool

In this pilot test, we focus on the traffic operation performance of I-15 in Salt Lake County, which spans from MP 285 to MP 310. Managed lanes with flush-buffer access exist across the entire corridor. In addition, since the corridor traverses the Salt Lake City metropolitan area with high population density and is jointed with I-80, many ramps exist along the corridor. On each direction of the 25-mile freeway corridor, there are around 70 segments in the FREEVAL+ model. Creating these many segments in the map-based platform is quite time-consuming and it is difficult to identify the locations where new segments should be started. Therefore, we have developed a python-based segmentation and visualization tool for automatically dividing corridor into segments. The visualization output of the tool can help users identify errors in geometric feature data collection and review the segmentation results.

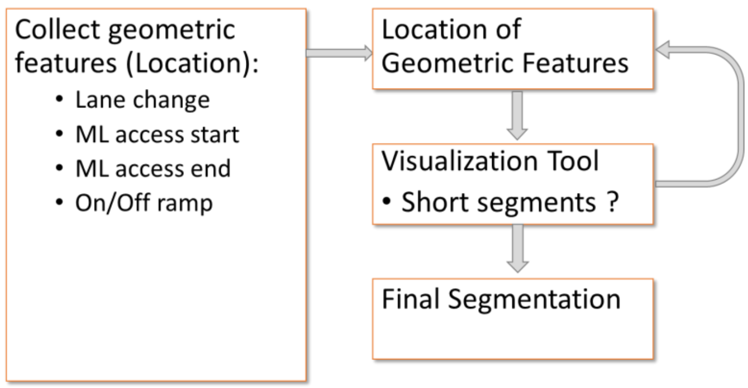


Figure 4.4 Workflow of the Segmentation Tool

Figure 4.4 shows the process of how the segmentation tool fulfills the function. The first step of constructing segments in the FREEVAL+ model is to collect geometric features, including ramps, managed lane accesses, and number of lanes along the corridor. The collected geometric information will be input into the segmentation tool. Then the segmentation tool will run its core part, a loop of dividing corridor based on the segmentation rules and adjusting the segmentation results.

Before further explaining the loop, we will briefly introduce the segmentation rules applied in FREEVAL+. In FREEVAL+, there are five types of general-purpose lane segments: basic, on-ramp, off-ramp, weaving, and overlap. The segmentation process FREEVAL+ follows the HCM facility segmentation guidance (HCM Chapter 10), which are as follows:

1. The first and last segments of the defined facility are basic freeway segments.
2. A new segment should be started whenever capacity changes.
3. The influence area of a ramp is considered 1,500 ft, downstream from the gore point for on-ramps and upstream of the gore point for off-ramps.

4. When the gore-to-gore length between two adjacent merge and diverge segments exceeds 3,000 ft and no auxiliary lane exists, the section should be coded as a series of three segments (merge, basic, diverge). The basic segment length is the difference between the gore-to-gore spacing and 3,000 ft.
5. When the gore-to-gore length of two adjacent merge and diverge segment is less than 3,000 ft but longer than 1,500 ft and no auxiliary lane exists, the section should be coded as a series of three segments, with the middle segment being defined as an overlap segment (merge, overlap, diverge). In this case, the overlap segment length is the difference between 3,000 ft and the gore-to-gore spacing, and the merge and diverge segment lengths are equal to the gore-to-gore spacing minus 1,500 ft.
6. Any remaining unassigned segments after all merge, diverge, weave, and overlap segments have been defined are labeled as basic segments.

Corridor segmentation is fulfilled by applying these rules to the corridor with measured geometric features. However, one challenge in corridor segmentation is the undersized segments. Figure 4.5 shows a typical example of undersized segment. In Figure 4.5, there exists one managed lane access and one on-ramp. According to the segmentation rules in HCM, a new segment should be started at the end of managed lane access, which is location A. Since location B is the gore point of the on-ramp, an on-ramp segment should be started from location B. So, there is a very short segment between locations A and B. Similar undersized segments are very common on the study corridor. Performance analysis of the undersized segment, which is usually shorter than 50 ft, would be vacuous. Therefore, we introduce a looping process to calibrate the segmentation results: in the segmentation tool, once any undersized segments are identified, the tool will alert the user the existence of undersized segments. Then the user will slightly adjust the locations of geometric features to merge the start and end points of undersized segments. The segmentation tool will repeat the process until no undersized segment is identified.

Figure 4.5 Example of Undersized Segment

Once the looping is completed, the segmentation tool will write the results into the output file and visualize them. In the output file, all the segments are sorted by the distance between them and the start of the corridor. Each segment is labeled with their geometric feature (ramp, weaving, overlap, etc.) and length. Figure 4.6 illustrates the visualization of I-15 NB corridor segmentation results. In this figure, the black horizontal lines represent general-purpose lanes, pink horizontal lines represent managed lane access, and red horizontal lines represent managed lanes. The red vertical lines represent the locations where new segments start. The green and blue arrows represent on-ramps and off-ramps, respectively. The number above each segment represents segment length in feet. The visualization provides users a direct view of the study corridor and help them identify any errors in data collection process.

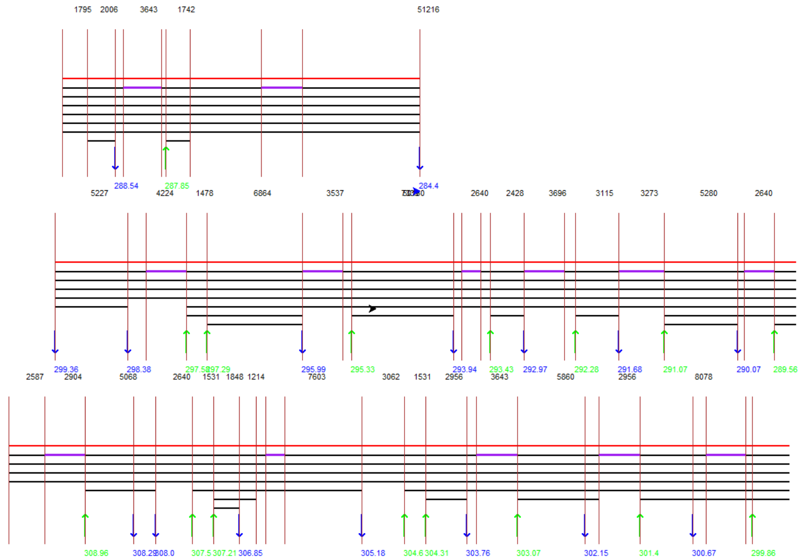


Figure 4.6 Visualization of I-15 NB Corridor Segmentation Results

<u>4.2.2 Seed File Generator</u>

With the corridor being divided into segments, the next step to construct FREEVAL+ model is to input the geometric and operational features of each segment into FREEVAL+. There are two methods to input data: 1. Manually input the features of each segment on the interface; 2. Create a seed file with all the features, which can be imported into FREEVAL+. Since we need to create models with more than 140 segments, we have developed a python-based code to generate the seed file, serving the second component of the tool suite. In each FREEVAL+ project on corridor with managed lanes, there are 12 global features, 33 general-purpose lane features, and 32 managed lane features. Table 4.6 shows the features and their definitions.

Table 4.6 Features in FREEVAL+ Model

Feature	**Definition**	***Feature***	**Definition**
<001> Project Name	-	*<002> Study Period Start Time*	The start of study period, usually the peak period, HH:MM
<003> Study Period End Time	End of study period, HH:MM	*<004> # of Segments*	Number of segments on the corridor
<005> Free Flow Speed Known?	If free flow speed is available, True/False	*<007> Managed Lane Used?*	If managed lanes are available on the corridor, True/False
<008> Capacity Drop (%)	-	*<009> Jam Density (pc/mi/ln)*	-
<010> Seed Demand Date (YYYY-MM-DD)	YYYY-MM-DD	*<011> GP Segment Vehicle Occupancy (p/veh)*	Default value = 1
<012> ML Segment Vehicle Occupancy (p/veh)	Default value = 1	*<101> General Purpose Segment Type*	Segment type, Basic = 0, ONR = 1, OFR = 2, Overlap = 3, Weaving = 4, Access = 8
<102> Segment Length	Length in feet	*<103> Lane Width*	Lane width in feet
<104> Lateral Clearance	ft	*<105> Terrain*	Level = 1, Rolling = 3, Varying = 4
<106> Truck-PC Equivalent	Truck PCE	*<107> RV-PC Equivalent (ER)*	RV PCE
<108> # of Lanes: Mainline	Number of GP lanes	*<109> Free Flow Speed*	Mph
<110> Mainline Dem.	Demand on GP lane, vph	*<111> Truck*	Truck percentage in demand, default = 5%
<112> RV (%)	RV percentage in demand, default = %	*<113> Seed Capacity Adj. Fac.*	Capacity adjustment factor, Default = 1.0
<114> Seed Entering Dem. Adj. Fac.	Entering demand adjustment factor, default = 1.0	*<115> Seed Exit Dem. Adj. Fac.*	Exit demand adjustment factor, default = 1.0
<116> Seed Free Flow Speed Adj. Fac.	Default = 1.0	*<118> Acc/Dec Lane Length (ft)*	-
<117> ONR Side	The direction of on-ramp (right = 0, left = 1)	*<119> # Lanes: ONR*	Number of on-ramp lanes
<120> ONR/Entering Dem.	On-ramp demand	*<121> ONR Free Flow Speed*	On-ramp free flow speed
<122> ONR Metering Rate	Vph	*<123> OFR Side*	Direction of off-ramp (right = 0, left = 1)
<124> # Lanes: OFR	Number of off-ramp lanes	*<125> OFR/Exit Dem*	off-ramp demand, vph
<126> OFR Free Flow Speed	Off-ramp free flow speed, mph	*<127> Weave Segment Ls*	Length of weaving segment, ft
<128> Weave Segment LCRF	Minimum number of lanes change from ramp to freeway	*<129> Weave Segment LCFR*	Minimum number of lanes change from freeway to ramp
<130> Weave Segment LCRR	Minimum number of lanes change from ramp to ramp	*<131> Weave Segment NW*	Number of lanes weave
<132> Ramp to Ramp Dem	vph	*<133> Ramp Metering Used?*	If ramp metering used, True/False
<201> ML Segment Type	Basic = 0, ONR = 1, OFR = 2, Overlap = 3, Weaving = 4, Access = 8	*<203> ML Type of Separation*	Marking = 0, Buffer = 1, Barrier = 2
<204> ML # of Lanes: Mainline	Number of lanes on managed lanes	*<205> ML Free Flow Speed*	Managed lane free flow speed, mph

<206> ML Mainline Dem.	ML demand, vph	*<207> ML Truck (%)*	ML truck percentage,5% default
<208> ML RV (%)	ML RV percentage, 0% default	*<209> ML Seed Capacity Adj. Fac.*	Default = 1
<210> ML Seed Entering Dem. Adj. Fac.	Default = 1	*<211> ML Seed Exit Dem. Adj. Fac.*	Default = 1
<212> ML Seed Free Flow Speed Adj. Fac.	Default = 1	*<213> ML Acc/Dec Lane Length (ft)*	Default = 0
<214> ML ONR Side	Direction of on-ramp on ML, right = 0, left = 1	*<215> ML # Lanes: ONR*	Number of on-ramp lanes on ML
<217> ML ONR Free Flow Speed	ML on-ramp free flow speed	*<216> ML ONR/Entering Dem.*	ML on-ramp demand,vph
<218> ML OFR Side	*Direction of off-ramp on ML, Right = 0, Left = 1*	*<219> ML # Lanes: OFR*	Number of off-ramp lanes on ML
<221> ML OFR Free Flow Speed	ML off-ramp free flow speed, mph	*<220> ML OFR/Exiting Dem. (vph)*	ML off-ramp demand, vph
<222> ML Length Short (ft)	ML weaving segment length	*<223> ML Weave Segment LCRF*	Minimum number of lanes change from ramp to freeway
<224> ML Weave Segment LCFR	Minimum number of lanes change from freeway to ramp	*<225> ML Weave Segment LCRR*	Minimum number of lanes change from ramp to ramp
<226> ML Weave Segment NW	Number of lanes weave on ML	*<229> ML Ramp to Ramp Dem.*	vph
<227> ML Min Lane Change	ML minimum lane change	*<228> ML Max Lane Chang*	ML maximum lane change
<230> Analysis of Cross Weave Effect	Whether GP lanes have weave effect	*<231> Cross Weave LC-Min*	ML cross weave minimum lane change
<232> Cross Weave Volume	Managed lane cross weave volume		

After the segmentation tool divides the corridor into multiple segments, the segment data, including location, geometric features, number of lanes, etc., will be processed by the seed file generator. Then the generator will automatically identify the features for each segment. The last step in seed file generator is to write the features of all segments based on the provided format into FREEVAL+, with example seed file available in the software.

4.2.3 Travel Demand Calibration

The segmentation results only provide geometric related features. However, among all features, the most critical ones in determining the freeway performance are the traffic demands, including the entering traffic from the upstream of the freeway corridor and the on-ramps, the exiting traffic to the downstream of the freeway corridor and the off-ramps, and the weaving movements at ML access. Therefore, the last component to finalize the model input is demand calibration.

In cases where travel demand information is available on any location along the corridor, the demand information can be written into the seed file and automatically imported into the FREEVAL+ model. Nevertheless, in most cases, the hourly or even finer resolution travel demands are not available. Especially when the scenarios are focusing on congested traffic conditions during peak periods, it is difficult to measure the actual traffic demands.

To calibrate the traffic demands from upstream and ramps, two approaches have been applied in this pilot test. The first approach is to estimate the hourly or even 15-minute demand based on AADT and the hourly distribution of demand. FREEVAL+ provides a large database of demand profiles on many freeway facilities. Users who conduct performance analysis on these facilities can use the demand profile from the database directly. For reliability analysis beyond these corridors, FREEVAL+ also provides three built-in models to describe the hourly distribution of demands, including unimodal profile, bimodal-AM peak profile, and bimodal-PM peak profile. Each model contains the hourly demand proportion to AADT. With the selected demand profile and AADT information collected from other data sources, users can estimate the entering demands and exiting demands of the freeway facilities. The second approach is to use traffic volume as the base demand and adjust the flow to match the modeled and actual speeds. In uncongested scenarios, traffic flow is considered to be equivalent to travel demand, but in congested situations, flow is much lower than the actual demand due to the congestion. In such cases, the modeled speed should be much higher than the actual speed. Therefore, by gradually increasing the input demand, we can decrease the modeled speed until it gets fairly close to the actual speed.

Another challenge is to estimate the weaving movement entering or exiting managed lane via HOV/HOT accesses. Therefore, two assumptions have been made to address this issue: 1. Since managed lane spans the entire corridor, travelers who would use the managed lane will enter from the very first access after they enter the freeway; travelers on managed lane who would exit the freeway will exit managed lane from the access right before their freeway off-ramp. All managed lane users will maximize their utilization of the lane in spite of travel costs. 2. A fixed portion of on-ramp traffic will enter the managed lane from the nearly access and a fixed portion of off-ramp traffic will exit from the managed lane nearly access. With the two assumptions, the weaving movement at each managed lane access can be estimated.

4.3 Case Study and Result Analysis

In this section, we will present the reliability analysis of I-15 NB and SB corridors (MP 285 to MP 310) in Salt Lake County, Utah (illustrated in Figure 4.7). Geometric features on the study corridor have been collected and the aforementioned tools have been used to create FREEVAL+ models. The evening peak hour (from 16:00 to 17:00) is considered as the study period. Both AADT-based and volume-based demand calibration approaches have been applied. The study period has been divided into four 15-minute periods, during which the reliability of corridor is evaluated. At managed lane access, we assume 8% of the ramp traffic are the weaving movements.

Figure 4.7 Illustration of Study Corridor I-15, Salt Lake City, Utah

4.3.1 I-15 NB Corridor

Table 4.7 shows the geometric features on I-15 NB: there are 18 on-ramps, 15 off-ramps, and 13 managed lane accesses along the corridor. Based on the geometric features of the corridor, segmentation tool divided the corridor into 70 segments. Figure 4. 8 illustrates the segmentation results of I-15 NB corridor.

Table 4.7 Geometric Features on I-15 NB

MP	Lane #	MP	Lane #	On-Ramp	Off-Ramp	Access_start	Access_End
287.5	6	299.45	5	288.54	287.86	286.11	286.69
287.86	5	299.9	4	290.1	289.4	287.95	288.54
288.54	6	300.85	5	291.65	290.98	289.51	290.1
288.84	5	301.32	4	292.95	292.22	291.13	291.65
289.4	4	301.93	5	293.91	293.35	292.22	292.95
290.6	5	303.04	4	296	295.28	293.35	293.91
290.98	4	304	5	298.3	297.45	295.45	296
291.65	5	304.3	4	298.86	297.6	297.76	298.3
292.22	4	304.51	3	299.21	299.9	300.15	300.69
292.95	5	305.1	5	300.69	301.32	301.4	301.93
293.35	4	305.3	4	301.93	303.04	303.26	303.78
293.91	5	305.59	5	303.78	304.3	306.15	306.65
295.28	4	305.7	4	304.89	304.51	308.04	308.31
296	5	306.65	5	305.59	307.2		
297.6	4	306.85	6	306.15	307.52		
298.3	5	307.2	4	306.65			
298.5	4	307.52	3	308.04			
298.86	5	308.04	5	308.31			
299.1	4	308.5	4				

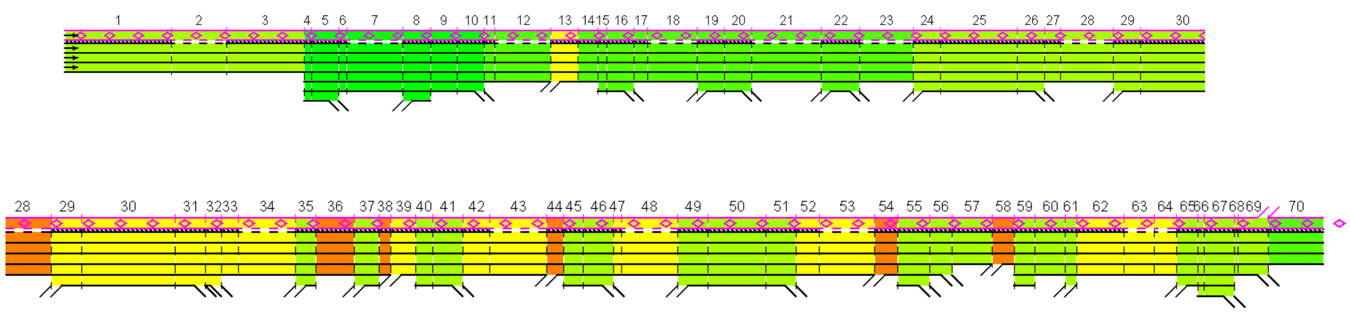


Figure 4.8 Illustration of Segmentation Results (I-15 NB)

4.3.2 I-15 SB Corridor

Table 4.8 shows the geometric features on I-15 SB corridor: there are 16 on-ramps, 16 off-ramps, and 13 managed lane accesses. The SB corridor has been divided into 71 segments. Figure 4.9 illustrates the segmentation results.

Table 4.8 Geometric Features on I-15 SB

MP	Lane #	MP	Lane #	On-ramp	Off-ramp	Access_Start	Access_End
309.51	3	297.29	6	308.29	308.29	309.51	308.96
308.96	4	295.99	4	308	308	306.49	306.23
308	3	295.33	5	306.85	306.85	303.63	303.07
307.5	4	293.94	4	305.18	305.18	301.96	301.4
307.21	6	293.43	5	303.76	303.76	300.49	299.96
306.85	5	292.97	4	302.15	302.15	298.13	297.58
306.62	4	292.28	5	300.67	300.67	295.99	295.45
305.18	3	291.68	4	299.36	299.36	293.83	293.56
304.6	4	291.07	6	298.38	298.38	292.97	292.42
304.31	5	290.07	5	295.99	295.99	291.68	291.07
303.76	4	289.56	6	293.94	293.94	289.97	289.56
303.07	5	289.27	5	292.97	292.97	288.44	287.91
301.96	4	288.92	6	291.68	291.68	286.56	286
301.4	5	288.54	5	290.07	290.07		
299.86	5	287.85	6	288.54	288.54		
299.36	4	287.53	5	284.4	284.4		
298.38	3	284.4	3				
297.58	5						

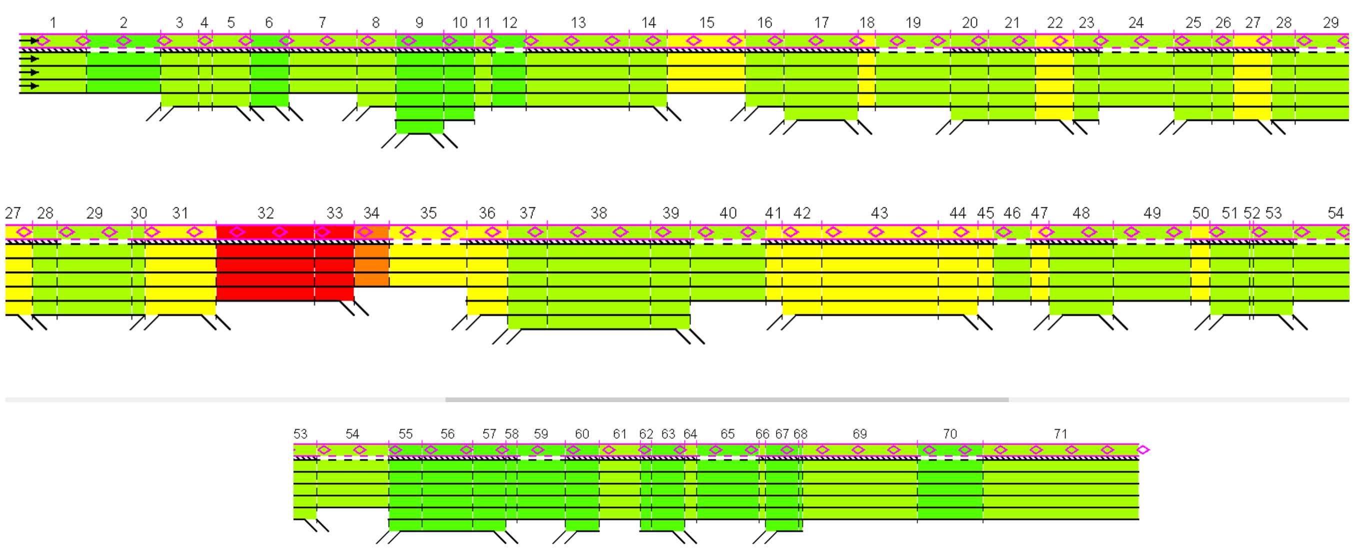


Figure 4.9 Illustration of Segmentation Results (I-15 SB)

4.3.3 AADT-Based Approach

For the AADT-based approach, bimodal-PM peak demand profile was used in our model. AADT in 2017 was retrieved from PeMS (https://udot.iteris-pems.com/) and used as the daily demand entering from upstream of the corridor and ramps. According the bimodal-PM peak demand profile, the traffic demand proportion to the AADT during each period is as follows:

- 16:00 - 16:15: 8.29%
- 16:15 – 16:30: 8.31%
- 16:30 – 16:45: 8.35%
- 16:45 – 17:00: 8.37%

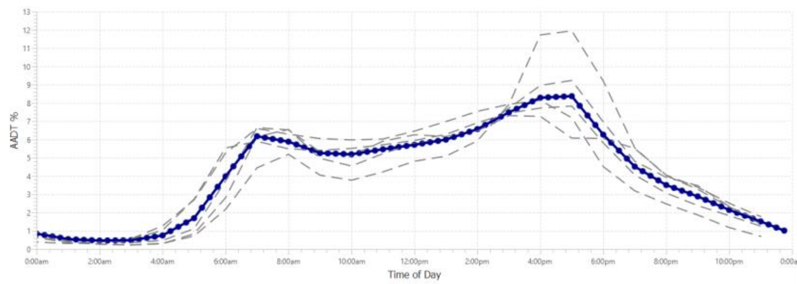


Figure 4.10 Bimodal-PM Peak Demand Profile

Using such generated demands, FREEVAL+ produced the profiles of modeled speed (illustrated in Figure 4.11 and Figure 4.12). In the NB model, it is observed that from MP 285 to MP 304, the two speed profiles match well and the calibrated speed overall is higher than the actual speed. In the SB model, modeled speed from MP 305 to MP 300 and MP 298 to MP 294 is much higher than the actual speed, meaning that the built-in demand profile model does not properly reflect the actual demand on these segments.

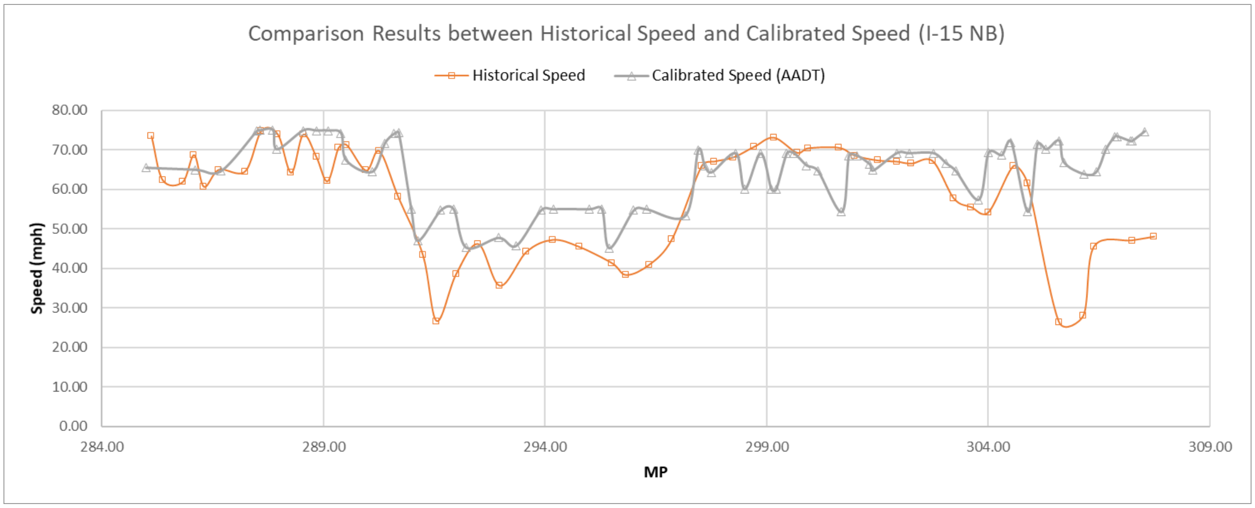


Figure 4.11 Average Speed Comparison Results on I-15 NB (AADT)

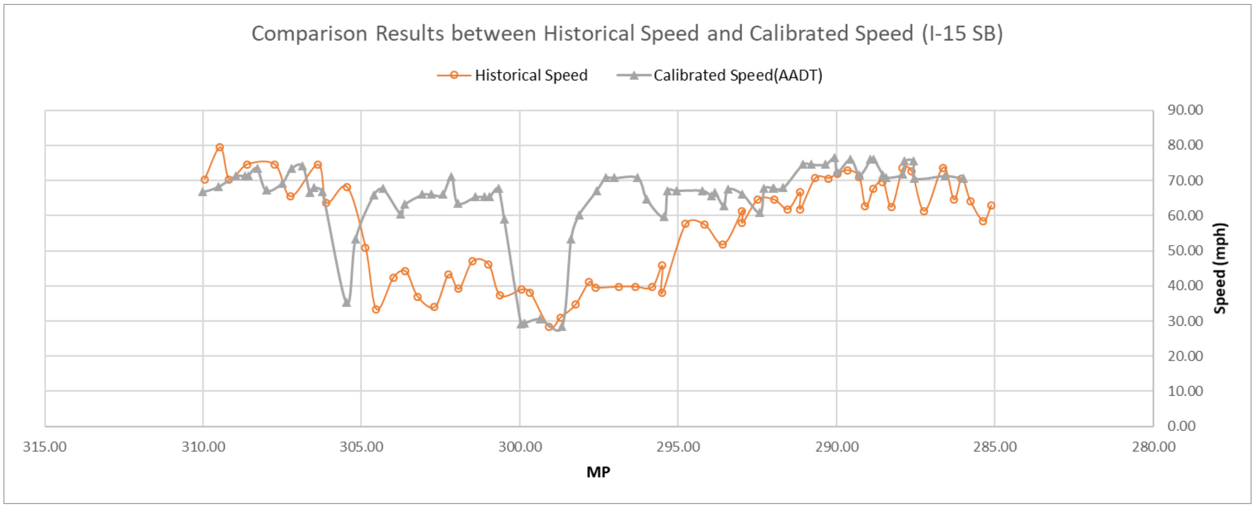


Figure 4.12 Average Speed Comparison Results on I-15 SB (AADT)

4.3.4 Volume-Based Approach

To apply volume-based approach, we have selected the average hourly volume on Tuesday, Wednesday, and Thursday in 2017 June as the base volume. In the calibration process, we manually increase the ramp demand to make the modeled speed match with the average speed. Figure 4.13 and Figure 4.14 show the comparison between actual speed and the speed under the calibrated demands. In the SB model, the two speed profiles match well. In the NB model, at most locations on the corridor, the calibrated speed is very close to the actual speed. But on the segment between MP 290 to MP 297, the calibrated speed is much higher than the actual speed, which may be cause by the queue spillbacks at the spaghetti junction at MP 287 between I-15 and I-215.

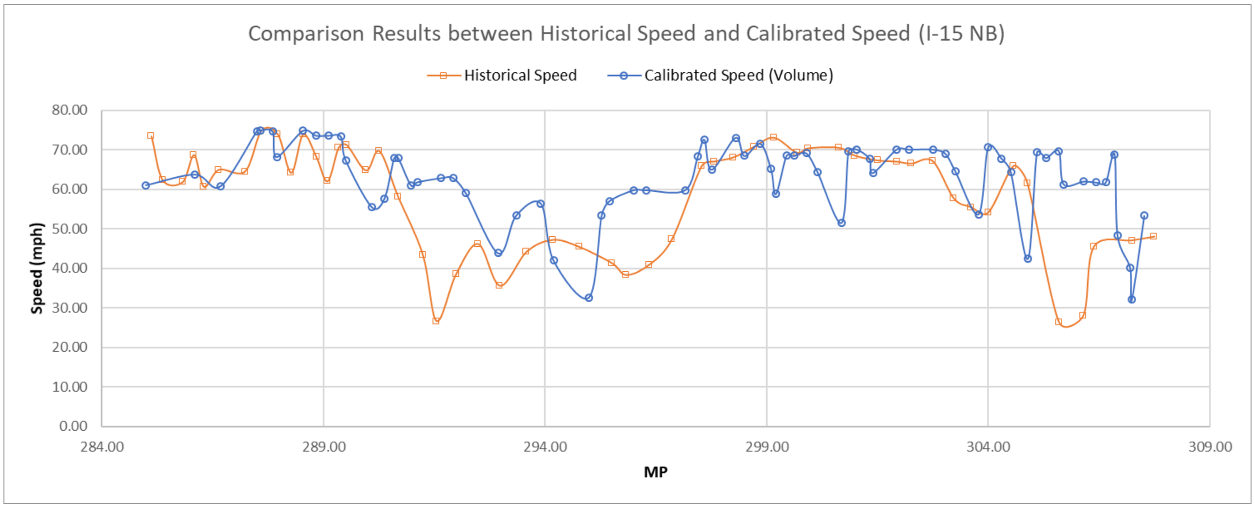


Figure 4.13 Average Speed Comparison Results on I-15 NB (Volume)

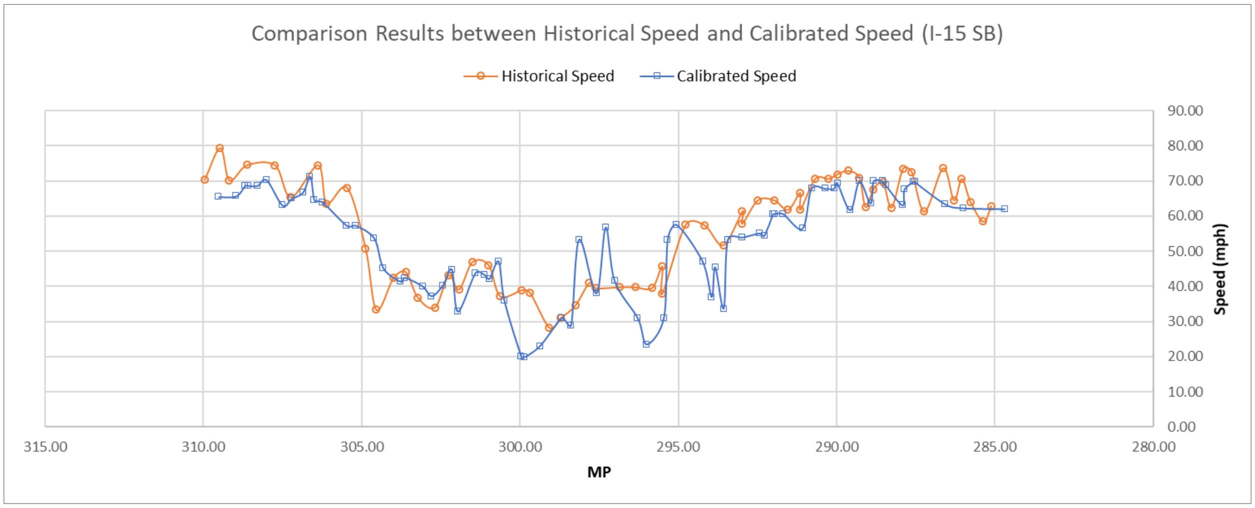


Figure 4.14 Average Speed Comparison Results on I-15 SB (Volume)

4.3.5 Reliability Analysis

To evaluate FREEVAL+'s capability of reliability analysis, we have also conducted a reliability analysis on the I-15 NB corridor with the model calibrated with volume-based approach. Since historical traffic data used is from June, 2017, when precipitation is very rare in Utah, we consider incident only as the non-recurrent factor. A sensitivity analysis has been conducted in evaluating the reliability: national average incident/crash ratio is 4.9 crashes per

100 million VMT. We conducted the sensitivity analysis with incident/crash ratios of 2.45, 4.9, and 9.8, respectively. Figure 4.15 shows the comparison results between the actual observed TTI and the modeled TTI. It is noted that as incident/crash ratio increases, the TTIs slightly increase along the entire corridor. The TTI profiles between historical data and the modeled cases have very similar trends, but at certain locations the TTI values of two profiles are still very different, which may be caused by the difference between the actual and calibrated speed.

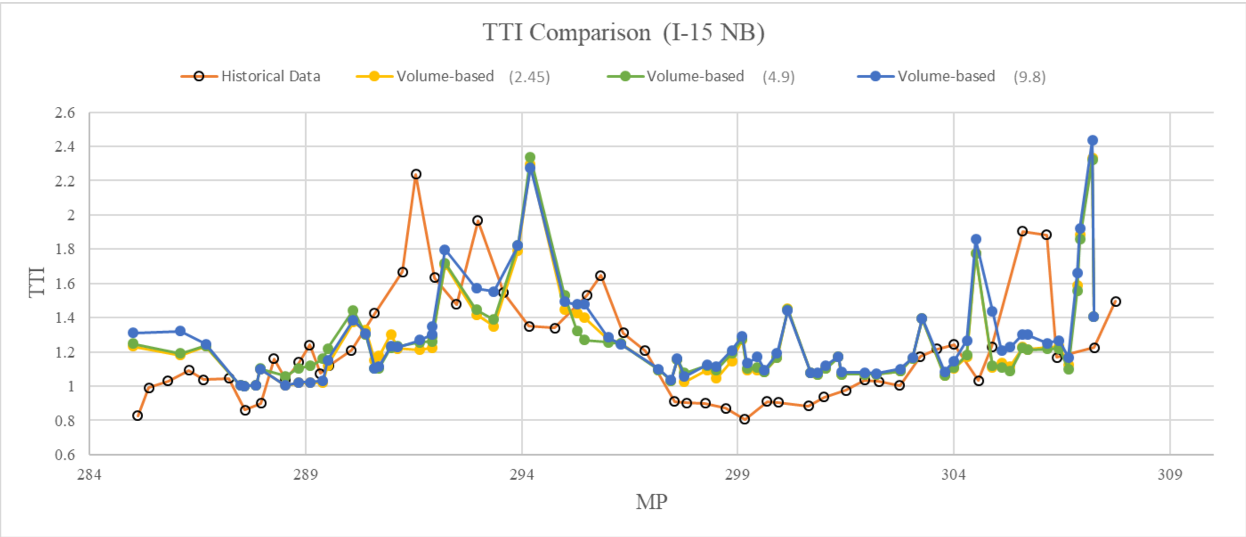


Figure 4.15 TTI Comparison between Historical TTI and Modeled TTI

4.4 Summary

In this pilot test, we have conducted a reliability analysis on I-15 corridor in Salt Lake City, Utah with the freeway facility methodology developed L08 project. The methodology consists of three components: data depository, scenario generator, and computational engine FREEVAL-RL. In data depository process, geometric and operational information is gathered to construct the scenarios in the FREEVAL-RL model. Scenario generator creates hypothetical scenarios based on the probability of demand variation, incident, and weather event on the study corridor. The scenarios then will be applied to the FREEVAL-RL model to evaluate the performance of the freeway corridor under non-recurrent events. The core component, FREEVAL-RL, was developed from the previous version of FREEVAL computational engine for freeway performance analysis, which is based on the HCM guidance.

To evaluate the performance of I-15 corridor, we have developed a series of tools to construct the FREEVAL+ model, including an automatic segmentation tool and a seed file generator. The segmentation tool implements the HCM freeway segmentation rules and automatically divides freeway corridors into segments based on the geometric features of the corridor. The tool embeds a calibration looping process, allowing users to adjust the segmentation rules or geometric features to customize the pattern of segments. The seed file generator uses the outputs from segmentation tool and automatically generates a seed file for FREEVAL+ engine. The seed file contains all the required geometric data and operational data, such as segment type, length, speed limit, lane number, etc., to build a FREEVAL+ model. Top enable I-15 analysis, traffic data was collected from PeMS. Two demand calibration methods have been proposed and applied in the pilot test. For the AADT-based method, built-in bimodal PM peak demand profile in FREEVAL+ was used to estimate the traffic demands with 15-minute interval. For volume-based method, a manual calibration process has been conducted.

With the aforementioned tools and data, we have conducted a performance evaluation on I-15 corridor with FREEVAL+. The FREEVAL+ computational engine models freeway corridor and generates multiple operational features to describe the performance of the corridor. According to the comparison between the modeled speed and the speed from historical data, it is observed that FREEVAL+ can generally predict the reliability trends on the freeway corridor, but for certain locations along the corridor with severe congestion, there still exists a gap between the modeled and actual performance.

5.0 CONCLUSIONS

In this study, we have conducted three pilot tests on the products of SHRP2 projects L02, L05, and L08 to evaluate their adoptability to address local transportation issues in the state of Utah.

In the L02 pilot test, we conducted TTR analysis on I-15 freeway corridor in Salt Lake City, Utah, using probe data. Both L02 and UDOT's current reliability methods are applied to the study corridor for cross validation. It is found that segments on I-15 freeway corridor demonstrate varying performance pattern in terms of travel-time reliability and such pattern changes over time. Between incident and adverse weather, incident contributes more to unreliability as the non-recurrent factor to most segments. The two measures produce consistent results in terms of TTR assessment and unreliability sources identification. The cross-validation process can help UDOT evaluate thresholds for the quadrant-based TTR measure. Future study on the L02 product can focus on applying simulation or modeling approach to construct statistical probability functions and cross-validating the measures at the network level.

In the L05 pilot test, the guideline was combined with UDOT's current project prioritization system and applied to five candidate highway improvement projects along Interstate 15. Based on the results, agencies can identify reliability deficiency at the site of each project which can be used in the project funding allocation process.

In the L08 pilot test, we have conducted a reliability analysis on I-15 corridor in Salt Lake City, Utah. A series of tool suites are developed to construct the FREEVAL+ model, including an automatic segmentation tool and a seed file generator. Two demand calibration methods have been proposed and applied in the test: AADT-based method and volume-based method. Assumptions have been made to estimate the demands of weaving movement at HOV/HOT access. According to the comparison between the modeled traffic condition and historical traffic, it is observed that FREEVAL+ can predict the overall reliability trends on the freeway corridor, yet gap still exists between the actual and modeled traffic condition on certain individual segments.

REFERENCES

1. FWHA. Travel Time Reliability: Making It There On Time, All The Time. 2006, pp. 1–17.

2. Nam, D., D. Park, and A. Khamkongkhun. Estimation of Value of Travel Time Reliability. *Journal of Advanced Transportation*, Vol. 39, No. 1, 2005, pp. 39–61. https://doi.org/10.1002/atr.5670390105.

3. FHWA. *Traffic Congestion and Reliability: Linking Solutions to Problems*. 2004.

4. Liu, X., and Z. Chen. *Data-Driven Freeway Performance Evaluation Framework for Project Prioritization and Decision Making*. 2015.

5. van Lint, J. W. C., H. J. van Zuylen, and H. Tu. Travel Time Unreliability on Freeways: Why Measures Based on Variance Tell Only Half the Story. *Transportation Research Part A: Policy and Practice*, Vol. 42, No. 1, 2008, pp. 258–277. https://doi.org/10.1016/j.tra.2007.08.008.

6. List, G. F., B. Williams, N. Rouphail, R. Hranac, T. Barkley, E. Mai, A. Ciccarelli, L. Rodegerdts, K. Pincus, B. Nevers, and Others. *Establishing Monitoring Programs for Travel Time Reliability*. Transportation Research Board, Washington, D.C., D.C., 2014.

7. Sobolewski, M., T. Polum, P. Morris, R. Loos, and K. Anderson. *Pilot Testing of SHRP 2 Reliability Data and Analytical Products: Minnesota*. 2015.

8. Hadi, M., Y. Xiao, T. Wang, P. Hu, J. Jia, R. Edelstein, A. Lopez, A. Consult, and others. Pilot Testing of SHRP 2 Reliability Data and Analytical Products: Florida. *SHRP2 Reliability Project L38C*, 2015.

9. Nisbet, J., D. Bremmer, S. Yan, D. Murshed, Y. Wang, Y. Zou, W. Zhu, M. Dunlap, B. Wright, T. Zhu, and others. *Pilot Testing of SHRP 2 Reliability Data and Analytical Products: Washington.[Supporting Datasets]*. 2014.

10. Pu, W. Analytic Relationships Between Travel Time Reliability Measures. *Transportation*

Research Record: Journal of the Transportation Research Board, Vol. 2254, No. 1, 2011, pp. 122–130. https://doi.org/10.3141/2254-13.

11. Yazici, M., C. Kamga, and K. Mouskos. Analysis of Travel Time Reliability in New York City Based on Day-of-Week and Time-of-Day Periods. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2308, 2012, pp. 83–95. https://doi.org/10.3141/2308-09.

12. Bhouri, N., and J. Kauppila. Managing Highways for Better Reliability. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2229, 2011, pp. 1–7. https://doi.org/10.3141/2229-01.

13. Lei, F., Y. Wang, G. Lu, and J. Sun. A Travel Time Reliability Model of Urban Expressways with Varying Levels of Service. *Transportation Research Part C: Emerging Technologies*, Vol. 48, 2014, pp. 453–467. https://doi.org/10.1016/j.trc.2014.09.019.

14. Yang, S., and Y.-J. Wu. Mixture Models for Fitting Freeway Travel Time Distributions and Measuring Travel Time Reliability. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2594, 2016, pp. 95–106. https://doi.org/10.3141/2594-13.

15. Barkley, T., R. Hranac, and K. Petty. Relating Travel Time Reliability and Nonrecurrent Congestion with Multistate Models. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2278, No. 1, 2012, pp. 13–20. https://doi.org/10.3141/2278-02.

16. Alvarez, P., and M. Hadi. Time-Variant Travel Time Distributions and Reliability Metrics and Their Utility in Reliability Assessments. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2315, No. 1, 2012, pp. 81–88. https://doi.org/10.3141/2315-09.

17. Fosgerau, M., and D. Fukuda. Valuing Travel Time Variability: Characteristics of the Travel Time Distribution on an Urban Road. *Transportation Research Part C: Emerging Technologies*, Vol. 24, 2012, pp. 83–101. https://doi.org/10.1016/j.trc.2012.02.008.

18. Liu, H. X., X. He, and W. Recker. Estimation of the Time-Dependency of Values of Travel Time and Its Reliability from Loop Detector Data. *Transportation Research Part B: Methodological*, Vol. 41, No. 4, 2007, pp. 448–461. https://doi.org/10.1016/j.trb.2006.07.002.

19. Tu, H., A. J. Pel, H. Li, and L. Sun. Travel Time Reliability During Evacuation. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2312, No. 1, 2012, pp. 128–133. https://doi.org/10.3141/2312-13.

20. Mauro, R., O. Giuffrè, and A. Granà. Speed Stochastic Processes and Freeway Reliability Estimation: Evidence from the A22 Freeway, Italy. *Journal of Transportation Engineering*, Vol. 139, No. 12, 2013, pp. 1244–1256. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000599.

21. Tu, H., H. Li, H. van Lint, V. Knoop, and L. Sun. Macroscopic Travel Time Reliability Diagrams for Freeway Networks. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2396, 2013, pp. 19–27. https://doi.org/10.3141/2396-03.

22. Kwon, J., T. Barkley, R. Hranac, K. Petty, and N. Compin. Decomposition of Travel Time Reliability into Various Sources. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2229, 2011, pp. 28–33. https://doi.org/10.3141/2229-04.

23. Kamga, C., and M. A. Yazici. Temporal and Weather Related Variation Patterns of Urban Travel Time: Considerations and Caveats for Value of Travel Time, Value of Variability, and Mode Choice Studies. *Transportation Research Part C: Emerging Technologies*, Vol. 45, 2014, pp. 4–16. https://doi.org/10.1016/j.trc.2014.02.020.

24. Mazloumi, E., G. Currie, and G. Rose. Causes of Travel Time Unreliability–a Melbourne Case Study. *Proc., 31st Australian Transport Research Forum*, No. January, 2008, pp. 195–202.

25. Crawford, F., D. P. Watling, and R. D. Connors. A Statistical Method for Estimating

Predictable Differences between Daily Traffic Flow Profiles. *Transportation Research Part B*, Vol. 95, 2016, pp. 196–213. https://doi.org/10.3109/08941939.2012.723954.

26. Caceres, H., H. Hwang, and Q. He. Estimating Freeway Route Travel Time Distributions with Consideration to Time-of-Day, Inclement Weather, and Traffic Incidents. *Journal of Advanced Transportation*, Vol. 2016, No. july, 2016, pp. 248–254. https://doi.org/10.1002/atr.

27. Woodard, D., G. Nogin, P. Koch, D. Racz, M. Goldszmidt, and E. Horvitz. Predicting Travel Time Reliability Using Mobile Phone GPS Data. *Transportation Research Part C: Emerging Technologies*, Vol. 75, 2017, pp. 30–44. https://doi.org/10.1016/j.trc.2016.10.011.

28. Mazaré, P., A. M. Bayen, and S. D. Hall. Trade-Offs between Inductive Loops and GPS Probe Vehicles for Travel Time Estimation : A Mobile Century Case Study. No. 6, 2012, pp. 16–32.

29. Chen, Z., X. C. Liu, and G. Zhang. Non-Recurrent Congestion Analysis Using Data-Driven Spatiotemporal Approach for Information Construction. *Transportation Research Part C: Emerging Technologies*, Vol. 71, 2016, pp. 19–31. https://doi.org/10.1016/j.trc.2016.07.002.

30. MesoWest User's Guide. https://mesowest.utah.edu/html/help/userguide.html. Accessed Jul. 31, 2018.

31. Edwards, M. B., and M. D. Fontaine. Investigation of Travel Time Reliability in Work Zones with Private-Sector Data. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2272, 2012, pp. 9–18. https://doi.org/10.3141/2272-02.