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Subject: Reliability Data and Analytic Products: Data Source Review and Product Pilot  
Testing

SHRP 2 Reliability Project

## **Pilot Testing of SHRP 2 Reliability Data and Analytical Products: Wisconsin**

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## Executive Summary

The second Strategic Highway Research Program (SHRP 2) has been investigating the reliability of highway travel time for several years. In its Reliability focus area, the research emphasizes improving the reliability of highway travel time by reducing the frequencies and effects of events that cause travel time to fluctuate in an unpredictable manner. Under SHRP 2 Reliability focus area, researchers identified contributing factors for reliability deficiencies, developed a number of methods to estimate travel time reliability, and analyze the impact of different solutions to improve travel time reliability. Multiple tools have been developed based on a variety of approaches such as sketch planning, analytical analysis, simulation analysis, and travel time monitoring.

Wisconsin participated in Implementation Assistance Program Round 7 (IAP7) with the goal of expanding the concept of reliability into highway improvement planning and evaluations. Mobility performance has been increasingly used to measure the service quality of Wisconsin highways. Tracking progress and trends of performance in terms of reliability and delay are driving efforts to expand real time performance monitoring in new areas of the Department of Transportation. Four key objectives of this project were to use data, analysis and decision making to

- Assess causes of non-recurrent congestion to improve traffic management strategies including roadway geometry and operation programs;
- Assess potential cost and operational effects of implementing solutions to improve reliability;
- Support WisDOT's interest in advancing tools to provide insight into the economic impacts of reliability and congestion; and
- Provide institutional feedback to SHRP 2 on findings of product testing and evaluation.

The project team included agency, university and consultant staff to test all five available products. The L02 product was tested on a 5-mile I-41 segment in Northbound near Appleton, WI and data output was reviewed by the University of Wisconsin -Madison Traffic Operations and Safety (TOPS) Laboratory. Travel time data and trends were produced in the format of reliability reports including CDF's, PDF's and histograms for the test site; and were developed for sites that supported tests of other products in the L38 Bundle such as L08 and C11. The C11 product was reviewed and compared with a WisDOT developed tool for quantifying congestion levels by agency staff in the Department's Bureau of State Highway Programs and SRF Consulting Group. Three highway corridors were tested which represented different highway functional classes (interstate and U.S. highways, urban and rural), including 5-mile I-41 corridor near Appleton, 45-mile I-39/90 corridor from the Wisconsin State Line to Madison, and US 14 from Cross Plains to Middleton. The L07 and L08 products were reviewed by the University of Wisconsin-Milwaukee transportation research team and agency staff in the Bureau of Traffic Operations. The L07 test sites were selected to evaluate the impact of Freeway Service Team patrols on two freeway corridors: 12-mile I-41 corridor in Brown county with the presence of a long-term work zone and 10.7-mile I-39/90/94 corridor in Columbia County. Incident Management Benefit-Cost output

provided contrast in supporting this popular service program. The L08 test site was an urban freeway, US 12/14 located in Madison, WI, with a capacity expansion. Reliability results from the product represented operation conditions and deficiencies. Throughout the implementation and testing, reliability performance measures are being incorporated into planning and programming (L05).

This final report details the findings of SHRP 2 Reliability Data and Analytical Tool (RDAT) testing conducted in Wisconsin for L02, L05, L07, L08 and C11. Notable findings are listed as below:

- Project L02 identified methods to collect, archive, and integrate required data for reliability estimation, and methods for analyzing and visualizing the causes of unreliability based on the collected data. The test confirmed that all the necessary data types are available – both from traffic sensors and other systems and including travel times, incidents, work zones, etc. – and are generally ubiquitous on the interstate, though of decreasing availability on lower volume segments. The project also demonstrated the process taken for computing the PDF and CDF plots, which can be automated to a large extent by using standards-based scripts in commonly available computational platforms.
- Project L05 provided guidance regarding how to use reliability assessments to support the business processes of transportation agencies.
- Projects L07 and L08 provided analytical methods, techniques and tools for estimating reliability and its impact on alternative mitigating strategies. One of the challenging input variables for L07 is the event duration for both crash and non-crash incidents. For some highways, collecting complete incident count can be difficult too. Moreover, the overall benefit output from L07 under the long-term work zone condition is unreasonably high; whereas, the travel time reliability benefit is relatively low compared to the delay benefit.
- L08 required a significant amount of data to properly execute compared to the other reliability tools. Although the tool (i.e. FREEVAL-RL) can provide reasonable reliability output using the default values, the output may not resemble field conditions. With site-specific input values, FREEVAL-RL suggested that the tool may not provide reliable output in the presence of a downstream bottleneck, even after extending the study corridor to include the bottleneck. FREEVAL-RL also underestimated travel time in the congested traffic condition. The results of multiple scenarios indicated that the tool over-estimated in the lower portion (until 80<sup>th</sup> percentile) and under-estimated in the upper portion (over 80<sup>th</sup> percentile) of the TTI distribution. The disparities can be observed from the estimated misery index and semi-standard deviation. The limitation of capacity drop may play a significant role in estimating travel times for trips with excessive delay in the corridor.
- Project C11 provided methods in assessing the wider economic benefits of transportation capacity improvement projects. Incident duration is again the most difficult input to obtain, and any potential reduction under a build scenario. The C11 tool delay outputs were significantly lower than expected. When compared with other tools developed by WisDOT

to quantify nonrecurring effects, the delay results from C11 in most cases were lower by multiple orders of magnitude, and nonrecurring delay hours were minimal.

The Wisconsin IAP has helped demonstrate reliability applications on projects and treatments familiar to WisDOT staff involved in the planning, programming and evaluation of financial investments. A better understanding of the data needs, strengths and limitations of the L38 bundle has been successfully gained and effectively communicated.

# CHAPTER 1 BACKGROUND

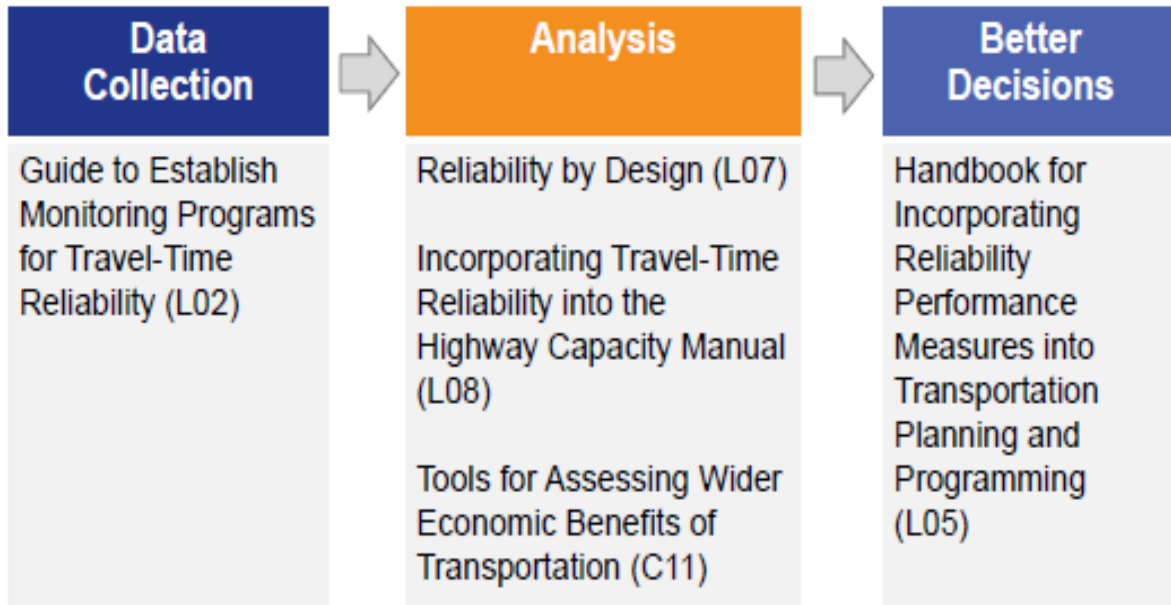
## 1.1 Introduction

Travel time reliability (TTR) is defined as “*the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day*” (1). In a simple term, it evaluates the degree of unexpected delay because the unexpected congestion distresses drivers the most and people tend to remember the bad days when they experienced unexpected delays. In fact, more than half of all traffic congestion in the U.S. is due to unexpected or nonrecurring delays, caused by crashes, work zone construction, special events, weather or other factors. Therefore, as a performance measure for our transportation system, TTR has received increased attention from system users including decision makers, operators, developers of reliability monitoring systems, travelers and shippers; and has become more tangible and measurable with more cutting-edge research being invested.

The second Strategic Highway Research Program (SHRP 2) has been focused on finding solutions to the challenges of highway safety, reducing congestion and improving methods for renewing roads and bridges (1). The Implementation Assistance Program (IAP) helps State DOTs deploy SHRP 2 solutions in the core areas of Safety, Renewal, Reliability, and Capacity. The Wisconsin Department of Transportation (WisDOT) received Round 7 of IAP funding to become a lead adopter of a bundle of products related to reliability. WisDOT’s suite of mobility performance measures – including delay and reliability – identify corridor impacts of recurring and non-recurring congestion. WisDOT was an early adopter of the National Performance Management Research Data Set (NPMRDS) for purposes of both internal and public performance measures. Reliability metrics have been used to identify extreme delay on urban corridors in the Madison and Milwaukee areas. WisDOT incorporates travel reliability as part of the benefit-cost analysis used to evaluate and prioritize highway improvement projects that contain a highway capacity improvement component.

WisDOT has already conducted some fundamental work to adopt reliability product(s) into their planning process. In 2013, WisDOT undertook the Traffic Operations Performance Management System (TOPMS) project (see [www.topslab.wisc.edu/its/topms](http://www.topslab.wisc.edu/its/topms)) (2). The project included elements of L02, such as inventorying existing traffic data sources and systems, learning from regional and national agency leaders through peer exchanges, and toward the end of the project launching the effort to develop mobility performance measures for “*Mobility, Accountability, Preservation, Safety, and Service*” (MAPSS). These measures of reliability, delay, and user cost utilize the National Performance Management Research Data Set (NPMRDS), in combination with WisDOT’s TRAFFIC DATA System (TRADAS) and other data sources, to produce regular performance reports. In addition to continuing these regular reports, WisDOT has some ability to investigate times and locations in greater detail, producing a variety of visualizations. Recently completed is a Delay Causality project, which supported even deeper investigation into attributable

causes of mobility impacts, including quantification. WisDOT and their university and consultant team evaluated five SHRP2 Reliability Data and Analytical Tool (RDAT) products, shown in Figure 1-1. The bundle of products was developed to help agencies address travel-time reliability as part of a logical path of improvement from data to decisions-making.



**Figure 1-1: IAP7 Reliability, Three Phases and Five Products (3).**

This IAP study assisted WisDOT in determining how these tools could be used to advance the decision-making process for project development, planning and programming. This document summarizes the efforts related to the SHRP 2 RDAT evaluation for Guide to Establish Monitoring Programs for Travel-Time Reliability (L02), Handbook for Incorporating Reliability Performance Measures into Transportation Planning and Programming (L05), Reliability by Design (L07), Incorporating Travel-Time Reliability into the Highway Capacity Manual (HCM) (L08), and Tools for Assessing Wider Economic Benefits of Transportation (C11).

## 1.2 Project Objectives

Travel Time Reliability is the variability in travel times from day to day and across different times of day. It is used to describe the variability of travel times so drivers can plan their trips and it is used to measure highway performance. Four key objectives of this project were to use data, analysis and decision making to

- Assess causes of non-recurrent congestion to improve traffic management strategies including roadway geometry and operation programs.
- Assess potential cost and operational effects of implementing solutions to improve reliability.

- Support WisDOT’s interest in advancing tools to provide insight into the economic impacts of reliability and congestion.
- Provide institutional feedback to SHRP2 on findings of product testing and assessments.

The specific plan for testing each of the five products is discussed below:

**L02: Establishing Monitoring Programs for Mobility and Travel Time Reliability**

Collect and process data for selected highway segments and sites by cause of delay and roadway features. Generate reliability reports, perform before and after testing and compare results to MAPSS to validate findings.

**L05: Incorporating Reliability Performance Measures into Transportation Planning and Programming**

Coordinate with WisDOT’s other functional areas to monitor the implementation progress the products to accelerate the inclusion of reliability into project planning and programming. Conduct outreach with agency stakeholders and through peer exchanges. Assess the product and prepare an assessment report to document institutional implementation and integration.

**L07: Evaluating Cost-Effectiveness of Highway Design Features/Reliability by Design**

Identify, collect, validate, and analyze required data using Excel-based analysis and SHRP2-provided tools. Compare results from running tools for site-specific scenarios and observed travel time data. Summarize findings with recommendations.

**L08: Incorporation of Travel Time Reliability into the Highway Capacity Manual**

Identify and collect required data for FREEVAL-RL using L02 and other data sources. Calibrate and correct issues in FREEVAL-RL tool to reflect real-world scenarios, and conduct before and after observational studies. Summarize findings with recommendations.

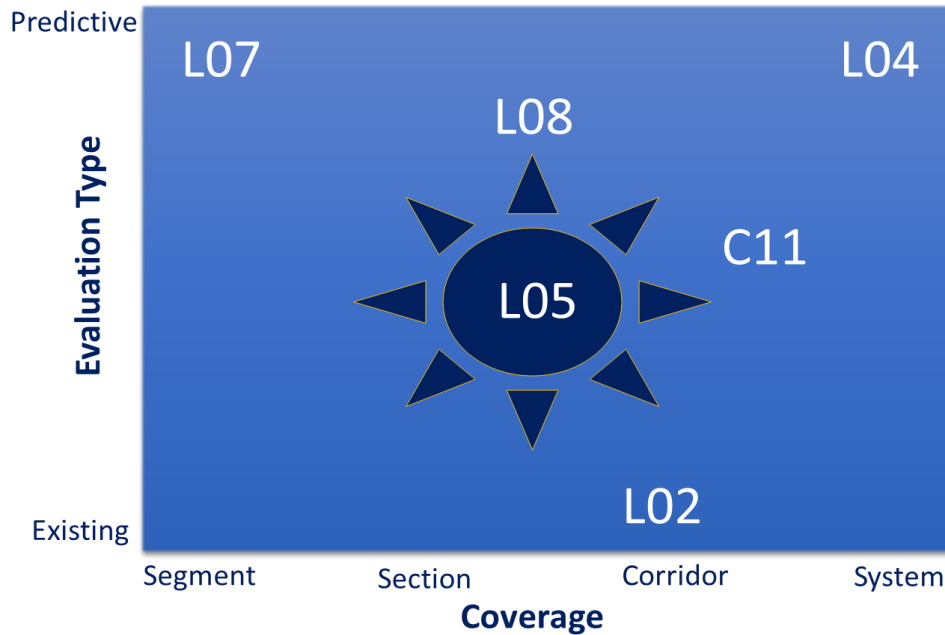
**C11: Tools for Assessing Wider Economic Benefits of Transportation**

Identify, collect, and validate required data using C11 tool for recently completed corridors and compare it to results of WisDOT benefit-cost analysis. Investigate C11 as a project reliability ranking tool. Summarize findings, benefits, work process incorporation potential and results.

**1.3 Tested Products**

The SHRP 2 RDAT help transportation planners and engineers improve monitoring and analysis of data to achieve more consistent, predictable highway travel condition. The reliability products (L02/L05/L07/L08/C11) have been comprehensively tested by agencies so they can consider a more complete set of benefits in their decisions. It is our understanding that the products evaluated in this IAP study cover a broad spectrum of analytical units and range from evaluation of existing

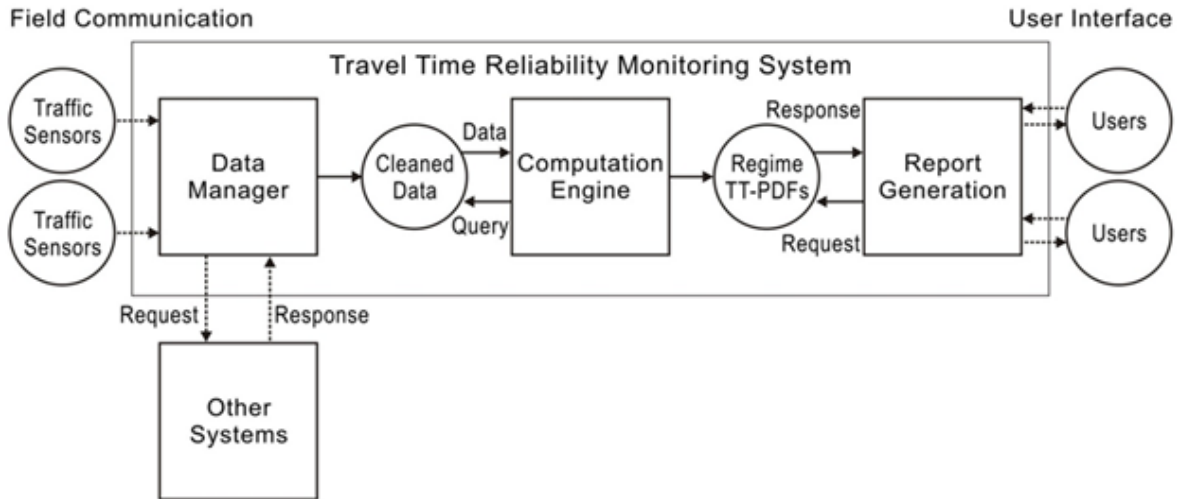
infrastructure to predictive methods, as illustrated in Figure 1-2. The specific product objectives are described in the following paragraphs.



**Figure 1-2: Evaluation Type and Coverage of SHRP2 RDAT Bundle.**

*L02: Guide to Establishing Monitoring Programs for Travel Time Reliability*

A TTRMS should be used because it provides features and capabilities that agencies use to manage and improve traffic operations (4). A TTRMS can help monitor the system performance, understand the impacts of the factors that influence TTR, provide credible information to the system users about TTR, and make better decisions to improve reliability. The TTRMS is not designed to be a stand-alone system, instead, it is intended to be an add-on to an existing traffic management system with a structure as shown in Figure 1-4. In that depiction of a high-level architecture, the boxes indicate modules, with circles for inputs and outputs.



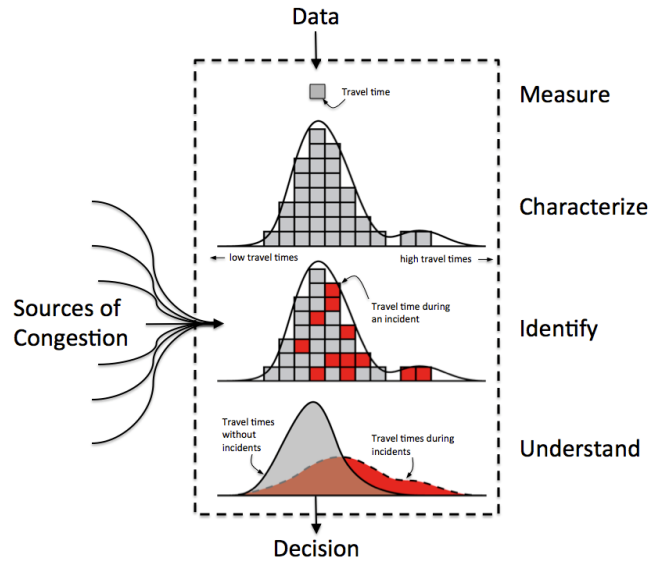
**Figure 1-3: TTRMS Architecture Overview (4).**

The three major modules representing the system are as follow:

- The data manager collects incoming data from traffic sensors and other systems and puts them in a database as “cleaned data” ready for analysis.
  - For WisDOT this entails several subsystems, including the Advanced Traffic Management System (ATMS), the WisTransPortal transportation data hub and associated applications, and other standalone applications or data services such as those in place from TomTom, Drakewell, or the National Performance Management Research Data Set (NPMRDS).
- The computational engine operates on the cleaned data to prepare “pictures” of the system’s reliability: when it is reliable and when not, under what conditions, and so on. This is shown by “Regime TT-PDFs” (travel time probability density functions) that illustrate the distribution of travel times under several conditions.
  - Herein lies much of the development work for this project. The team has strong familiarity with existing data sources, and as part of this implementation project, data are collected on selected test segments for demonstration and proof of concept. With data in hand, a larger effort entails conflating (combining) various data sources and types into a database from which PDFs can be generated under the different conditions or regimes.
- The report generator applies queries from users and uses the computation engine to analyze the data and offer information to be presented to the decision maker, whether in summary form or in greater detail.

Each module is covered in the guidebook, along with case studies to explain how these modules work together to answer questions that system managers would pose. Further details on how the modules work separately or together are provided in the supplemental material.

Histograms, PDFs, and CDFs (cumulative distribution functions) are the three common representations of the distribution of travel times or rates (a distance-neutral travel time, e.g., presented as seconds per mile). The overall analytical process described by the diagram of Figure 1-4 can be described by the steps described below.



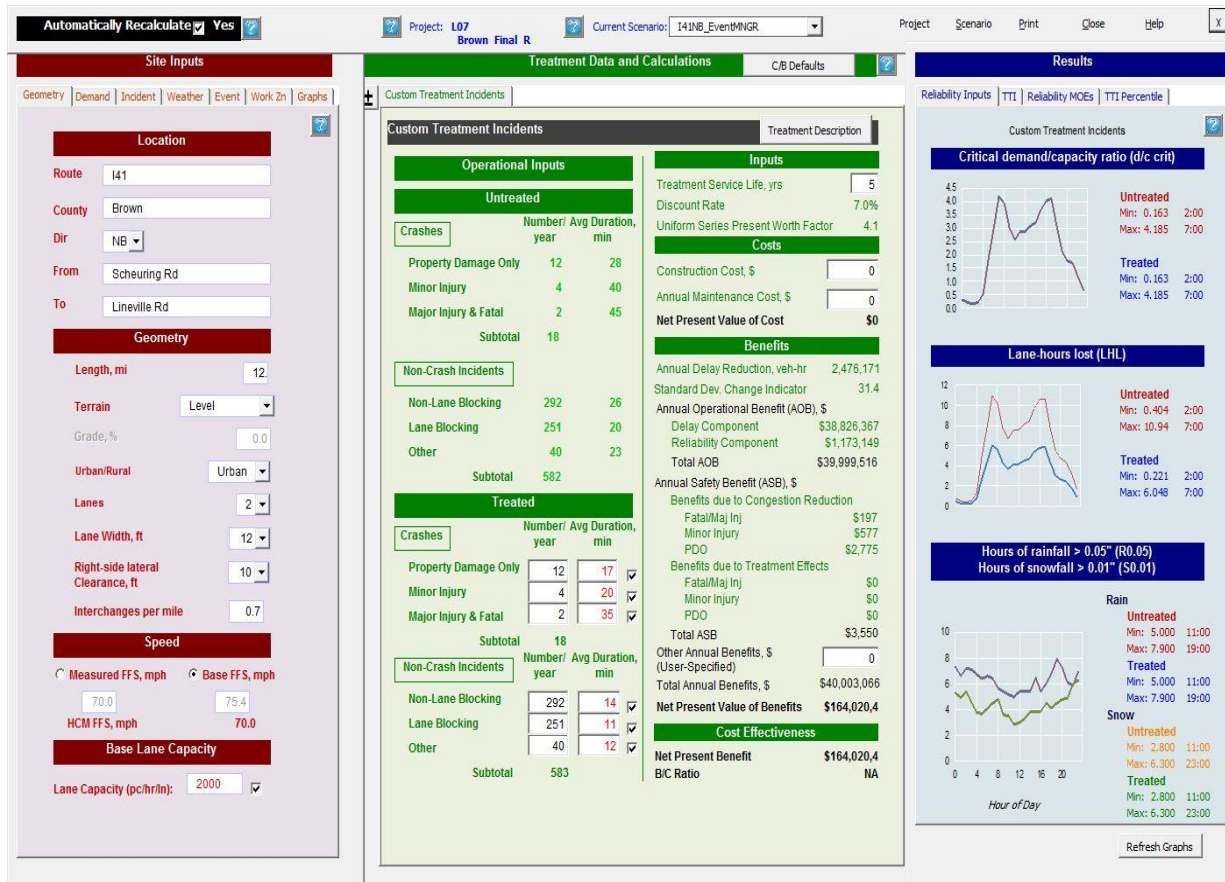
**Figure 1-4: Information Flow in a TTRMS (4).**

*L05: Handbook for Incorporating Reliability Performance Measures into Transportation Planning and Programming*

L05 is a Guide that is designed for planning, programming, and operations managers who will be making decisions on how to incorporate reliability performance measures into their daily operations (5). WisDOT’s performance measures have already included a Travel Time Index Reliability measure in the past and are being restructured while PM3 reporting is being developed. These measures and their historic results contribute to new tool applications in comparative performance results and established documentation of agency policies. The results of the testing provide supporting material for FST programming by quantifying benefits in reliability and delay associated with this service.

*L07: Evaluation of Cost-Effectiveness of Highway Design Features*

The L07 excel-based analysis tool developed under Project L07 is focused on the estimation of the effect of physical highway geometric design treatments on travel time reliability and the cost-effectiveness of these treatments (6). A snapshot of the tool interface is shown in Figure 1-5. The L07 analysis is based on the reliability estimation methods developed in the L03 project and can be considered as a sketch planning–level analysis. It provides an easy-to-read user interface that allows for a wide array of site inputs: site geometry, traffic demand, incident history, weather, special events, and work zones.



**Figure 1-5: L07 Excel-base Analysis Tool User Interface (7).**

In L07, Travel Time Index (TTI) is the measure of reliability. For a data-rich environment, the models developed in L03 and enhanced in L07 quantify the effect of incidents and work zones on reliability by predicting several percentiles of the TTI distribution based on three key variables:

- Lane hours lost (LHL) due to incidents and work zones, which is calculated as the average number of lanes blocked per incident (or work zone) multiplied by the average duration per incident (or work zone) and the total number of incidents (or work zones) during the time slice and study period of interest;
- Critical demand-to-capacity ratio ( $dc_{crit}$ ), which is defined as the ratio of demand to capacity during the most critical hour of the time slice and study period; and
- Hours of rainfall exceeding 0.05 inch (R05") or hours of snow exceeding 0.01 inch (S01") during the time slice and study period of interest.

The L07 Analysis Tool is originally designed to illustrate the benefits of various operational design strategies, since these benefits are difficult to show without modeling. As a result, the tool has built-in custom algorithms for modeling 16 different treatments using relatively simple input data on the treatment effects and cost parameters. These algorithms are based upon rules of thumb identified from literature reviews. In addition, the tool includes three custom treatments that allow the user to tailor the analysis if a specific treatment is not available for the strategy being tested.

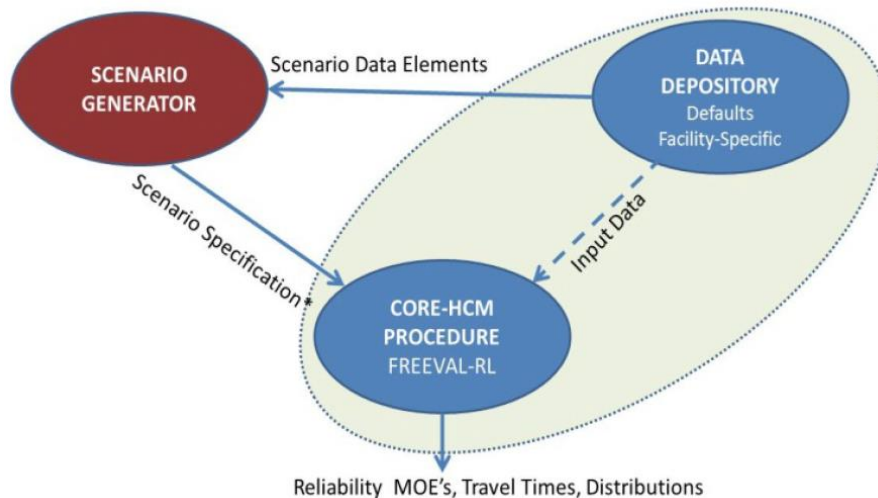
These three custom treatments plus the 16 tailored treatments result in 19 treatments available to the user for modeling.

*L08: Incorporation of Travel Time Reliability into the Highway Capacity Manual*

The L08 tool includes a guide that provides step-by-step procedures for predicting travel time reliability for freeway and urban street facilities, a methodology that quantifies the non-recurrent congestion factors that cause the unreliability of travel time, and a scenario generator that allows user input on the specifics of the scenario (e.g. weather, time of day, lane closure, and duration of incidents) (8). This tool expands the analysis horizon from a single study period to an extended time horizon of several weeks or months to assess the variability and the quality of service.

The L08 product, FREEVAL-RL, is based upon the FREEVAL model which implements the freeway modeling methodologies in the 2010 HCM. FREEVAL-RL enables the user to test the reliability impacts of projects by dynamically modeling multiple operating scenarios along the facility using a Monte Carlo-type strategy. Use of the tool itself can be broken down into five steps that a user must follow in order to conduct a reliability assessment of a freeway section. The components of freeway facility methodology is provided in Figure 1-6.

A scenario generator runs a seed file in multiple times to simulate different days along the facility. Since FREEVAL-RL is a more complicated tool, it has the potential to model reliability on a facility more accurately. The tool requires the user to designate and define several highway segments along the facility. This allows the tool to match the traffic impact in each segment and traffic queuing to spread from one segment to the rest.



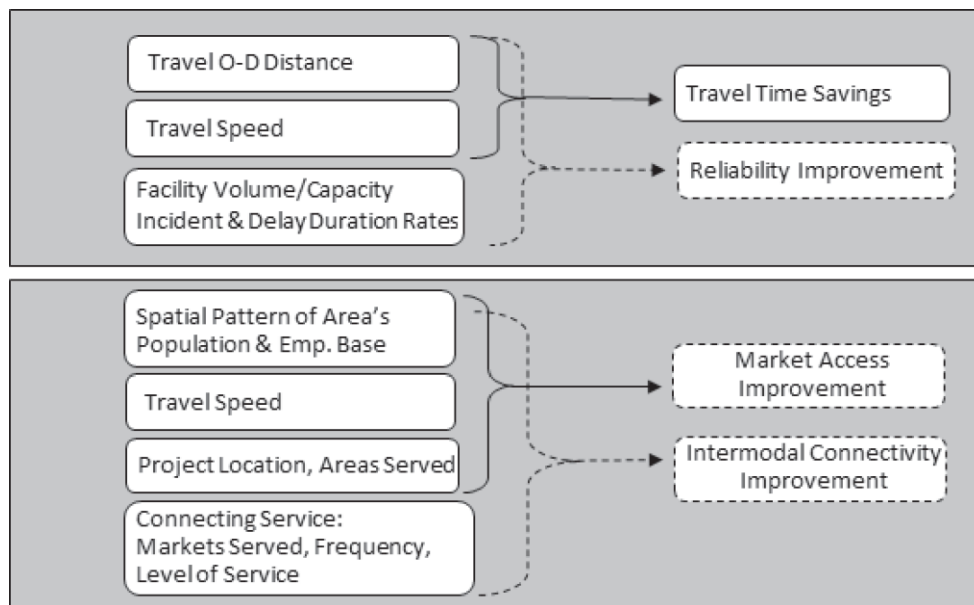
**Figure 1-6: Freeway Facility Methodology Component (8).**

*C11: Development of Tools for Assessing Wider Economic Benefits of Transportation*

The C11 research and tools are developed to improve the state of the practice in assessing the wider economic benefits of transportation capacity improvement projects (9). Specifically, they address the following three classes of project benefits shown in Figure 1-7. These benefits have previously been difficult for transportation agencies to measure in a systematic and quantitative manner. Accounting for the additional benefits means that transportation improvements have even more positive effects on users and the economy, than previously measured.

- **Travel Time Reliability Benefits:** These benefits are based on determining the reductions in recurring and non-recurring congestion for both passengers and freight.
- **Intermodal Connectivity Benefits:** The addition or improvement of intermodal terminals can lead to considerable reduction in access time to key transfer facilities such as intermodal rail facilities and airports.
- **Accessibility Benefits:** Some transportation projects can lead to economic growth because of improved access to markets for freight deliveries and to improved access for commuters traveling to labor markets. The tool can also be used to generate “order of magnitude” improvements in economic productivity.

Figure 1-7 shows the general factors affecting all three measures. These factors are used to reflect changes in characteristics of the transportation facilities and their use patterns. The C11 tools include spreadsheet tools to calculate all three of the wider economic benefits. These results can be used to develop more robust economic impact forecasting and analysis systems to more fully estimate the long-term regional economic growth implications of proposed capacity improvement projects. This study focused on the evaluation of Travel Time Reliability Benefits. The evaluation of the Intermodal Connectivity and Accessibility benefits will be considered in a future evaluation.



**Figure 1-7: Factors Affecting Benefits Measures in C11 (9).**

## **1.4 Final Report Organization**

This report comprises of nine chapters. Chapter 1 introduces the general background of the SHRP 2 L38 project and summaries the objectives of the research projects. Chapter 2 describes the sites selected to test each product from SHRP 2 Reliability focus area. Chapter 3 describes the data compilation and quality control process applied to the data. Chapters 4-8 provide the details of the research in analyzing reliability and improvement strategies, including case description, testing results, comparisons, and discussions of the L38 tools. Based on the testing results, Chapter 9 concludes the research and offers potential improvement directions for the tested SHRP 2 RDAT products.

## CHAPTER 2 TEST SITE SELECTION

Under the close coordination between WisDOT, the university and consultant team, test sites have been selected according to the appropriateness for the tool evaluation and data availability.

### 2.1 Selection of Facility for L02

To evaluate L02 product, I-41 Northbound near Appleton was selected. I-41 is an interstate with around 63,000 annual average daily traffic (AADT). The 5-mile segment between WI 15 and County E was investigated as shown in Figure 2-1.

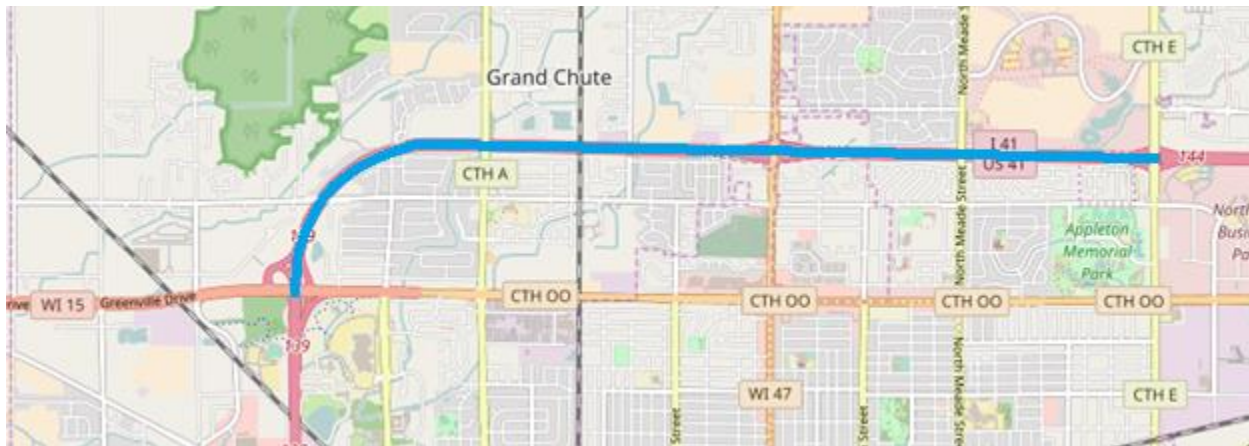


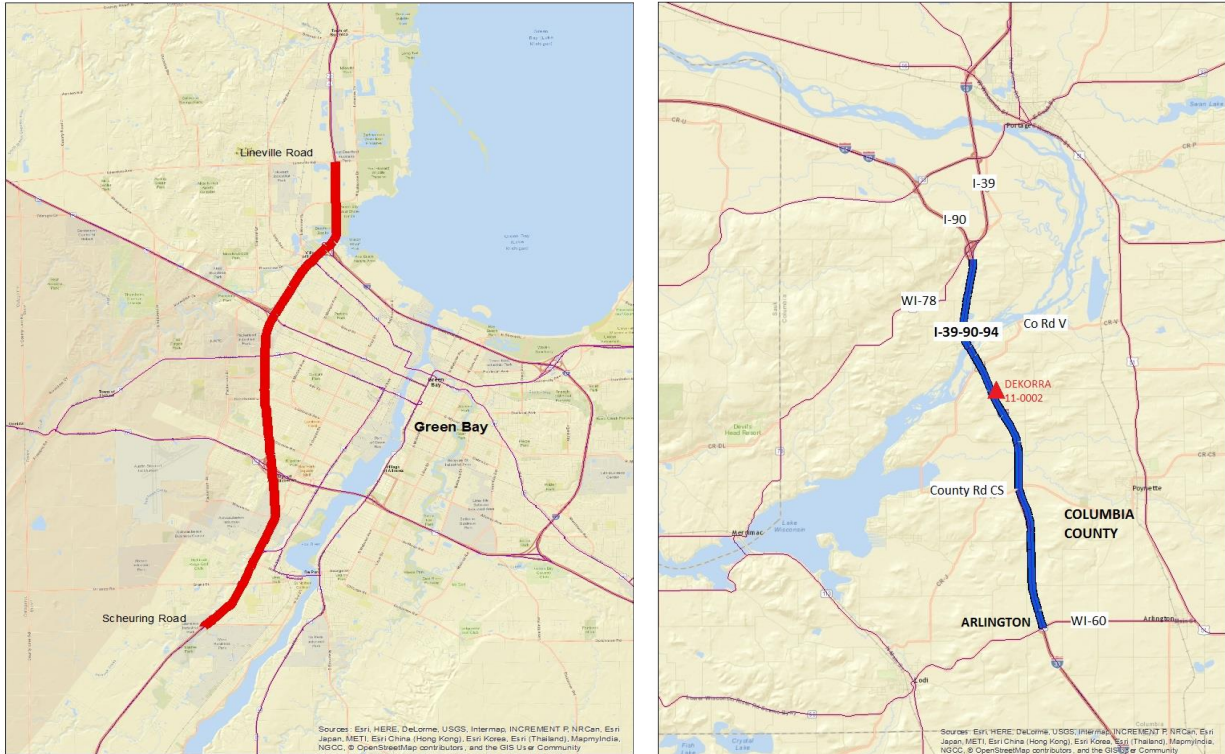
Figure 2-1: I-41 investigated segment in L02.

### 2.2 Selection of Facility for L07

To evaluate L07 excel-based analysis tool, a Freeway Service Team (FST) implementation was selected as a treatment to quantify the operational and safety benefits of the treatment. The FST, also known as freeway service patrol, highway assistance services, highway helpers and a variety of other names, is one of the main approaches used by incident management programs. The main goals of FSTs are to identify incident locations, reduce incident duration time, restore full freeway capacity, and reduce the risks of secondary accidents to motorists. These programs use vehicles to patrol heavily traveled segments and congested sections of the freeways that are prone to incidents. The patrol vehicles can clear most incidents without any assistance from other agencies. During major incidents, the patrols help to assess the equipment and manpower needed to clear the incidents, coordinate with other agencies, provide the needed traffic control, and act as a buffer between workers and traffic. They also help to detect and verify incidents like major accidents and pass on the information to transportation management centers (TMCs), which reduces delay, congestion, wasted fuel, emissions, and potential for secondary accidents.

WisDOT used FST on I-41 corridor in Brown county from Scheuring Road to Lineville Road, a 12-mile long stretch of I-41 in both direction (I-41 NB/SB). The FST provided service in a work

zone environment from January to October, 2016. In addition, a potential site was selected where FST will be implemented in near future to evaluate the benefits of FST implementation. The potential study site is located on I-39/90/94 corridor in Columbia County from WI-60 to WI-78, a 10.7-mile long stretch of I-39/90/94 in both direction. Both the existing and potential FST sites are shown in Figure 2-2.



a) FST Site in Brown County

b) Potential FST Site in Columbia County

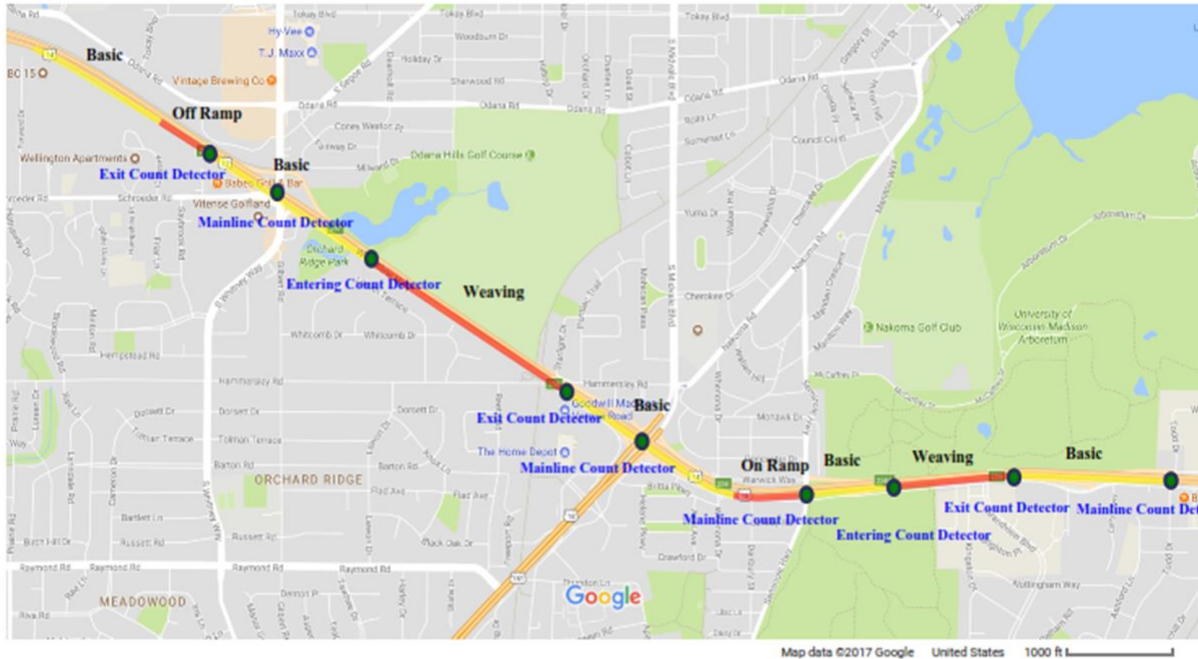
**Figure 2-2: FST Treatment Site Evaluation in L07.**

Although L07 is primarily used for evaluating highway design features, the potential safety and operational benefits of FST due to reduced frequency and duration of incidents can be quantified using the procedures and methodologies in L07. As a treatment option, FST is not available in L07 tool but was created using “Custom Incident Treatment”. The custom option allows the user to input crash and non-crash incident counts and durations with and without the treatment.

### 2.3 Selection of Facility for L08

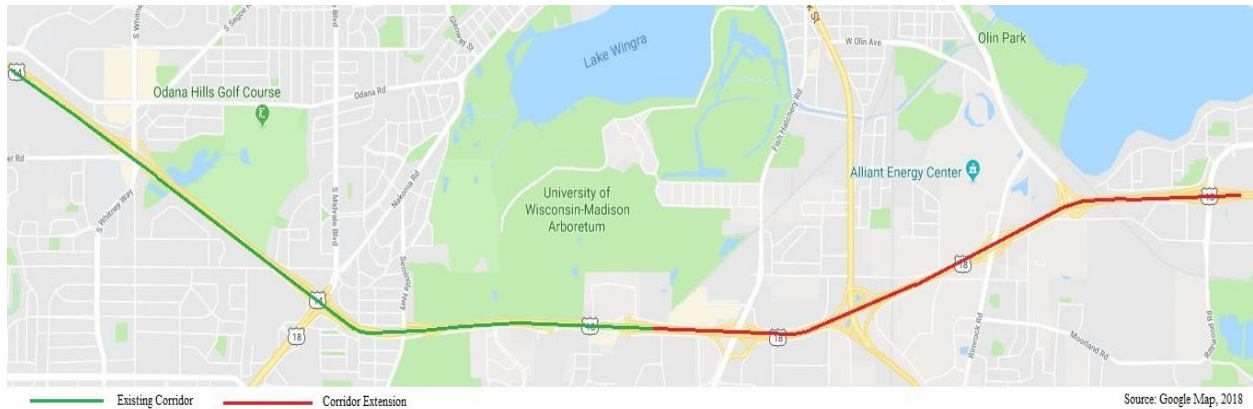
The US-12/14 eastbound Beltline Freeway Corridor located in Madison, Wisconsin was selected to evaluate L08 FREEVAL-RL computational engine. This urban freeway corridor is 3.8-miles long, beginning from Forward Drive to Todd Drive and includes three on-ramps and four off-ramps. This corridor is a suitable study area because it has all segment types including Basic, On-

ramp, Off-ramp and Weaving segments. From South Whitney Way to Verona Road, construction work was done to improve the roadway capacity. A before-after analysis was conducted in FREEVAL-RL to evaluate the operational improvement due to capacity improvement for this corridor. The “Before Improvement” analysis period was assigned to the period before the construction and the “After Improvement” analysis period was when the construction was cleared and the geometric expansion was completed. There are nine locations along the corridor where traffic detectors are available which can provide traffic demand information on the corridor. A map of the corridor is illustrated in Figure 2-3, including nine segments and detection locations.



**Figure 2-3 L08 FREEVAL-RL Study Site, US 12/14 Madison, WI.**

The study corridor was further extended to incorporate the location of the downstream bottleneck based on analysis provided in Chapter 5. The extended study corridor is 7.4 miles long, starting at Forward Dr. and ending at the South Town Rd entrance on US 12/14. Now, there are 21 segments, including 10 basic segments, 2 on-ramp segments, 2 off-ramp segments and 7 weaving segments. The weaving segment intensity is high along the extended study corridor as the study corridor is located in an urban area and the spacing between the consecutive on-ramp and off-ramp segments is relatively small. A map of the extended study corridor is presented in Figure 2 4.



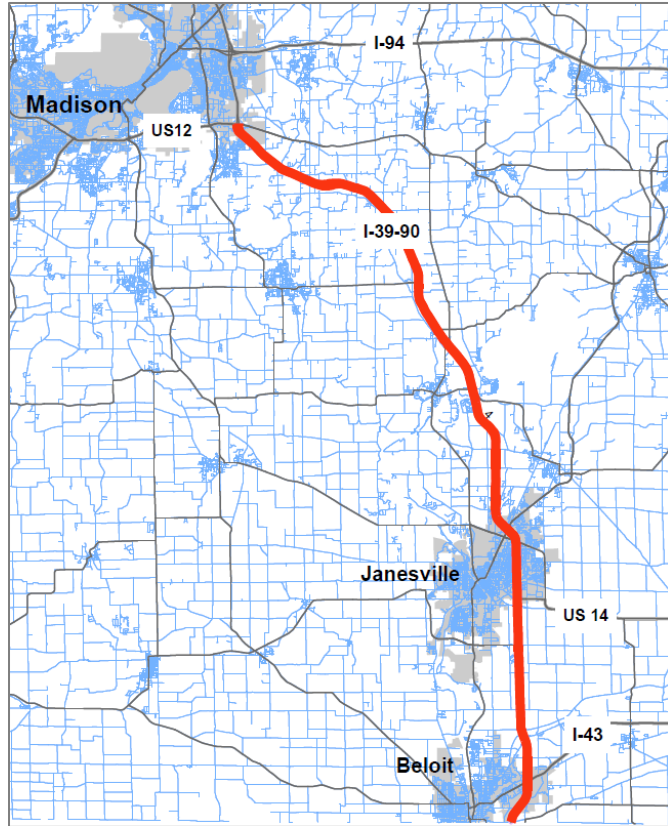
**Figure 2-4 Extended Study Site for L08 FREEVAL-RL.**

## 2.4 Selection of Facility for C11

Three corridors were chosen to evaluate the C11 tool. These corridors were chosen to include a range of facility types and traffic patterns. The corridors consist of an urban freeway, a rural freeway and a two-lane arterial. These corridors were also selected because they currently contain some degree of traffic congestion during peak hours. When crashes occur on these corridors, they can have a significant impact on travel time and delay. The evaluation of all three corridors involved a comparison between existing geometric conditions and a theoretical capacity expansion, which included adding one lane in each direction.

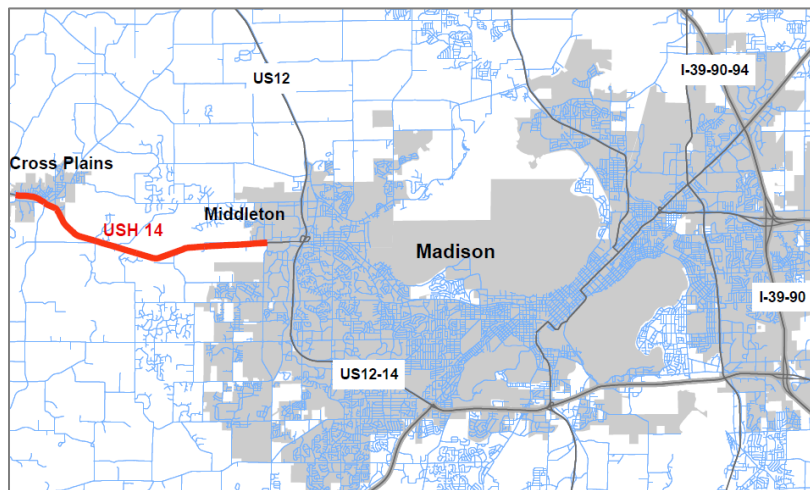
The first corridor selected is Interstate 41 near Appleton as shown in Figure 2 6. This corridor is the same corridor that was used to evaluate L02, which extends from Wis 15 to County Highway E. This 5-mile corridor currently carries between about 56,000 and 59,000 AADT and has traffic patterns consistent with urban freeway facilities.

The second corridor selected for the C11 evaluation is Interstate 39/90 (shown in Figure 2-5). This 45-mile corridor is a rural interstate that extends from the Wisconsin State Line to Madison. This corridor has heavy recreational traffic combined with the regular intercity and local traffic traveling in and between Beloit, Janesville and Madison. I-39/90 carries about an average of 50,000 AADT, which can grow to over 70,000 vehicles per day in the summer. This corridor also carries significant truck traffic, as heavy trucks account for 28 percent of total traffic.



**Figure 2-5: I-39/90 evaluated for C11**

The third corridor selected for the C11 evaluation is US 14 from Cross Plains to Middleton. This seven-mile two-lane arterial currently carries about 10,000 to 13,000 AADT. The seven-mile corridor is shown in Figure 2-6. The traffic in this corridor consists of rural and daily commuters traveling to and from Madison.



**Figure 2-6: US 14 evaluated for C11**

## **CHAPTER 3 DATA COLLECTION**

The data required for the SHRP 2 Reliability Data and Analysis Tool evaluation are comprehensive. They have been collected from a variety of sources in support of this evaluation. A brief description of data sources and data elements is provided in this section.

### **3.1 Speed and Travel Time Data**

Speed data are available from WisDOT's detectors, contracted data providers (e.g., TomTom), and the NPMRDS. The Federal Highway Administration (FHWA) provides the NPMRDS for use in performance monitoring and management and is available to State Departments of Transportation and Metropolitan Planning Organizations (MPOs). Through January 2017, the data were provided by HERE (formerly NAVTEQ and Nokia), and consist of the following:

- Average travel times;
- Five-minute bins, referred to as epochs;
- National Highway System (NHS) coverage, including all interstates and US highways;
- By traffic message channel (TMC) links;
- By passenger, freight (5+ axle, class 7-8 per ATRI), and combined;
- With GIS shapefiles;
- From October 2011 to present, updated monthly; and
- On a state by state basis, with a usage agreement required.

The data have been available since October 2013. From February 2017 to present, the data source is INRIX, and while the nature of the data is quite similar to the prior version, there are some technical differences, but these will not be addressed here.

### **3.2 Incident and Work Zone Data**

The WisTransPortal is managed by the Wisconsin Traffic Operations and Safety Laboratory (TOPS Lab) in partnership with Wisconsin Department of Transportation. It contains data on incidents and lane closures.

The Traffic Incident Alert (TIA) System provides a mechanism for distributing email alerts and media releases. An archive of the higher impact incidents and events that cause a TIA are available in the WisTransPortal.

Wisconsin Lane Closure System (WisLCS) contains all lane closures on WisDOT facilities. Closure information includes detailed location, description, dates, and times. WisLCS presents a tracking system and an archive for all closures.

WisTMP is WisDOT's Transportation Management Plan routing and approval system and is hosted on WisTransPortal. This resource provided base lane work zone capacity for the L07 test in Brown County.

WisDOT's Traffic Management Center (TMC) maintains an Event Manager dataset that records traffic incidents responded by TMC staff. This dataset contains both crash (named as "accident" in incident type) and incident information collected at the TMC. L07 reliability tool application related features such as incident duration, incident type (e.g. accident, disabled vehicle, fire etc.) and severity on a scale of 1-5, incident start time and end time are available from this dataset. The description of severity scale used in this dataset are given below:

- Severity 1: incident blocks either the shoulder or the median lanes
- Severity 2: incident blocks less than 50% of the highway lanes and/or a service ramp
- Severity 3: incident blocking 50% or more of the highway lanes
- Severity 4: incident blocking all lanes in one direction and/or a system ramp
- Severity 5: incident blocking all lanes in both directions

### **3.3 Volume Data**

Archived hourly volume data are accessible through WisDOT's Traffic Data System (TRADAS). TRADAS is managed by the Bureau of State Highway Programs and it contains volume, speed, and vehicle classification data. The data is stored in an Oracle database and is accessible via the WisTransPortal or direct query by researchers. Volume data is also obtained from V-SPOC (Volume-Speed Occupancy) database hosted by UW-Madison's Traffic Operations Research Lab.

### **3.4 Weather Data**

Weather Underground is an internet weather service that has been sharing weather information with the public since 1993. Forecasts are generated from a proprietary forecasting system called BestForecast™. Weather Underground provides historic information regarding temperature, humidity, wind direction and speed, precipitation, condition among other weather characteristics.

### **3.5 Special Events**

Sport related events such as the Packer Football game or other gathering events such as EAA AirVenture can affect travel time. WisDOT and the TOPS Lab have compiled a list of these major events, with characteristics such as frequency, attendance, and location.

### **3.6 Crash Data**

The crashes occurring on Wisconsin roadway network is stored in MV4000 database maintained by the TOPS Lab. This dataset contains geocoded police reported crashes occurred on any roadway in Wisconsin. SHRP2 reliability tool application related features such as crash occurrence date, time, crash severity and location can be obtained from this dataset.

### **3.7 Freeway Service Team (FST) Dataset**

This dataset contains information about the incidents serviced by Freeway Service Team. L07 reliability tool application related features such as incident/stop location (travel lane, shoulder, median, ramp), stop cause (crash, disabled, debris, abandoned etc.), service duration are available in this dataset.

### **3.8 WisDOT Meta-Manager Management System Data Base**

The WisDOT Meta-Manager Management System Data Base (Meta-Manager) contains a geographically integrated set of corporate databases for the Wisconsin State Trunk Highway Network. This database is managed by the Bureau of State Highway Programs. The roadway geometric features and attribute information available in this dataset, was used for this study.

## CHAPTER 4 TESTING AND RESULTS OF SHRP 2 L02 PRODUCT

### 4.1 Introduction

The existing reliability of a highway corridor can be assessed based on real-world data. *The SHRP 2 Reliability Project L02 Guide to Establishing Monitoring Programs for Travel Time Reliability* provides guideline to determine the factors affecting travel time reliability. The L02 project aims at developing data integration system and visualization techniques that monitors travel time reliability and quantifies the impact of varying conditions on the reliability.

### 4.2 Analytic Process of L02 Guide

The overall analytical process can be described by the steps described below.

#### *Step 1: Collect and manage traffic data*

The two broad categories of traffic data sources are infrastructure-based sources (devices mounted along the roadside) and vehicle-based sources, which can be further separated into four categories of traffic data sources:

1. Infrastructure-based detectors that can sense volume, occupancy, and other measures, but not speeds;
2. Infrastructure-based detectors that can sense speeds, as well as other measures;
2. Examples of infrastructure-based sources are loop detectors, wireless magnetometer detectors, video image processors, radar detectors, and others;
3. Automated vehicle identification (AVI) systems such as Bluetooth, license plate readers, radio-frequency identification (RFID), and vehicle signature matching;
4. Automated vehicle location (AVL) systems such as global positioning system (GPS) probes, connected vehicle, and cellular location networks.

#### *Step 2: Measure travel times*

To measure the travel times, the process first requires

- Imputing missing data  
Data sources are often incomplete for several reasons such as sensor malfunction, gaps in system coverage, and incomplete sensor coverage. The guidebook presents a series of techniques for detecting broken detectors, eliminating poor data, and filling in the missing data with imputed values. These techniques include a series of regression methods and the use of temporal or cluster medians.
- Computing segment travel times and route travel times  
Suggested analytical techniques for estimating segment-level and route-level travel times and rates are also presented in the guidebook.

#### *Step 3: Characterize observed travel times*

Characterization involves observations based on the operating conditions that were extant when the travel time was observed (e.g., congested vs uncongested, AM vs PM peak). PDFs are used as the statistical model to describe the performance of a given segment/route.

*Step 4: Collect, manage, and impute nonrecurring event data*

The TTRMS can connect nonrecurring event data to the travel times observed. These events act as a source of congestion. The seven major sources of unexpected congestion are:

1. Incidents;
2. Weather;
3. Work zones;
4. Fluctuation in demand;
5. Special events;
6. Traffic control devices; and
7. Inadequate base capacity.

*Step 5: Identify sources of congestion and unreliability*

After collecting route travel time measures, they can be analyzed in conjunction with nonrecurring event data to identify sources of unreliability. The guidebook describes two methods of source identification: a tagging approach and a statistical approach.

*Step 6: Understand the impact of the sources of unreliability*

The impact of the sources of unreliability can be analyzed using the distributions developed for specific facilities or routes. Different metrics can be used to quantify the impact of the sources of unreliability.

*Step 7: Make decisions*

Decisions are made based on the understanding gained from the analytical analysis.

### **4.3 Example Case Studies**

Five case studies are presented in the guidebook that illustrate the application of some aspects of the guide.

*San Diego, California*

This case study focuses on using a mature reliability monitoring system in San Diego to illustrate the state of the art for existing practice (10). The purpose of this case study was as follows:

- Assemble regimes and travel time PDFs (TT-PDFs) from individual vehicle travel times.
- Explore methods to analyze transit data from automated vehicle location (AVL) and automated passenger count (APC) equipment.
- Demonstrate high-level use cases encompassing freeways, transit, and freight systems.

- Relate travel time variability to the seven sources of congestion.

#### *Northern Virginia*

This case study provides an example of a more traditional transportation data collection network operating in a mixture of urban and suburban environments (11). The purpose of this case study was as follows:

- Describe the data acquisition and processing steps needed to transfer information between the existing system and the PeMS reliability monitoring system.
- Demonstrate methods to ensure the data quality of infrastructure-based sensors by comparing probe vehicle travel times using the procedures described in Chapter 3.
- Develop multistate travel time reliability distributions from traffic data.

#### *Sacramento–Lake Tahoe, California*

This case study illustrates an example of a rural transportation network with a fairly sparse data collection infrastructure (12). The purpose of this case study was as follows:

- Examine vehicle travel time calculation and reliability using Bluetooth and RFID re-identification systems.
- Filter out travel times from trip times collected by Bluetooth and electronic toll collection (ETC) devices.
- Explore the following aspects of the Lake Tahoe region ETC and Bluetooth reader (BTR) networks: detailed locations and mounting structures, lanes and facilities monitored, percentage of traffic sampled, and percentage and number of vehicles re-identified between readers.
- Quantify the effects of adverse weather- and demand related conditions on travel time reliability using data derived from Bluetooth and ETC systems.

#### *Atlanta, Georgia*

This is an example of a mixed urban and suburban site that primarily relies on video detection cameras for real-time travel information (13).

The main objectives of the Atlanta case study were as follows:

- Demonstrate methods to resolve integration issues by using real-time data from Atlanta's traffic management system for travel time reliability monitoring.
- Compare probe data from a third-party provider with data reported by agency-owned infrastructure.
- Fuse the regime estimation and nonrecurring congestion analysis methodologies to inform on the reliability impacts of nonrecurring congestion.

#### *New York and New Jersey*

The New York City site was chosen to provide insight into travel time monitoring in a high-density urban location (14).

The main objectives of the New York and New Jersey case study were as follows:

- Obtain time-of-day travel time distributions for a study route based on probe data.
- Identify the cause of bimodal travel time distributions on certain links.
- Explore the causal factors for travel times that vary significantly from the mean conditions.

#### 4.4 Data Analysis

##### *Filtering unrepresentative data*

It is necessary to identify the presence of invalid data points to remove them. The mean plus/minus a coefficient (1, 2, or 3) times the standard deviation is one of the methods commonly used. This method is based on the characteristics of normal distribution for which 68.27%, 95.45% and 99.73% of the values lie within 1, 2 and 3 standard deviations of the mean, respectively. Using the mean as the central trend indicator presents three problems.

- This method assumes a normally distributed data (outliers included).
- The mean and the standard deviation are strongly influenced by outliers.
- This method fails to detect outliers in a small sample size.

The median, another central trend indicator, is considered a resistant estimator and is very insensitive to outliers' presence in the sample. The median absolute deviation (MAD) is defined as follows:

$$MAD = \text{median}\{|x_i - \tilde{x}|\}$$

where  $x_i$  is the individual observation and  $\tilde{x}$  is the median of all the data set. A MAD value is calculated for each 5-minute interval in the data set as the absolute difference between the speed and the median of all speeds. The modified Z-score  $M_i$  is defined as follows:

$$M_i = \frac{0.6745 (x_i - \tilde{x})}{MAD}$$

If the absolute value of the modified Z-score  $|M_i|$  exceeds 3.5, the corresponding 5-minute interval is considered an outlier.

##### *Probability Density Function (PDF)*

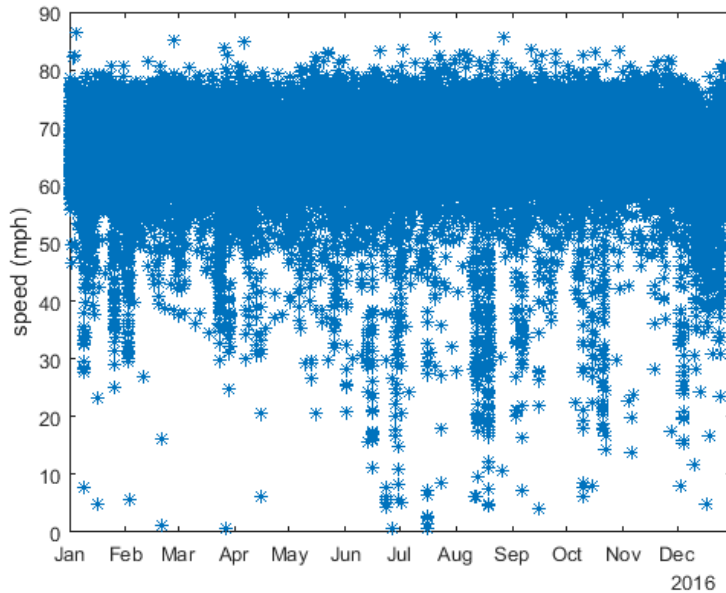
PDF is the probability that the variable has the value  $x$ . For continuous variables, the probability at a single point is zero, so this probability is often expressed in terms of an integral between two points:  $\int_a^b f(x)dx = pr(a \leq X \leq b)$ .

##### *Cumulative Distribution Function (CDF)*

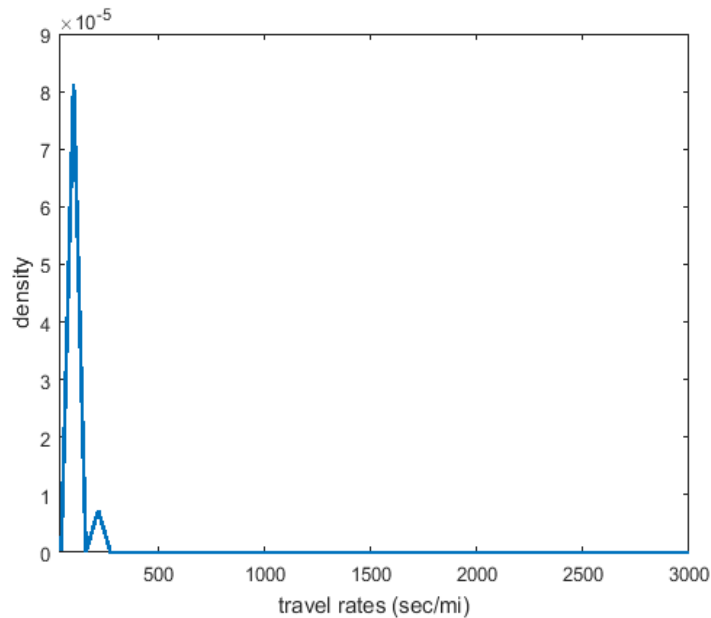
CDF is the probability that the value takes a value less than or equal to  $x$ . For continuous variables, it is expressed as follows:  $F(x) = \int_{-\infty}^x f(t)dt$

#### 4.5 Evaluation of L02 Guide

The L02 results shown here are all based on the I-41 pilot section described above. The second location, the Madison Beltline, is fully documented in the separate L02 memo. To get a sense of the speed data, the speed flow scatter of all the 2016 including non-recurring data is first plotted (Figure 4-1) along with the distribution of travel rates in a PDF format (Figure 4-2).



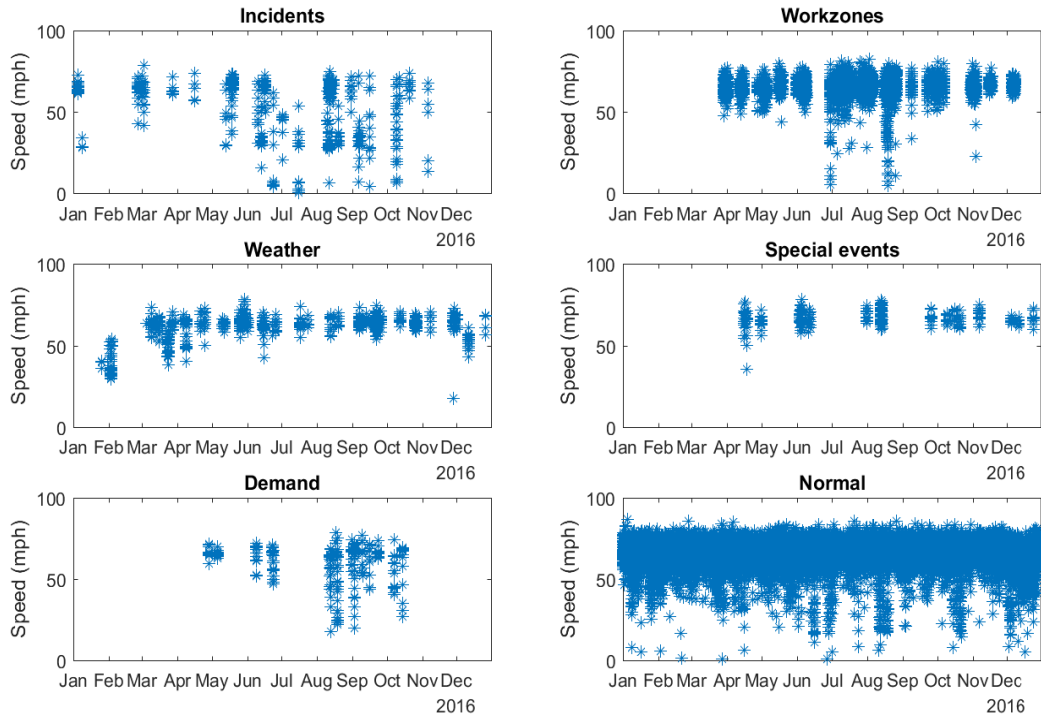
**Figure 4-1: Step 1-Collected Traffic Data.**



**Figure 4-2: Step 2-Compute Travel Rates.**

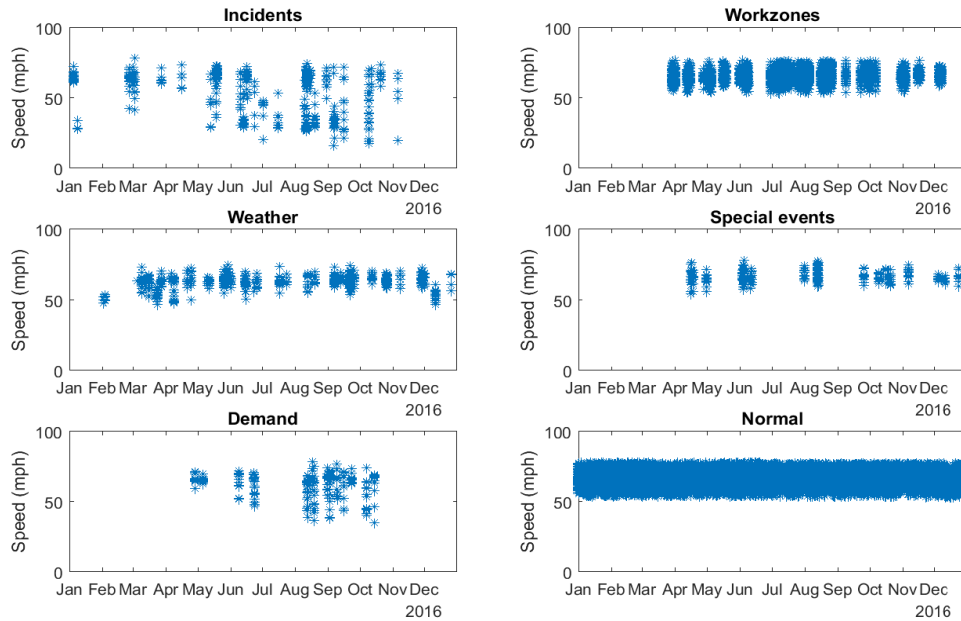
To create PDFs for the facility, sources of unexpected congestions should be identified at first. For this roadway segment, incidents, work zones, weather special events, and demand were identified

as non-recurring events. The 5-min observation corresponding to each factor was removed from the initial data set and assigned to the corresponding factor. Incidents were identified first, followed by work zones, then weather, special event and finally demand. Figure 4-3 shows a scatter plot of the speed in function of time for each of the identified factor.



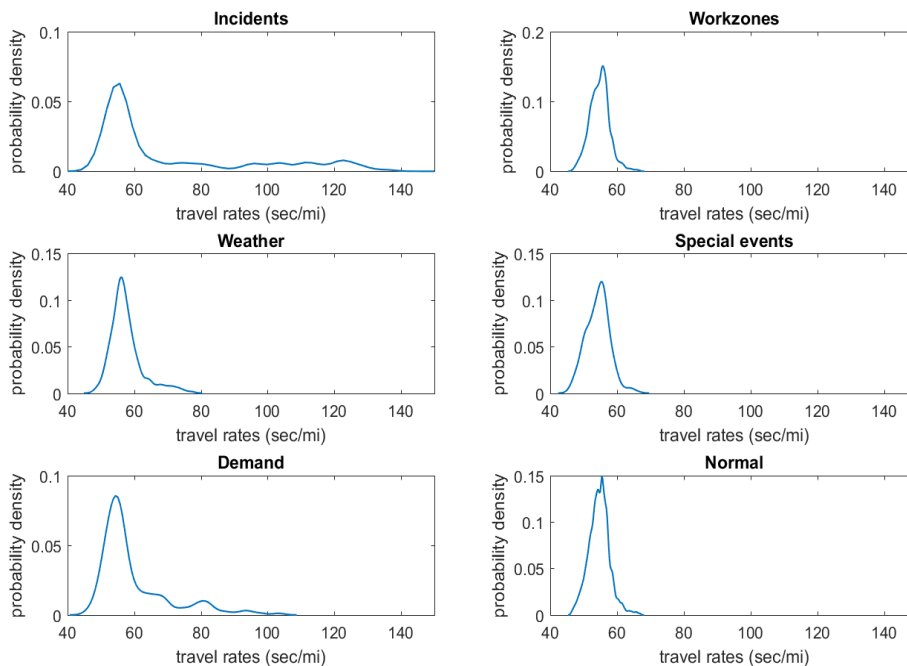
**Figure 4-3: Step 3- Generate Travel Rate -PDFs.**

Very low values can be seen in each scatter plot indicating the presence of outliers. This was already confirmed by the long tail of Figure 4-2. The median absolute deviation (MAD) procedure was applied for each factor and the results are shown in Figure 4-4.



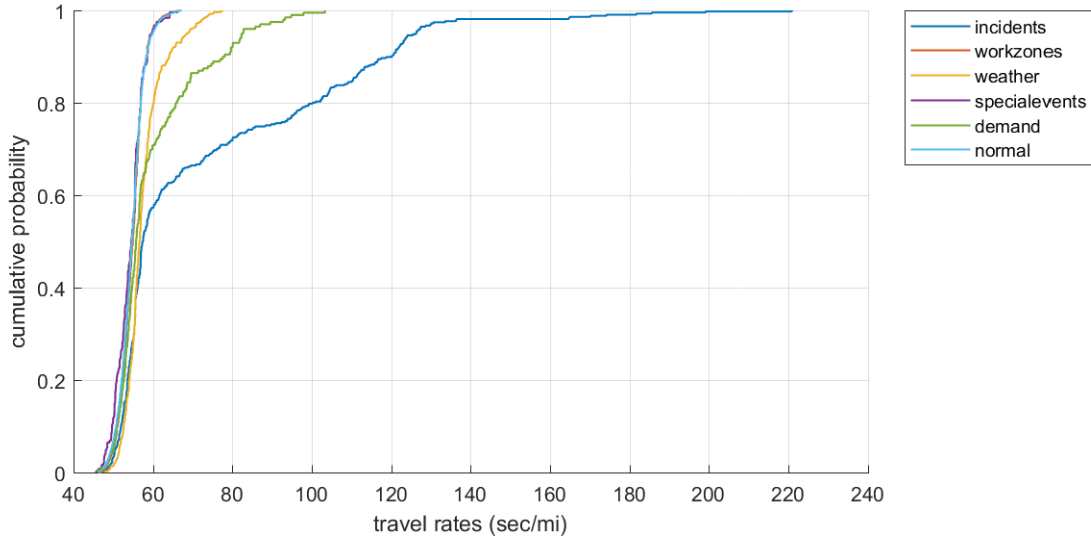
**Figure 4-4: Step 3- Generate Travel Rate -PDFs after Removing Outliers.**

PDFs for each factor are created based on the filtered data set and the plots are shown in Figure 4-5. The 6 plots have a bell shape indicating normality. A long tail can be seen for incidents and demand. This indicates that these two factors affect travel rates the most.



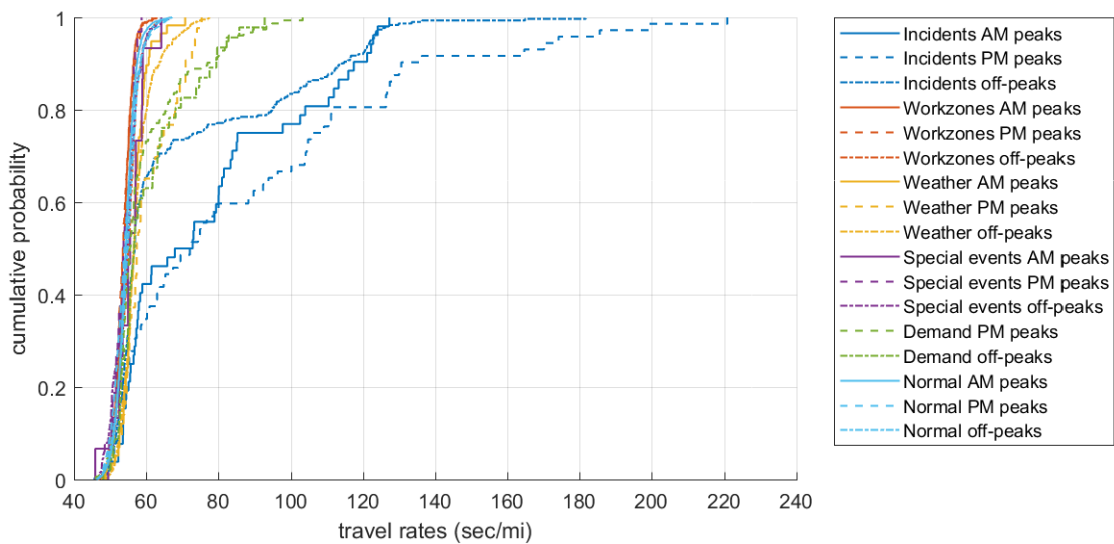
**Figure 4-5: Step 3- Travel Rate PDFs.**

Figure 4-6 shows the CDF for each factor. As previously shown in the PDFs, incidents and demand affect travel rate significantly.



**Figure 4-6: Step 4- Generate Travel Rate CDFs.**

Figure 4-7 shows the CDF for each factor by peak/off peak periods using TIA crash data. Incidents and demand affect travel rate mostly in the PM peak.



**Figure 4-7: Step 5- Identify Source of Unreliability.**

## CHAPTER 5 RESULTS OF SHRP 2 L05 PRODUCT

L05 is a Guide that describes how to incorporate reliability into transportation planning and programming. This Guide is designed for planning, programming, and operations managers who will be leading these efforts and making decisions how to execute the plans. The Guide and the associated Technical Reference can help agency planners and system operators identify the data, tools, and methodologies for examining reliability, including emerging analysis tools to directly estimate or forecast reliability, as well as tools and methodologies to help an agency begin to bridge the gap.

Testing SHRP2 RDAT products with WisDOT sites allows for demonstration of Reliability applications on projects and treatments familiar to staff involved in the planning, programming and evaluation of financial investments. Developing dialogue and familiarity around Reliability encourages Agency understanding. WisDOT's performance measures have included a Travel Time Index (TTI) Reliability measure in the past and are being restructured while PM3 reporting is being developed. These measures and their historic results contribute to new tool applications in comparative performance results and established documentation of agency policies. Reliability has been incorporated into the Wisconsin's Traffic Management Center Standard Operating Procedures. Its application focuses on priority messaging on dynamic message signs in accordance with corridor-based reliability performance. The results of the testing provide supporting material for programs such as Freeway Service Team (FST) by quantifying benefits in reliability and delay associated with this service (Refer to Chapter 6 for details). The ability to include cost benefits to the treatment supplement the programming decisions surrounding options for providing FST in Wisconsin. This program supports several approaches for funding. Performance benefits of this treatment will support project prioritization for investment decisions.

A Fact Sheet developed by our project team provides an overview of the RDAT products and how they have been applied. It is intended for staff exploring opportunities to incorporate reliability into the planning or evaluation process. WisDOT uses reliability for evaluation and planning of the investment program as well as performance measures. Adding the application to more processes including program support and justification has been recognized and is increasing by program managers in the following areas:

- Suggested alternative highway design strategies and design features
- Identify and track reliability performance in work zones and during weather events
- Identify and track reliability performance of the statewide highway system
- Identify reliability performance thresholds for the urban freeway to support traffic management strategies
- Corridor analysis of recurrent and non-recurrent congestion

Outputs for reliability tracking to support performance measures follow the L02 product format. Agency performance measures communicate to a broad audience. These include definitions of measures to help understand the relationship between the data and driver experiences.

## CHAPTER 6 TESTING AND RESULTS OF SHRP 2 L07 PRODUCT

### 6.1 Introduction

With improved travel time and event data, agencies are better equipped to analyze current conditions and the effects of various design and operational treatments intended to improve reliability. L07 includes a spreadsheet-based treatment analysis tool and design guidebook that help agencies estimate the effectiveness and economic benefits of design treatments at specific locations (6). The tool can predict benefits of a wide range of treatments and strategies so that reliability and nonrecurrent congestion considerations can become more integral to the planning and design process.

### 6.2 Travel Time Reliability Under FST

Although many data sources are useful to obtain required data elements for FST evaluation in L07 tool, the data issues due to varying practices and requirements by different agencies are an impediment to a rigorous evaluation. The presence of a work zone when FST was deployed further complicated the evaluation as work zones may change traffic patterns, increase congestion and the chance of incidents. Hence, necessary assumptions were made to minimize possible biases.

Figure 6-1 shows the overview of data sources, data issues and assumptions made to overcome limitations in each dataset. One of the most prominent assumptions is that FST won't change the frequency of crash- and non-crash incidents. Other assumptions were made to estimate roadway capacity and travel demand. The base traffic lane capacity can be estimated through the speed-flow curve corresponding to the free flow speed (FFS) of the freeway facility. FFS is the mean speed of traffic as measured when flow rates are low to moderate. In this study, neither NPMRDS median speed nor posted speed limit was considered as a reliable measure for FFS because the NPMRDS data is based on probe vehicles and the speed limit usually refers to the 85<sup>th</sup> percentile of all vehicle speed. Hence, the HCM method for estimating the base traffic lane capacity was employed where FFS was determined by the roadway characteristics of lane width, lateral clearance and ramp density (15). Most key input geometric characteristics were collected from Meta-Manager (16). Some were supplemented by reviewing Google Maps such as interchange density. Traffic demand was estimated using the WisDOT ATR\_Ratio. For the segments with missing ATR\_Ratio values, ATR\_Ratio of 1 was assumed.

Crash data and non-crash incidents can be retrieved from sources such as MV4000, TMC-Event Manager database, and FST service logs (17). However, there are many discrepancies and limitations between data sources. For example, MV4000 data do not have any crash duration information. The incidents including both crash and non-crash incidents reported to WISDOT's TMC and archived in its Event Manager only constitute a small percent of all incidents that happened on the corridor. The significant ones with long clearance time (e.g., longer than 4 hours) are archived in Traffic Incident Alert (TIA) database. During the same time period, FST services

have logged hundreds of incidents; over ten times more than those recorded in the Event Manager database. However, 4% of the incidents recorded by FST lasted less than five minutes and more problematically, information is only available when FST was in service. Hence, two scenarios were designed as a compromise to data issues and limitations. The first scenario uses incident duration from WISDOT’s TMC-Event Manager database and the second scenario uses incident duration from the FST database.

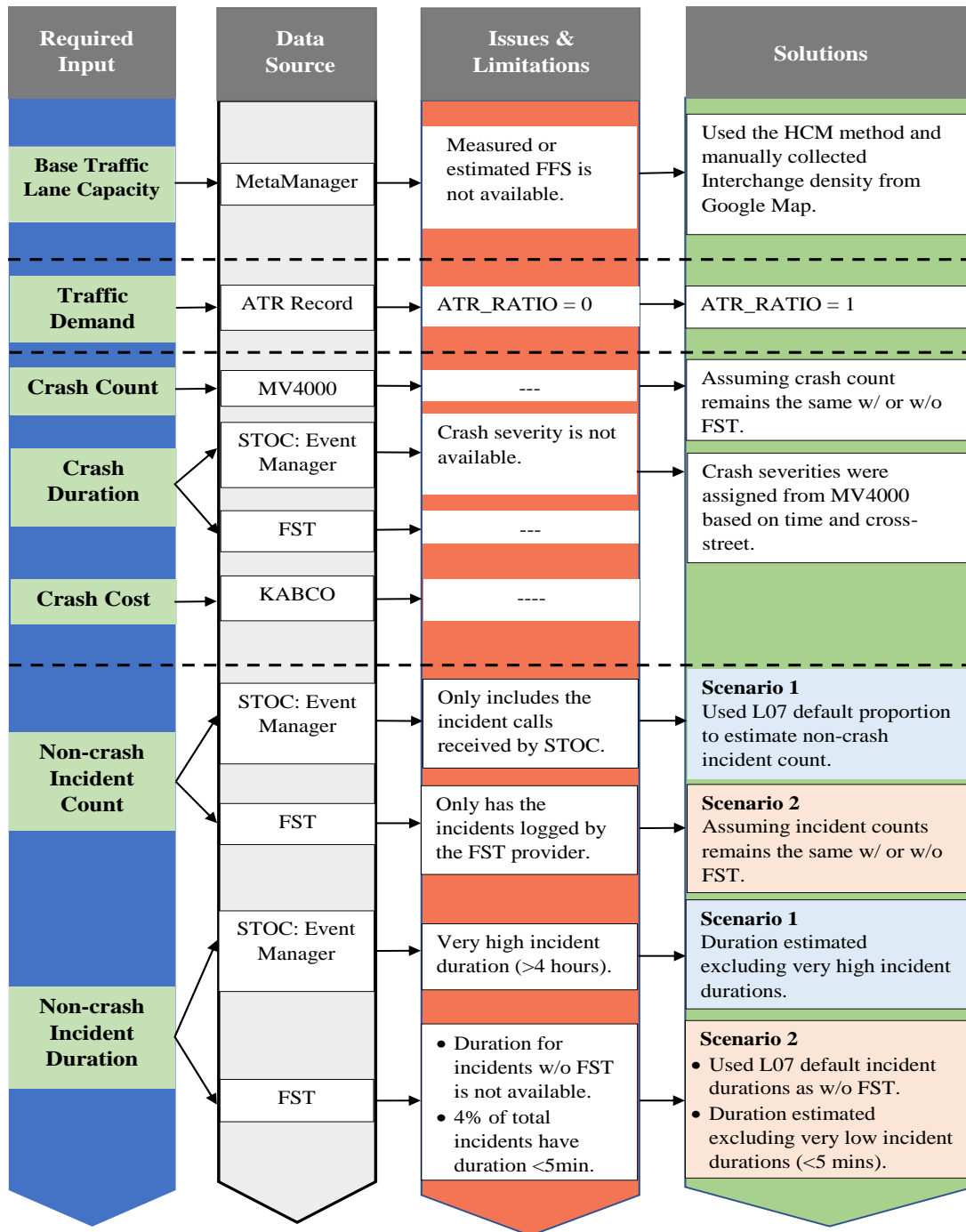


Figure 6-1: Limitations and Assumptions Used for FST Evaluation.

Roadway geometric information about the selected sites are needed to evaluate FST service in L07 tool. The geometric information used in L07 tool for both study sites are provided in Table 6-1. Based on available incident information from two different data sources and discrepancies between them, the Brown County site was evaluated for two different scenarios. Unlike Brown county, no FST service was implemented in Columbia County. To obtain crash and non-crash incident durations with FST service at Columbia county, two difference approaches were conducted. Both study sites were applied in the presence of a long-term work zone. For the Brown County study site, a 190 days of long term work zone was used in L07 tool with zero (0) number of lane closed, 1520 pc/hr/ln work zone lane capacity, 55 MPH speed limit, 11 feet of lane width and 2 feet of lateral clearance from the edge of travel way to the work zone. Similar work zone information was also used in Columbia County study site L07 application. More detailed description and L07 tool analysis results for both study sites are provided in the following sections.

**Table 6-1 Required Geometric Attributes of Selected Sites in L07 Tool .**

<b>Geometric Attribute</b>	<b>Brown County</b>	<b>Columbia County</b>
From	Lineville Rd	WI-60
To	Scheuring Rd	WI-74
Length	12 miles	10.7 miles
Terrain	Level	Level
Urban/ Rural	Urban	Rural
No. of Lanes	2	3
Lane Width	12 feet	12 feet
Right-side Lateral Clearance	10 feet	11 feet
Interchanges per mile	0.7	0.7
Base FFS	75.4 mph (default)	
Lane Capacity	2400 pc/hr/ln (default)	

### 6.2.1 Analysis Results for Brown County Study Site

#### *Scenario 1: Using Incident Duration from WISDOT's TMC-Event Manager Database*

In this scenario, consistently collected and archived incident duration data are credible source in the STOC-Event Manager. The data from the year of 2016 was used as a study section with FST service and data from the year of 2015 was used as a study section without FST. Although average incident duration may be skewed towards a higher value due to the practice of reporting more significant incidents, the deviation is assumed to be similar during the before and after time periods. The incident frequency in the TMC-Event Manager, however, is clearly underreported according to the 2016 FST records. Alternatively, L07 default value that 22% of all incidents are crashes was used to estimate the number of total incidents given the MV4000 crash frequency that is a reliable count. Table 6-2 provides the detailed incident input used in Scenario 1 for the NB direction. Note that the only difference in incident input in the SB direction is in crash incident

counts. There are 13, 3 and 1 crash incidents that occurred in the SB direction for PDO, Injury and Fatal crashes respectively. The non-crash incident counts are then generated from crash incident counts based on default proportion provided in L07 tool.

**Table 6-2 Detailed Incident Input Used in Brown County NB Scenario 1.**

Incident	W/O FST		With FST	
	Count <sup>1</sup>	Average Incident Duration <sup>2</sup> (min)	Count	Average Incident Duration <sup>2</sup> (min)
<b>Crash Incident</b>				
PDO	12	29	Same as “before”	20
Injury	4	52		36
Fatal	2	45 <sup>3</sup>		NA (35) <sup>4</sup>
<b>Non-Crash Incident</b>				
Disabled-Lane Blocking	22% of all incidents are crashes <sup>3</sup>	56	22% of all incidents are crashes <sup>3</sup>	13
Disabled-Non-Lane Blocking		65		27
Other		NA		NA

1. The crash count is the five-year annual average from 2011 to 2015. Use annual average is to overcome the limitation of random fluctuation due to one-year observation.
2. Crash/ Non-crash incident duration is averaged over both NB and SB direction.
3. L07 default value.
4. Assumed value.

The L07 tool analysis can provide an overall estimate of the treatment benefits at the planning stage. The B/C calculation incorporates a delay component and a reliability component in “Annual Operational Benefits”. The output from the L07 tool provides quantitative operational and safety benefits due to FST service in Scenario 1. These are represented in Table 6-3.

**Table 6-3 Benefit Estimation for Scenario 1 in Brown County.**

Particular	NB	SB	Total
Annual Delay Reduction (veh-hr)	1,454,240	1,082,085	2,536,325
Std. Dev. Change Indicator <sup>1</sup>	39.9	27.3	
<b>Annual Operational Benefit (AOB) in \$</b>			
Delay Component	\$22,802,488	\$16,967,100	\$39,769,588
Reliability Component	\$1,487,034	\$1,016,942	\$2,503,976
Total AOB	\$24,289,522	\$17,984,042	\$42,273,564
<b>Annual Safety Benefit (ASB) in \$</b>			
Benefit due to congestion reduction			

Fatal/ Major Injury	\$55	\$57	\$112
Minor Injury	\$155	\$123	\$278
PDO	\$746	\$263	\$1,009
Benefit due to treatment effect			
Fatal/ Major Injury	\$0	\$0	\$0
Minor Injury	\$0	\$0	\$0
PDO	\$0	\$0	\$0
Total ASB	\$957	\$443	\$1,400
<b>Total Annual Benefit</b>	\$24,290,476	\$17,984,485	\$42,274,961

1. Change in Std. Dev. of Travel Time Index (TTI) due to treatment

*Scenario 2: Using Incident Duration from FST Database*

In Scenario 2, the FST dataset was used to estimate crash and non-crash incident durations rather than the TMC-Event Manager. As the FST data is only available for the year of 2016, their average incident durations were used as “Treated”; for “Untreated” condition, L07 default incident durations were used. The non-crash incident counts were obtained from the FST dataset. Detailed incident input in Scenario 2 is presented in Table 6-4.

**Table 6-4 Detailed Incident Input Used in Brown County NB Scenario 2.**

Incident	W/O FST		With FST	
	Count	Annual Incident Duration (min) <sup>1</sup>	Count	Annual Incident Duration (min)
<b>Crash Incident</b>				
PDO	12	28	Same as “before”	17
Injury	4	40		20
Fatal	2	45		NA (35) <sup>2</sup>
<b>Non-Crash Incident</b>				
Disabled-Lane Blocking	Same as “after”	20	292	11
Disabled-Non-Lane Blocking		26	251	14
Other		23	39	12

1. L07 default duration.

2. Assumed value.

Table 6-5 shows the L07 tool output of operational and safety benefits due to FST in Scenario 2. Annual safety benefit (ASB) is just a fraction of the total annual operational benefit (AOB) in Scenario 2. Compared with Scenario 1, total annual benefit in Scenario 2 is substantially greater than that in Scenario 1 because of the higher incident frequency in Scenario 2. However, despite

its higher total annual benefit, the reliability component in Scenario 2 is considerably less than that of Scenario 1.

**Table 6-5 Benefit Estimation for Scenario 2 in Brown County.**

<b>Particular</b>	<b>NB</b>	<b>SB</b>	<b>Total</b>
Annual Delay Reduction (veh-hr)	2,476,171	2,558,266	5,034,437
Std. Dev. Change Indicator <sup>1</sup>	31.4	32.1	
<b>Annual Operational Benefit (AOB) in \$</b>			
Delay Component	\$38,826,367	\$40,113,607	\$78,939,974
Reliability Component	\$1,173,149	\$1,198,936	\$2,372,085
Total AOB	\$39,999,516	\$41,312,543	\$81,312,059
<b>Annual Safety Benefit (ASB) in \$</b>			
Benefit due to congestion reduction			
Fatal/ Major Injury	\$2,775	\$1,073	\$3,848
Minor Injury	\$577	\$502	\$1,079
PDO	\$197	\$221	\$418
Benefit due to treatment effect			
Fatal/ Major Injury	\$0	\$0	\$0
Minor Injury	\$0	\$0	\$0
PDO	\$0	\$0	\$0
Total ASB	\$3,550	\$1,796	\$5,346
<b>Total Annual Benefit</b>	<b>\$40,003,066</b>	<b>\$41,314,339</b>	<b>81,317,405</b>

1. Change in Std. Dev. of Travel Time Index (TTI) due to treatment

## 6.2.2 Analysis Results for Columbia County Study Site

### *Scenario 1: Using Incident Duration from FST Database of Brown County*

In Scenario 1, the FST dataset from Brown County was used to estimate crash and non-crash incident durations with FST treatment. Crash and non-crash incident durations for “Untreated” condition was estimated from TMC-Event Manager database for Columbia County. The crash incident counts were collected from MV4000 dataset and non-crash incident counts were collected from TMC-Event Manager database. The crash and non-crash incident counts were kept similar in both “Untreated” and “Treated” condition. Again, the only difference in incident input in SB direction is in crash incident counts. Detailed incident input in Scenario 2 is presented in Table 6-6. The L07 tool output of operational and safety benefits due to proposed FST service in Columbia County in Scenario 1 is presented in Table 6-7.

**Table 6-6 Detailed Incident Input Used in NB Scenario 1 in Columbia County.**

Incident	W/O FST		With FST	
	Count <sup>1</sup>	Annual Incident Duration (min) <sup>1</sup>	Count	Annual Incident Duration (min)
<b>Crash Incident</b>				
PDO	31	44	Same as “before”	17
Injury	6	50		20
Fatal	1	80		NA (70) <sup>3</sup>
<b>Non-Crash Incident</b>				
Disabled-Lane Blocking	22% of all incidents are crashes	91	“Same as before”	11
Disabled-Non-Lane Blocking		33		14
Other		56		12

1. The crash count is the five-year annual average from 2011 to 2015.
2. Crash/ Non-crash incident duration is averaged over both NB and SB direction.
3. Assumed value.

**Table 6-7 Benefit Estimation for Scenario 1 in Columbia County.**

Particular	NB	SB	Total
Annual Delay Reduction (veh-hr)	318,029	326,731	644,760
Std. Dev. Change Indicator <sup>1</sup>	2.1	2.2	
<b>Annual Operational Benefit (AOB) in \$</b>			
Delay Component	\$4,986,701	\$5,123,149	\$10,109,850
Reliability Component	\$69,391	\$71,703	\$141,094
Total AOB	\$5,056,093	\$5,194,852	\$10,250,945
<b>Annual Safety Benefit (ASB) in \$</b>			
Benefit due to congestion reduction			
Fatal/ Major Injury	\$535	\$3,024	\$3,559
Minor Injury	\$1,002	\$1,118	\$2,120
PDO	\$486	\$358	\$844
Benefit due to treatment effect			
Fatal/ Major Injury	\$0	\$0	\$0
Minor Injury	\$0	\$0	\$0
PDO	\$0	\$0	\$0
Total ASB	\$2,002	\$4,501	\$6,503
<b>Total Annual Benefit</b>	<b>\$5,058,115</b>	<b>\$5,199,353</b>	<b>\$10,117,468</b>

1. Change in Std. Dev. of Travel Time Index (TTI) due to treatment

*Scenario 2: Using Incident Duration Reduction Percentage of Brown County*

In Scenario 2, the reduction percentage in incident duration from Brown County was used to estimate crash and non-crash incident durations with FST treatment. Crash and non-crash incident durations for “Untreated” condition was kept similar as Scenario 1. Using the estimated incident duration reduction percentage, the incident duration in “Treated” condition was calculated from “Untreated” incident durations in this scenario. Detailed incident input in Scenario 2 is presented in Table 6-8. The L07 tool output of operational and safety benefits due to proposed FST service in Columbia County in Scenario 2 is presented in Table 6-9.

**Table 6-8 Detailed Incident Input Used in Scenario 2 in Brown County.**

Incident	W/O FST		With FST	
	Count <sup>1</sup>	Annual Incident Duration (min)	Count	Annual Incident Duration (min) <sup>2</sup>
<b>Crash Incident</b>				
PDO	31	44	Same as “before”	27
Injury	6	50		25
Fatal	2	80		NA (70) <sup>3</sup>
<b>Non-Crash Incident</b>				
Disabled-Lane Blocking	22% of all incidents are crashes	90	Same as “before”	50
Disabled-Non-Lane Blocking		33		18
Other		56		30

1. L07 default value.
2. Estimated durations from percent reduction in incident durations in Brown County.
3. Assumed value.

**Table 6-9 Benefit Estimation for Scenario 2 in Columbia County.**

Particular	NB	SB	Total
Annual Delay Reduction (veh-hr)	696,902	546,800	1,243,702
Std. Dev. Change Indicator <sup>1</sup>	2.2	3.9	
<b>Annual Operational Benefit (AOB) in \$</b>			
Delay Component	\$10,927,416	\$8,573,825	\$19,501,241
Reliability Component	\$164,987	\$127,168	\$292,155
Total AOB	\$11,092,403	\$8,700,994	\$19,793,397
<b>Annual Safety Benefit (ASB) in \$</b>			
Benefit due to congestion reduction			
Fatal/ Major Injury	\$791	\$3,786	\$4,577
Minor Injury	\$1,480	\$1,393	\$2,873
PDO	\$705	\$443	\$1,148

Benefit due to treatment effect			
Fatal/ Major Injury	\$0	\$0	\$0
Minor Injury	\$0	\$0	\$0
PDO	\$0	\$0	\$0
Total ASB	\$2,977	\$5,595	\$8,572
<b>Total Annual Benefit</b>	\$11,095,379	\$8,706,588	\$19,801,967

2. Change in Std. Dev. of Travel Time Index (TTI) due to treatment

## CHAPTER 7 TESTING AND RESULTS OF SHRP 2 L08 PRODUCT

### 7.1 Introduction

This section describes the evaluation of the FREEVAL-RL computational engine using data collected from the US 12/14 Beltline freeway corridor. There are two subsections. The first subsection describes the output of the FREEVAL-RL pilot test using default data (except for traffic demand) provided by the FREEVAL-RL tool. In the second subsection, most tool default values were replaced with facility-specific data.

### 7.2 Test 1: Testing of the FREEVAL-RL Tool

For the US 12/14 Beltline freeway corridor study site, a pilot run of the FREEVAL-RL tool was conducted with the minimum required input for the morning peak hour period (6:00 am to 9:00 am)<sup>1</sup>. Traffic volume data is one of the most important input variables in the FREEVAL-RL analysis. Hourly flow rate data were collected in 15-min intervals from V-SPOC, Wisconsin's traffic detector archive database (18). Corridor geometric data were collected from Google Map (19) and WisDOT Meta-Manager Management System Data Base (16), Wisconsin's highway inventory database. Table 7-1 presents the site-specific input values used in the pilot run. Note that Table 7-1 only lists the site-specific values used to conduct Test 1. The FREEVAL-RL default values deemed suitable for this study were used for the remaining input variables.

**Table 7-1 Sample Data Input for Test Run in FREEVAL-RL.**

Name	Unit	Trial Run Input and Source
Study period start time	hh:mm	6:00
Study period End time	hh:mm	9:00
Analysis year	Year	2013
RRP Start Date	MM/DD	1-Jan
RRP End Date	MM/DD	31-Dec
Seed Demand Day in RRP	(MM/DD)	10-Jun
Number of HCM Segments	Count	9
Type of Each Segment	Basic/On-ramp/Off-ramp/Weaving	HCM Definition
Length	feet	Google Map
Number of Lanes	Count	Google Map
Segment Demand	vph	V-SPOC
On-Ramp Demand	vph	V-SPOC
Off-Ramp Demand	vph	V-SPOC

[Note: All other parameters were kept at the default value]

<sup>1</sup> The morning peak hour period was chosen for the pilot testing of FREEVAL-RL tool.

Using the above-mentioned input values, a seed file was generated in FREEVAL-RL. The next step in reliability assessment is scenario management. Scenario generator, a macro-based computational tool developed in Microsoft Excel, is used to generate and manage scenarios. Scenario generator is the source of recurring and non-recurring congestion. The scenario generator requires input in three scenarios: 1) demand, 2) weather and 3) incident. In the demand scenario management section, all default values for an urban corridor were used because the study corridor is located in an urban area. For weather scenarios, the default value from Madison, Wisconsin was used. One of the major sources of non-recurring congestion is incidents. The FREEVAL-RL tool provides two options for incident input: poor data facilities and rich data facilities.

The option for poor data facilities pertains to the cases when incident logs are not available or are of insufficient quality to enable direct calculation and entry of incident probabilities. In order to estimate the incident probabilities, three different paths are recommended. The first path is to determine if incident rates (per 100 million Vehicle Miles Traveled) are available for the facility. If so, then the incident rates can be entered on a monthly basis. The user is allowed to change incident rates by month if incident rate information is available. If not, the second path is to use monthly facility crash rates and an estimated local incident to crash ratio to estimate monthly incident rates. A national default ratio is provided in the Scenario Generator tool but can be overwritten by the user. If neither crash nor incident rate is available, a third path is to generate crash rates using the Highway Economic Requirements System (HERS) model. If the HERS model is used, the user must provide input on what portion of the AADT occurred during the study period.

The option for rich data facilities allows the user to code facility-specific monthly incident probability data if available. All available options result in a table of incident probabilities by type and by month of the year. The user can change estimated probabilities in the incident table if such data is available.

In the pilot testing, the study corridor was treated as a poor data facility in Test 1 and the HERS model was used to estimate the incident probabilities. The two input variables required in the HERS model are “National Default Ratio” which represents the specific crash to incident ratio (4.90) and portion of AADT (38.84%) during the defined study period. For both variables, the national default values provided by the Scenario Generator were used.

For weather scenarios, a threshold probability needs to be defined in the Freeway Scenario Generator (FSG) to produce scenarios with unreliable travel conditions. A threshold value for base scenario probability of 0.01% was used in the pilot run. Considering the defined threshold value, the FSG generated 650 scenarios with a probability more than the threshold value. Table 7-2 summarizes the 650 scenarios from FSG. Among all scenarios, 136 are caused by weather events alone; 400 scenarios are caused by incidents; and 102 scenarios are caused by the combination of the two. The bottom part of Table 7-2 summarizes the reliability performance measures of the

study corridor in the reliability reporting period. By definition, the TTI is defined as the ratio of the actual time spent traversing a given distance to the free-flow travel time for that same distance. In Table 7-2, the mean TTI is 1.13, suggesting that the average travel time on the study corridor is 13% higher than the free flow travel time. The estimated 95<sup>th</sup> percentile TTI or Planning Time Index (PTI) is 1.29, indicating a traveler should budget 29% more time than free flow travel time to ensure on-time arrival in AM peak period 95% of the time or at least 5% of all trips will experience travel time at 29% more than the free flow travel time. The Misery Index, Semi-Standard Deviation, Reliability Rating and Percent VMT at TTI>2, all these performance measures provide insight on the travel time experience in worst trips occurred on the study corridor. The Misery Index or 97.5<sup>th</sup> percentile TTI is 1.80 which indicates it takes 80 percent more time than free-flow travel time to travel the worst 2.5% trips on the corridor in AM peak period. The estimated reliability rating was 96.82%, indicating that 96.82% of the total trips had a TTI ≤1.33 which is the threshold travel time index for freeways.

**Table 7-2 Summary of Generated Scenarios in Pilot Run Test 1.**

Facility Description			
Facility Length (miles)	3.8	Number of Demand Scenarios	12
Total Number of Scenarios <sup>1</sup>	650	Number of Weather Scenarios	136
Duration of Scenario (hrs)	3.0	Number of Incident Scenarios	400
		Numb. of Incident + Weather Scen.	102
Facility Reliability Performance Measures			
Mean TTI	1.13	Misery Index	1.80
50th Percentile TTI	1.08	Semi-Standard Deviation	9.41
80th percentile TTI	1.14	Reliability Rating	96.82%
95th Percentile TTI (PTI)	1.29	Percent VMT at TTI > 2	0.75%

Table 7-3 shows the system vehicle hours of delay, including delays at on-ramps, for the entire Reliability Reporting Period (RRP) and for the average 15-minute analysis period. Table 7-3 also shows the percent time when recurring and nonrecurring congestion occurs. In this pilot run, an incident and/or a weather event exists in 13.6% of all 15-minute time-periods analyzed. From the vehicle hours of delay (VHD) figures provided in Table 7-3, it can be noted that 44 percent (7,918 veh-hr) and 56 percent (10,048 veh-hr) of VHD occurred due to non-recurrent and recurrent congestion, respectively.

**Table 7-3 Percent Contribution to Total Vehicular Hours of Delay (VHD).**

VHD Under Condition	Total	During RRP	Average in 15 min	%Time in Condition
Recurring		10,048	3.21	86.4%
Non-Recurring		7,918	2.53	13.6%
Total		17,966	5.74	100.0%

Table 7-4 presents the vehicular delay that occurred on the study site in all scenarios and scenarios with recurring congestion. The maximum demand/capacity (d/c) ratio is for the combination of all scenarios is 5.12 whereas the maximum d/c ratio in recurrent congestion is 0.9, which shows the significant effect of non-recurrent congestion on the d/c ratio. The non-recurrent congestion has a very high impact on the maximum 15 min facility TTI with a value of 45. The 1.93 percent of time when the queue is present on the facility is solely attributed to non-recurrent congestion. Finally, 100% percent VMT served in the study period indicates that there is no unserved VMT in either congestion types.

**Table 7-4 Test Run Output Details for Recurring and Non-Recurring Congestion.**

Scenarios with Recurring Congestion		All Scenarios	
Maximum 15 min Segment d/c Ratio	0.9	Maximum 15 min Segment d/c Ratio	5.12
Maximum 15 min Facility TTI <sup>1</sup>	1.20	Maximum 15 min Facility TTI	45
% Time with Queues on the Facility	0.00%	% Time with Queues on the Facility	1.93%
% Time without Queues on the Facility	100.00%	% Time without Queues on the Facility	98.07%
% VMT <sup>2</sup> Served in the Study Period	100.00%	% VMT Served in the Study Period	100.00%
% VMT Unserved in the Study Period	0.00%	% VMT Unserved in the Study Period	0.00%

<sup>1</sup>. TTI=Travel Time Index; <sup>2</sup>.VMT=Vehicle Miles Traveled;

### 7.3 Test 2: Detailed Analysis with Facility-Specific Data

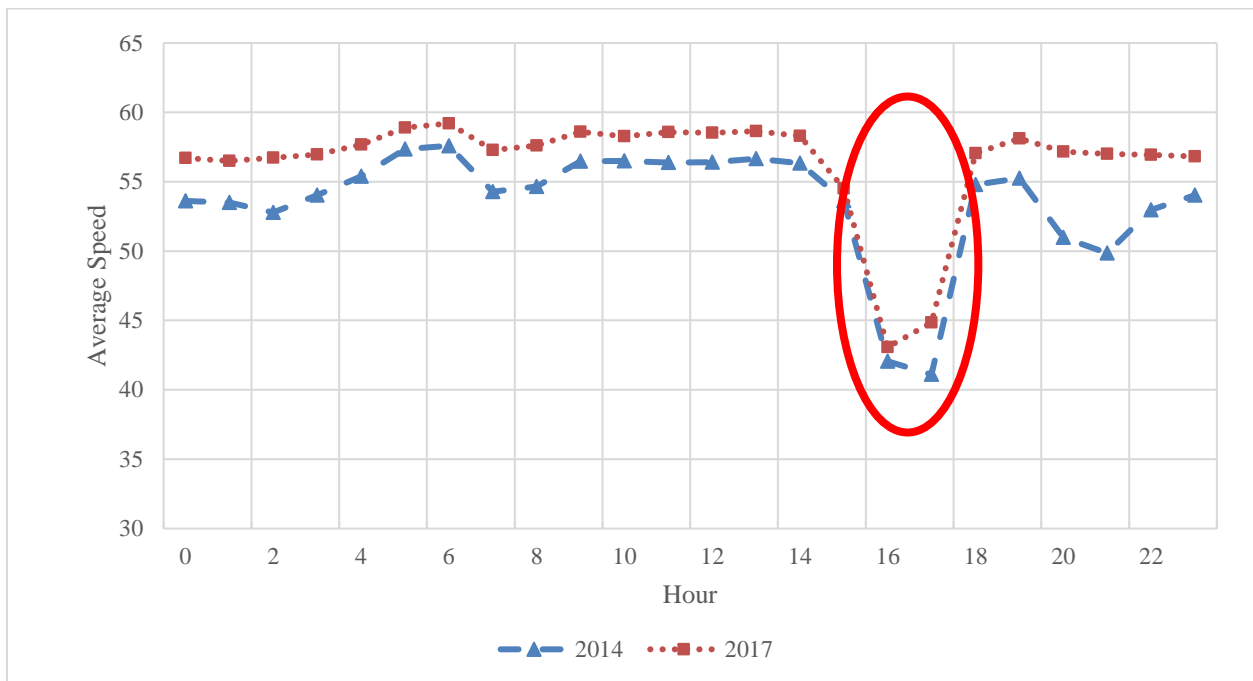
A detailed analysis was conducted with facility-specific data after the pilot with the minimum required data. Most default input values were replaced with facility-specific input values to obtain more realistic output from the FREEVAL-RL computational engine. As discussed in the study site selection, construction work was done to improve the geometric configuration of the site. Thus, a “before-after” analysis was conducted to evaluate the operational improvement. The lane restriction started on 09/10/2014 and ended on 11/04/2016. In this test, the year of 2014 was used as the “Before Improvement” period and the year of 2017 was used as the “After Improvement” period. The changes in geometry due to construction are listed in Table 7-5.

**Table 7-5 Changes in Roadway Geometry on Study Corridor.**

Segment	Segment Label	Before Period			After Period		
		Type	Length (ft)	No. of Lanes	Type	Length (ft)	No. of Lanes
1	S01	Basic	1500	2	Basic	1500	2
2	S02	Off Ramp	1500	2	Off Ramp	1500	2
3	S03	Basic	2500	2	Basic	2500	3

4	S04	Weaving	3600	3	Weaving	3600	4
5	S05	Basic	2600	2	Basic	2600	3
6	S06	On Ramp	1500	3	On Ramp	1500	4
7	S07	Basic	1820	3	Basic	1820	4
8	S08	Weaving	2450	4	Weaving	2450	4
9	S09	Basic	2450	3	Basic	2450	3

A study period needs to be selected to evaluate FREEVAL-RL in the congested flow condition. Historical traffic trend shows that the eastbound US 12/14 Beltline freeway corridor is usually congested during the afternoon peak period. The average speed profile for the eastbound US 12/14 Beltline freeway corridor was constructed using the National Performance Management Research Data Set (NPMRDS). Figure 7-1 shows the average speed profile over a day on the study corridor for both 2014 and 2017. From Figure 7-1, it can be noted that the average speed starts decreasing just before 15:00 and the traffic condition returns to the free-flow condition after 18:00. Hence, a study period between 15:00 to 18:00 was selected.

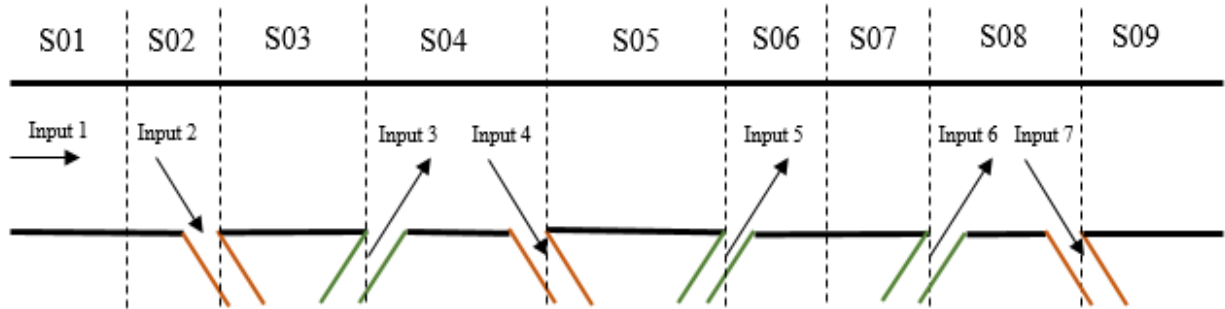


**Figure 7-1: Average Speed Profile Over the Day on the Study Corridor.**

### 7.3.1 Site-Specific Data Collection

The FREEVAL-RL user manual recommends using facility-specific input parameters to obtain more realistic outputs from the FREEVAL-RL computational engine. Starting with demand input, the FREEVAL-RL tool requires traffic demand input for every 15-minute interval within the analysis time period. The study period selected for this test is 3 hours. Thus, the tool required 12 traffic demand inputs (3 hours x 4 slices per hour = 12) for each segment. The real-time traffic data were collected from V-SPOC for each 15-minutes time slice between 15:00 to 18:00. The

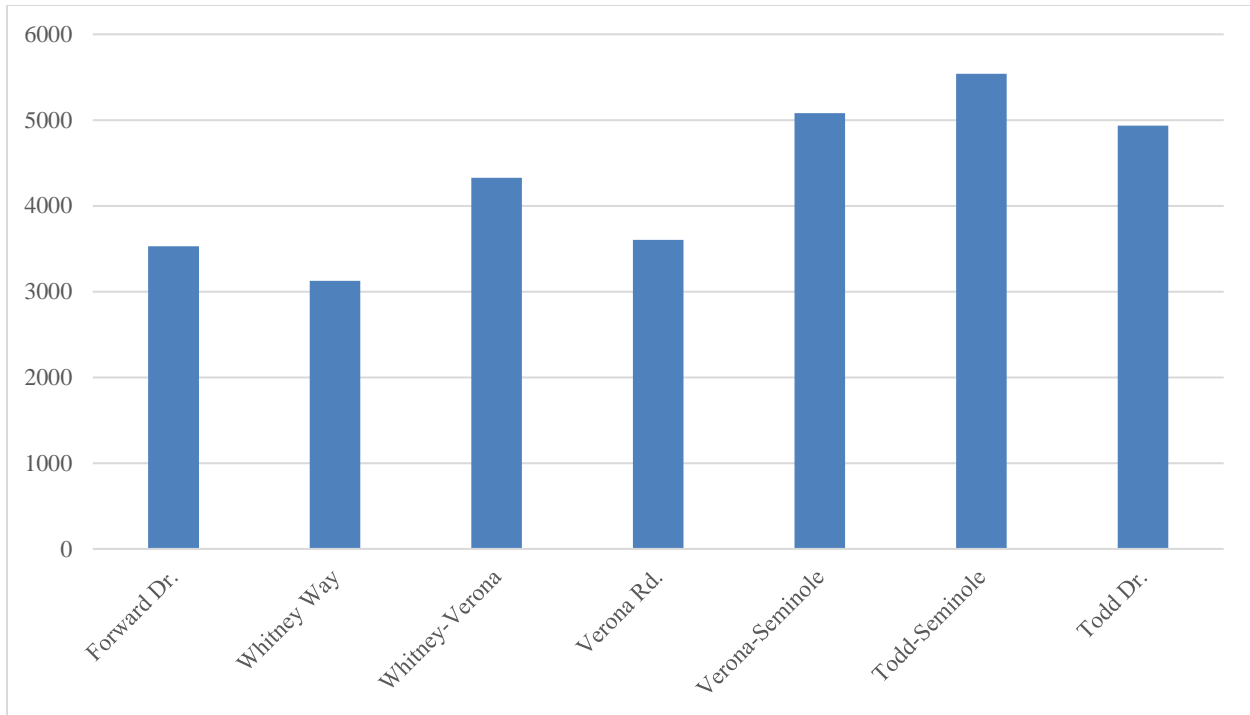
traffic detector in V-SPOC is for each lane so the demand will be the sum of all lanes. Figure 7-2 and Table 7-6 show the schematic diagram of the study corridor and traffic demand input values used in FREEVAL-RL. In Figure 7-3, a longitudinal profile of traffic demand is generated for demand input from 16:45 to 17:00. A seed file was created using site-specific demand values and geometric configurations.



**Figure 7-2: Schematic of Study Corridor.**

**Table 7-6 Demand Input Values for the Study Corridor.**

Time	Input 1 (vph)	Input 2 (vph)	Input 3 (vph)	Input 4 (vph)	Input 5 (vph)	Input 6 (vph)	Input 7 (vph)
15:00-15:15	2960	290	1172	676	1503	417	424
15:15-15:30	3010	272	1192	712	1516	411	436
15:30-15:45	3349	297	1232	726	1476	463	455
15:45-16:00	3187	336	1368	682	1490	489	481
16:00-16:15	3597	352	1404	710	1523	513	477
16:15-16:30	3482	358	1376	702	1465	488	482
16:30-16:45	3700	447	1364	733	1538	509	494
16:45-17:00	3527	403	1204	726	1479	457	602
17:00-17:15	3498	430	1228	678	1445	473	503
17:15-17:30	3382	373	1224	734	1337	384	595
17:30-17:45	3042	417	1240	711	1333	406	459
17:45-18:00	2834	356	1156	671	1356	460	443



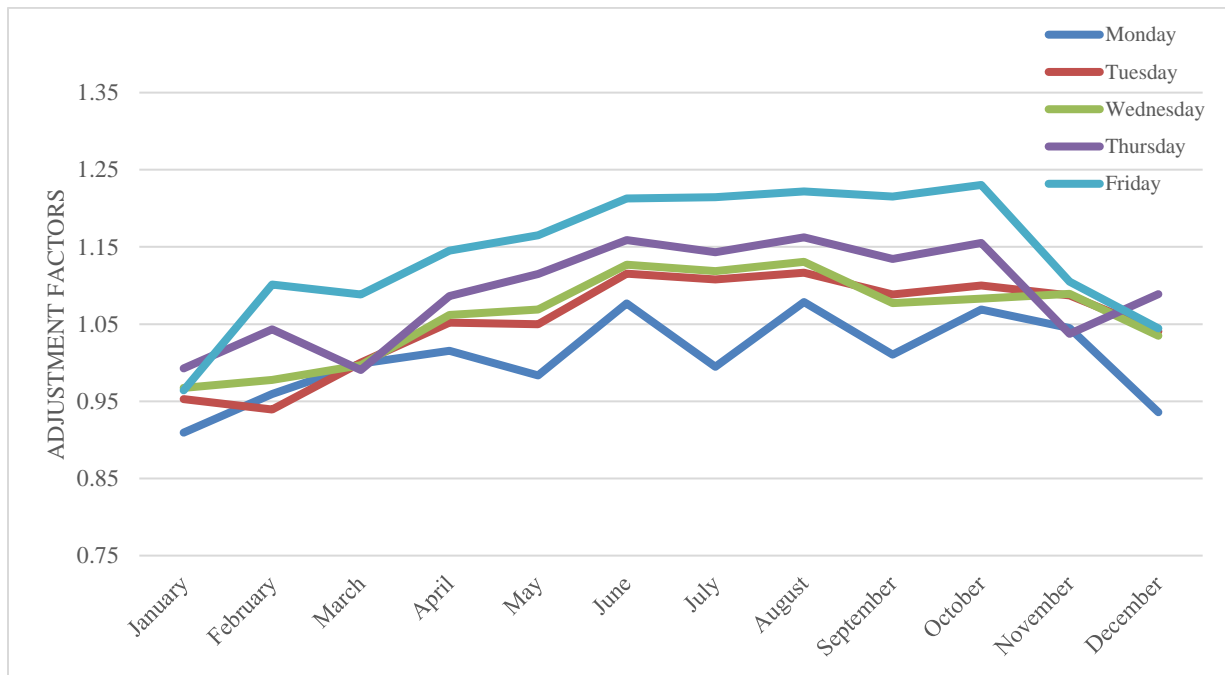
**Figure 7-3: Longitudinal Demand Profile (16:45-17:00)**

The scenario management requires a series of input variables such as demand, weather and incident to generate scenarios for reliability analysis. The FSG process consists of five steps, in which the user enters different types of information to generate the recurring and non-recurring congestion scenarios. The five steps, each consisting of its own worksheet within the FSG, should be completed in order; otherwise, the scenario generation process could fail.

1. Start Worksheet
2. Demand Pattern Worksheet
3. Weather Probability Worksheet
4. Incident Probability Worksheet
5. Detailed Scenario Worksheet

The seed file created using facility-specific demand value was used to complete Step 1 in the FSG analysis. Step 2 is used to configure demand pattern. In this step, the time-dependent demand patterns are defined in the Reliability Reporting Period (RRP). Step 2 requires input in two separate worksheets. In the first worksheet, the user needs to configure similar seasons, months, and weekdays that need to be combined within the same demand pattern. For this analysis, two demand patterns (FSG default value) were chosen for the demand pattern within a week. More specifically, the demand patterns are same between Tuesday to Thursday and, a separate code defines demand pattern for Monday and Friday. For seasonal demand patterns, the option of four seasons within a year was chosen. In the second worksheet, the user can configure the daily and monthly demand adjustment factors (DAF) based on the daily and monthly variability of traffic demand. WisDOT

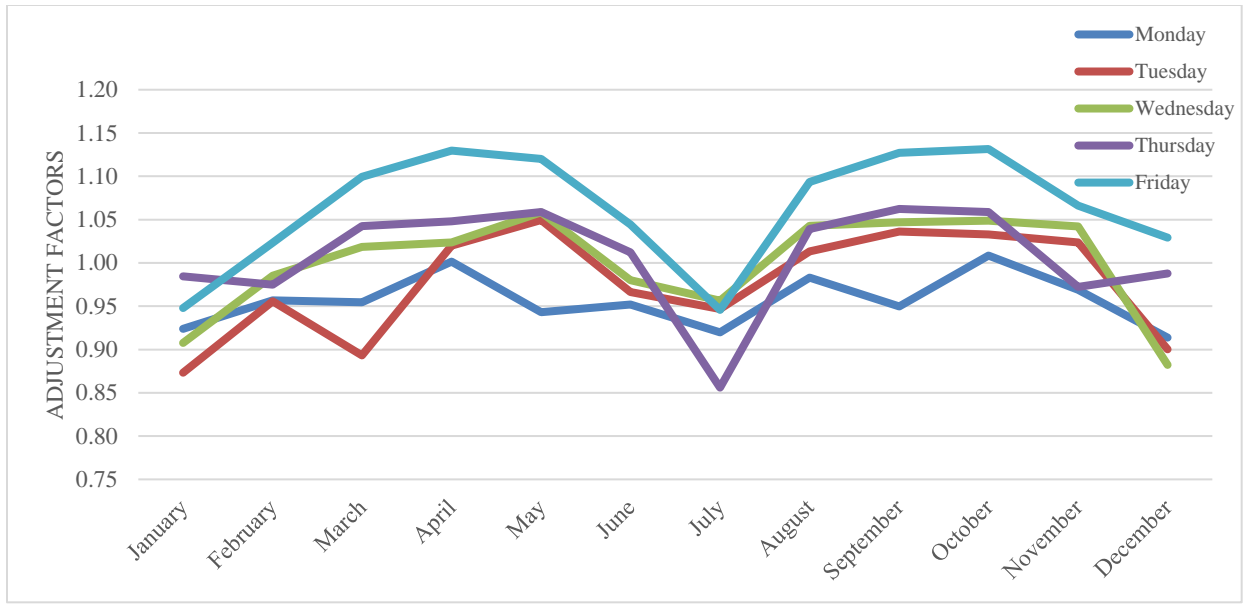
developed and maintains monthly and daily demand adjustment factors for different facility types. The DAFs are generated based on count location traffic data from the entire state. The 2016 DAF for “Group – Urban Interstate” was used because the study location is in the City of Madison, the “Urban Interstate” is the closest group of DAFs that is available from WisDOT. Figure 7-4 shows the DAF for urban interstate highways generated by WisDOT.



**Figure 7-4: State-Specific Demand Adjustment Factors.**

FREEVAL-RL provides national default values for DAF but research in SHRP2-L08 and testing through SHRP2-L38 suggested that the default values in fact rarely match the facility-specific demand adjustment factors (8; 20; 21). The state-specific DAFs collected from WisDOT may not be appropriate for the study facility either because they were estimated from statewide data. Hence, it is recommended to use facility-specific demand adjustments. A separate DAF table was generated using facility-specific demand values. The hourly traffic data on the study corridor were collected for a whole year and a DAF table was generated based on facility-specific AADT. Figure 7-5 shows the facility-specific DAFs estimated from hourly traffic data (22).

The weather probability worksheet in Step 3 of FSG is for all necessary weather information. The weather probability worksheet in FSG provides weather defaults based on the 10-year average for a specified metropolitan area. The study site is located near Madison, WI so the 10-year Madison average weather defaults were used.



**Figure 7-5: Site-Specific Demand Adjustment Factors.**

In Step 4 of FSG, the incident probability worksheet characterizes incident events in terms of probability of occurrence, duration and severity on the freeway facility. The crash and non-crash incident data were collected from the Safety table in Meta-Manager, a WisDOT source of roadway segment data. In this detailed analysis, crash rate was used to estimate the incident probabilities. The crash rate can be estimated using the following equation:

$$Crash\ Rate = \frac{Corridor\ wide\ total\ crash\ within\ 5\ years \times 100,000,000}{5\ year\ AADT \times Length \times 5 \times 365} \quad (1)$$

Since the study corridor only covers one-direction of travel, 50 percent of the AADT was used to calculate the crash rate. In the Safety table of Meta-Manager, the crash data is available for each Meta-Manager segment. The study corridor has five (5) Meta-Manager segments with varying AADTs and segment lengths. Equation 2 is formulated to estimate a corridor level crash rate. Using Equation 2, the estimated crash rate for the study corridor is 104.7 crashes/100 MVMT.

$$Crash\ Rate = \frac{(C_1 + C_2 + C_3 + C_4 + C_5) \times 100,000,000}{(V_1 L_1 + V_2 L_2 + V_3 L_3 + V_4 L_4 + V_5 L_5) \times 365} \quad (2)$$

Where,

$C_1, C_2, C_3, C_4, C_5$  are the average number of crashes occurred on each segment per year;

$V_1, V_2, V_3, V_4, V_5$  are the AADT for each segment;

$L_1, L_2, L_3, L_4, L_5$  are the segment lengths.

In Table 7-7, the distribution of incident type, duration and standard deviation of duration for different incident types were estimated using WisDOT TMC Event Manager dataset. Using both crash and incident data, the crash to incident ratio was calculated as 4.6.

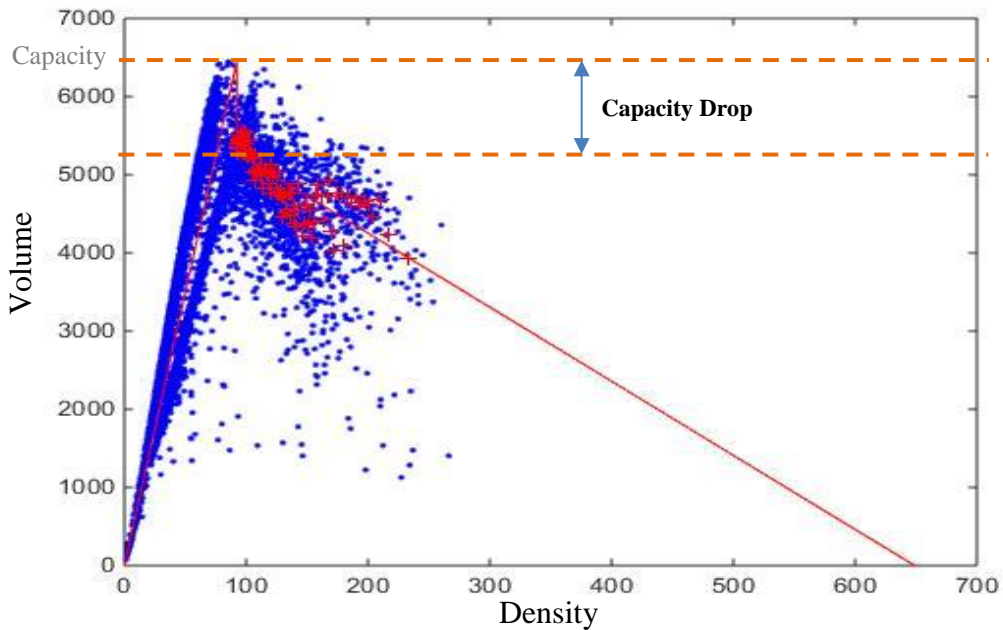
**Table 7-7 Required Incident Input Values for Data Poor Facilities.**

Incident Type	Incident Type Distribution	Expected Duration (min)	Std. Dev. of Duration
Shoulder Closure	69.34%	45	35
One Lane Closure	21.70%	42	29
Two Lane Closure	4.72%	66	37
Three Lane Closure	2.36%	75	40
Four Lane Closure	1.89%	85	45

Now, detailed scenarios can be generated in the final step of FSG where each scenario is a unique combination of demand, weather and incident characteristics. The weather events, incident and demand patterns are considered as independent events. Thus, the number of possible scenarios can be large. To reduce runtime, some unlikely (low probability) scenarios were eliminated from consideration prior to running the core computational model by specifying a filtering percentage threshold. A threshold value of 0.01 percent was used in this study. FREEVAL-RL was implemented for both “Before” and “After” Improvement periods. For comparison, all input values were kept the same except for the roadway geometry. The hypothesis is that the FREEVAL-RL evaluation using the same input information provides net benefits obtained from capacity improvement (adding lanes).

### 7.3.2 Fundamental Diagram Calibration

The FREEVAL-RL tool allows the user to input capacity drop, a traffic flow phenomenon that can be observed from real-time traffic data. Previous studies have shown that traffic flow performance is different when a queue is built up from when a queue is dissipated (23). The traffic discharge flow rate diminishes once the queue forms upstream. Higher capacity values are normally achieved when the traffic queue builds up. The FREEVAL-RL tool doesn’t have the ability to model capacity drop from the input data but allows the user to input a capacity drop value with the maximum value of 10%. In this study, the site-specific traffic capacity drop was estimated by calibrating fundamental traffic flow (FD) diagrams using real-time traffic data. To do this, a FD diagram was calibrated for the study corridor using V-SPOC traffic detector data. The traffic detector data were collected in 5-minute bins between the months of March and September. The FD diagram was only calibrated for mainline traffic detector locations (three in total) within the study corridor. The FD diagram calibration plot for Todd Drive is shown in Figure 7-6.



**Figure 7-6: FD Diagram Calibration for Todd Drive.**

From Figure 7-6, it can be observed that the traffic demand builds up to capacity until the queue starts. The horizontal dashed line indicates the maximum capacity at Todd Drive. Once the queue starts building up after achieving capacity, the capacity drop can be observed. The plot clearly shows that the capacity dropped to a certain value when the queue starts to form.

Estimating a best-fit regression line in the congested traffic condition can provide the jam density. The estimated capacity, percent capacity drop and jam density obtained from calibrating the FD diagrams are provided in Table 7-8. The calibrated capacity drop and jam density were used to replicate the congested traffic conditions that occurred on the study corridor.

**Table 7-8 Estimated Capacity, % Capacity Drop and Jam Density for the Study Corridor.**

Location	Capacity (veh/hr/ln)	Dropped Capacity (veh/mile/ln)	% Capacity Drop	Jam Density (veh/mi/ln)
Whitney Way	2046	1624	20.60%	223.8
Verona Rd	2307	1902	17.60%	229.6
Todd Dr.	2148	1759	18.10%	216.3

Table 7-8 indicates that the capacity drop ranges between 18 to 20 percent on the study corridor. Since FREEVAL-RL only allows the maximum value of capacity drop to be 10 percent, the maximum allowed capacity drop was used in this study. The average jam density on the study corridor was 222 veh/mi/ln. Due to the restriction on capacity drop input, a reduced jam density

of 210 veh/mi/ln was used. An exploratory analysis showed that the FREEVAL-RL outputs are not sensitive to smaller changes in the value of jam density.

### 7.3.3 FREEVAL-RL Calibration and Result

Although FREEVAL-RL was developed based on the HCM methodology, like any traffic simulation tool, calibration is required to reflect local driving behavior. Since there is no established calibration methodology for FREEVAL-RL, six scenarios were proposed in Table 9. The output values from each scenario were compared with the NPMRDS data to identify opportunities for calibration. The purpose of the calibration is to obtain more reliable and consistent model results that are comparable to travel time reliability measured from field data Table 7-9.

**Table 7-9 Scenarios for FREEVAL-RL Computational Model Calibration.**

Scenario	Demand Multiplier	CAF	SAF	Std. Dev. of Incident Duration
Scenario 1	State-specific <sup>a</sup>	x	x	x
Scenario 2	Site-specific <sup>b</sup>	x	x	x
Scenario 3	State-specific <sup>a</sup>	0.9	x	x
Scenario 4	State-specific <sup>a</sup>	0.9	0.9	x
Scenario 5	State-specific <sup>a</sup>	0.9	0.9	50% reduction in Std. Dev.
Scenario 6	State-specific <sup>a</sup>	0.8	Varying SAF over time	x

a: Provided by WisDOT (Figure 7-4); b: Calculated from the field data (Figure 7-5); x: Estimated Std. Dev. (Table 7-7)

The demand factors were chosen as the first option to calibrate the FREEVAL-RL tool. The overall demand levels need to be adjusted to determine the best demand level that recreates the observed traffic conditions. In this study, two sets of demand factors were used. The first set of demand factors were estimated based on state-level count location data from the same facility type (Figure 7-4). This produces demand factors representative of typical Urban-Interstates similar to the study corridor; however, they are not specifically estimated for the target study site. Scenario 1 and Scenario 3-6 were generated based on state-specific demand factors. The second set of demand factors were estimated based on hourly traffic data from the study site (Figure 7-5). Only Scenario 2 were generated based on site-specific demand factors presented in Figure 7-5.

In the previous L38 projects conducted by multiple state DOTs, one limitation noted in the project report is that FREEVAL-RL over-estimates the capacity of the study facility (24). To overcome this issue, an adjustment factor needs to be applied to the capacity estimated in FREEVAL-RL. The FREEVAL-RL computational engine provides flexibility to adjust capacity and speed for each segment at each time slice. For Scenario 3-6, various capacity adjustment factors (CAF) and speed adjustment factors (SAF) were applied to adjust over-estimation of capacity and to test the sensitivity of the FREEVAL-RL tool with CAFs and SAFs. The incident durations were estimated

from WisDOT’s Traffic Management Center’s Event Manager data. In Scenario 5, the standard deviations of incident durations were reduced by 50% to test the sensitivity of the standard deviation of incident duration. In Scenario 6, the SAF was varied over time with a value between 0.80 to 1 and with a fixed CAF of 0.8 for all segments.

The summary of all six scenarios is presented in Table 7-10, including travel time reliability performance measures and total vehicle hours of delay in the vehicle-hour unit. NPMRDS database was used to compare the FREEVAL-RL reliability outputs with the field data. Due to construction work, the lane restriction on the study corridor began on October 2014. Thus, the NPMRDS data from January to September 2014 were used to estimate reliability performance measures (see the last column of Table 7-10). Using 0.01 percent threshold for base scenario probability in the scenario generator, 99.60 percent of the scenario distribution was covered.

**Table 7-10 FREEVAL-RL Output for different Scenarios in the "Before" period.**

Particular	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	NPMRDS
Mean TTI	1.41	1.32	1.7	1.75	1.76	2.03	1.21
50th Percentile	1.15	1.12	1.52	1.56	1.56	1.78	1.08
80th Percentile	1.42	1.22	1.87	1.91	1.95	2.31	1.70
95th Percentile	2.2	1.98	2.55	2.59	2.58	2.97	3.33
Semi-Standard Deviation	13.46	13.08	16.8	16.84	13.25	20.58	21.82
Misery Index	4.27	4.02	4.77	4.79	4.74	5.47	4.28
Total Vehicle Hour Delay	244,404	156,222	464,150	477,536	502,354	790,254	x

x: Estimate not available

Note: The FREEVAL-RL tool was run with a total of 900 scenarios: Number of Demand scenarios: 8; Number of Demand and Incident scenarios: 336; Number of Demand and Weather scenarios: 76; Number of Demand, Incident and Weather Scenarios: 480.

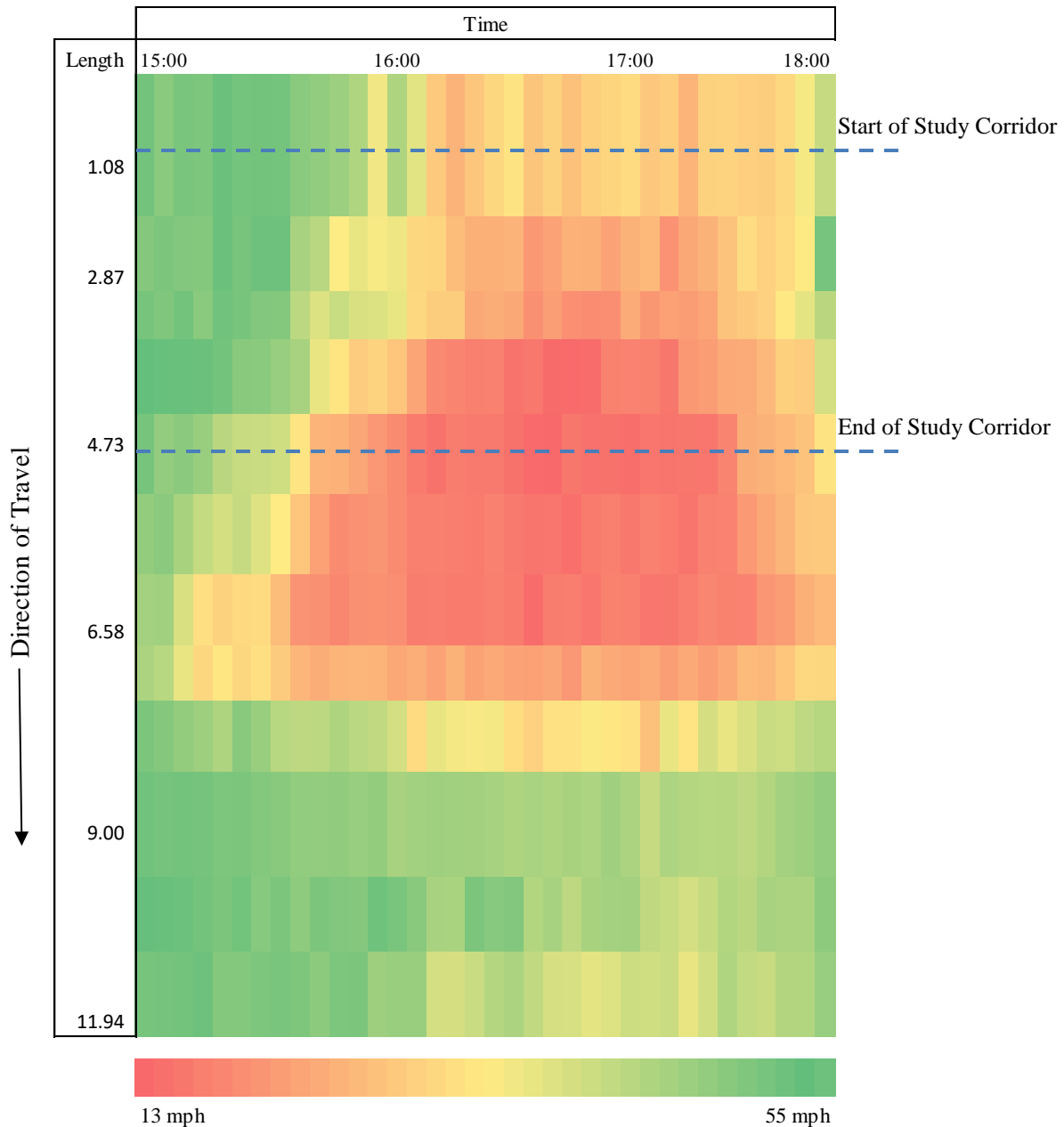
In Table 7-10, the mean NPMRDS TTI is 1.21, which is much lower than all the estimated scenarios. However, its TTI distribution has a long tail with 80<sup>th</sup> and 95<sup>th</sup> percentile value as 1.70 and 3.33, respectively. The 95<sup>th</sup> percentile TTI values from the FREEVAL-RL tool for all scenarios were smaller than the field data. Based on what is known during the calibration, the TTI outputs from the tool can be adjusted using higher CAF or SAF or the combination of both. Variations in the mean TTI and 95<sup>th</sup> percentile TTI indicate that the output TTI distribution did not match with the field conditions. The comparison between Scenarios 3 and Scenario 4 suggests that TTI is more sensitive to CAF than SAF. A varying SAF was used in Scenario 6 with a fixed CAF of 0.8. The

semi-standard deviation and 95<sup>th</sup> percentile output from FREEVAL-RL are similar to the field condition in Scenario 6. One possible reason for the difference noted in 80<sup>th</sup> to 95<sup>th</sup> percentile of TTI outputs from FREEVAL-RL could be the existence of a downstream bottleneck which affects the traffic flow on the study corridor.

The variation in estimated outputs from field data can be caused by an exogenous factor such as a downstream/ upstream bottleneck. In previous L38 pilot run reports, Florida DOT noted that FREEVAL-RL reliability prediction model need to be calibrated to incorporate the impact of an upstream or downstream bottleneck (20). In the traffic flow theory, the lane flow drops upstream of a bottleneck when demand for a bottleneck exceeds its capacity (23). Thus, the same level of flow can be observed at different speeds on an upstream lane compared to downstream travel speed due to the existence of a downstream bottleneck. Previous L38 reports also indicated that the FREEVAL-RL tool may not provide reliable outputs if a downstream bottleneck exists (20). A bottleneck analysis including a downstream section of the study corridor may provide insight on the variation in the TTI output from the FREEVAL-RL computational engine.

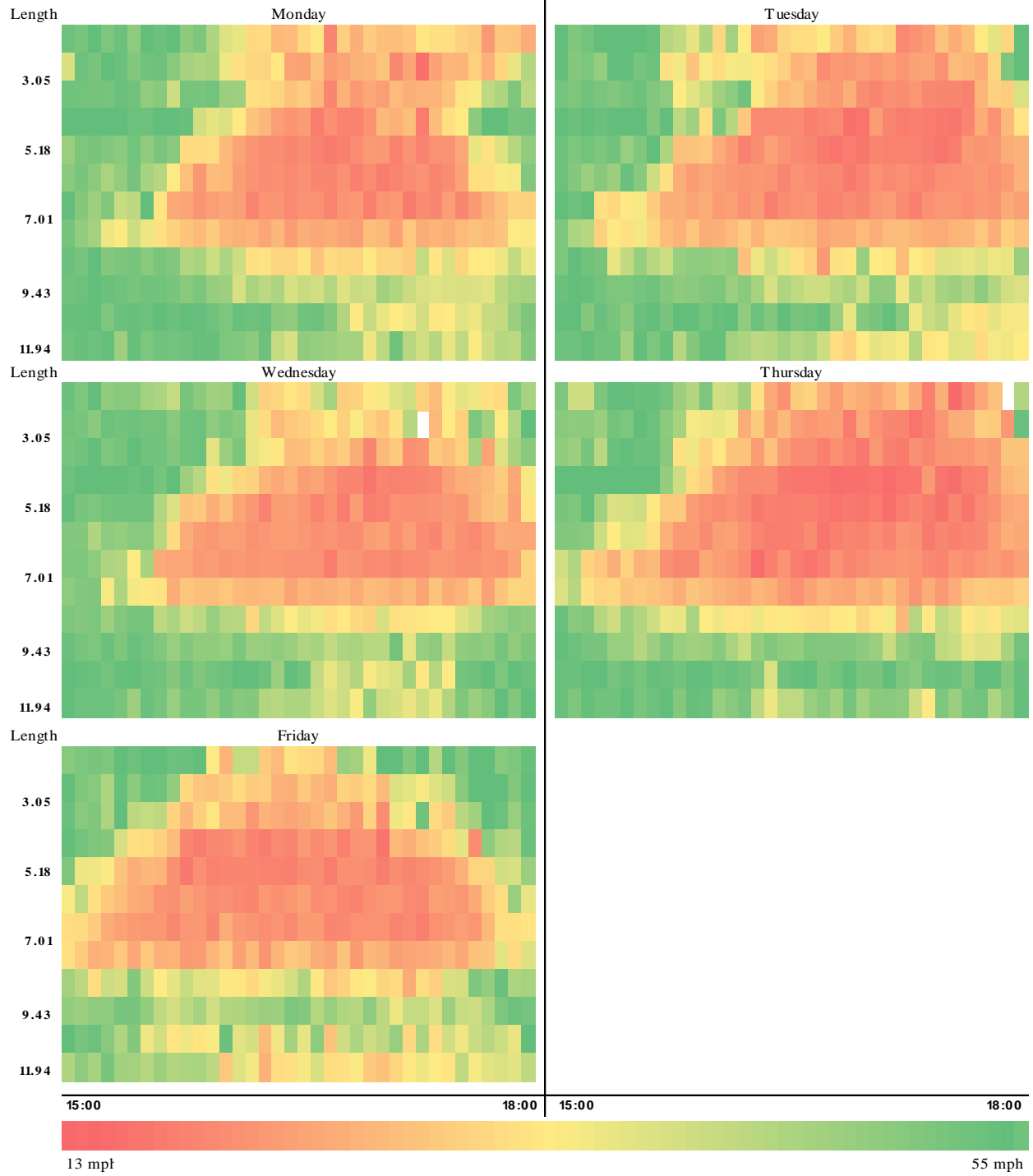
#### **7.3.4 Bottleneck Analysis**

A bottleneck analysis was conducted on the 11.94-mile long corridor which includes the 3.77-mile study corridor, 0.5-mile of corridor located upstream of and rest of 7.67 miles of corridor located downstream of the study corridor (Figure 2-3 and Figure 2-4). The NPMRDS data in 5-minute bins from 24 Traffic Message Channels (TMC) were collected for June 2014 between 3 pm to 6 pm. The final dataset contains 16,322 observations. A corridor speed heat map is provided in Figure 7-7. The speed heatmap in Figure 7-7 shows that congestion begins after 7.08 miles on the corridor where the entrance ramp from John Nolen Drive merges with US 12/14. The congestion usually begins around 3:20 pm near the entrance ramp of John Nolen Drive. The shockwave propagates upstream of the location and affects the FREEVAL-RL study corridor for about 5.4 miles upstream. The speed heatmap also indicates that 2.42 miles of the study corridor chosen for evaluation in FREEVAL-RL tool were affected by the downstream congestion.

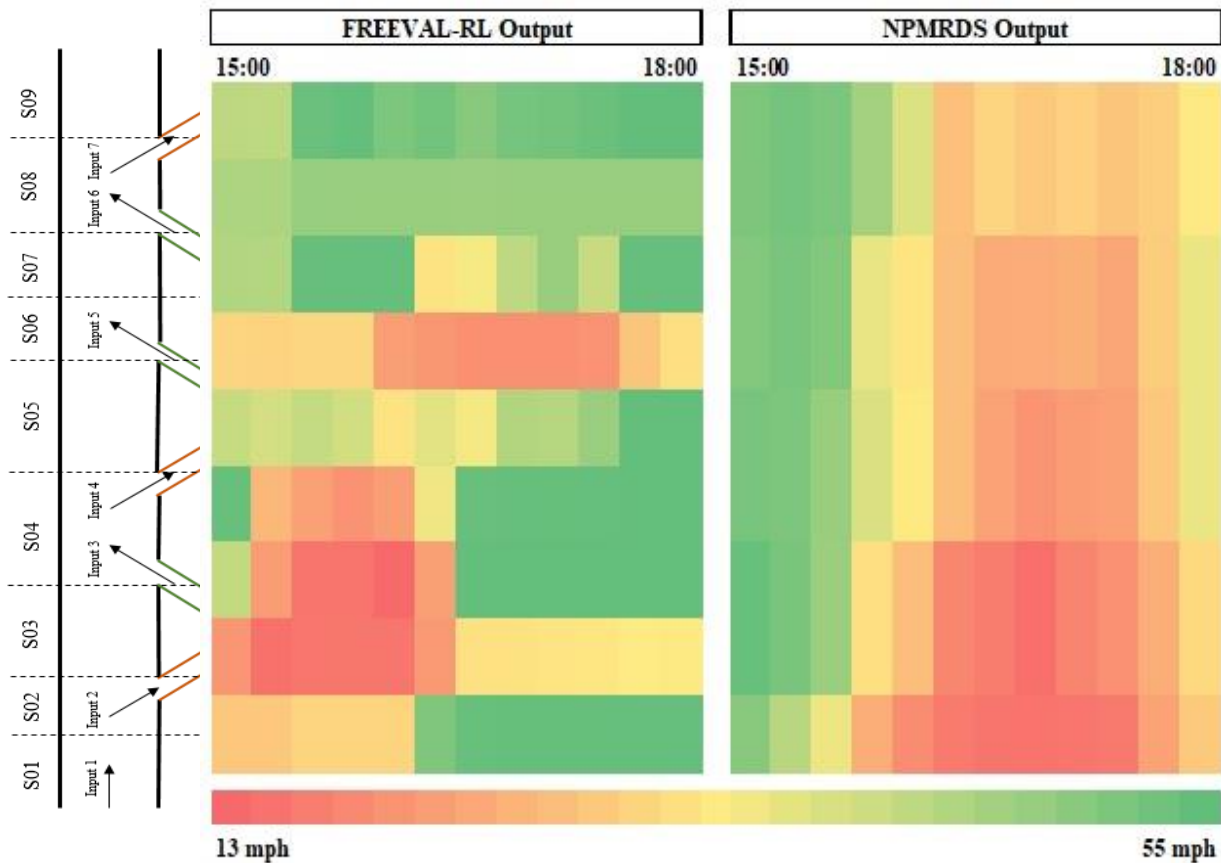


**Figure 7-7: Speed Heatmap for 11.94-mile Study Corridor.**

A speed heatmap for each weekday was generated and presented in Figure 7-8. The weekday speed heatmaps in Figure 7-8 illustrate similar patterns as Figure 7-7 for the whole month of June 2014. This observation clearly indicates the existence of a downstream bottleneck which affected the study corridor. In Figure 7-9, a speed heatmap using the FREEVAL-RL speed output was generated and placed side by side with the NPMRDS speed output. The left side is the FREEVAL-RL output and the right side is the NPMRDS output.



**Figure 7-8: Speed Heatmap for Each Weekday on 11.94-mile Corridor.**



**Figure 7-9: Comparison between FREEVAL-RL output and NPMRDS data.**

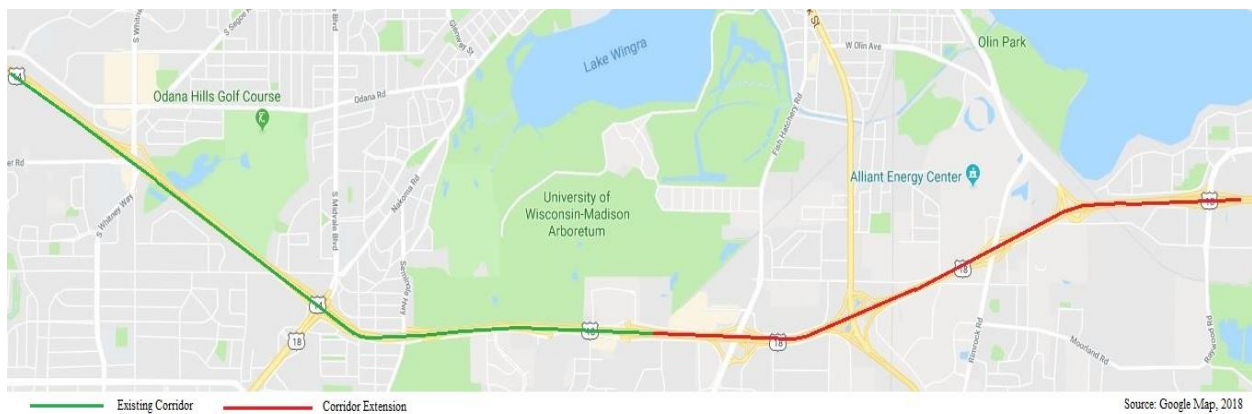
The existence of a bottleneck can lead to a capacity drop on a corridor. Bertini and Horowitz investigated the effect of a freeway bottleneck in Portland, Oregon (25). The authors found capacity can drop up to 8% due to a recurrent bottleneck whereas capacity can drop up to 20% due to a non-recurrent bottleneck. However, the capacity drop is not the only traffic phenomenon attributed to the downstream bottleneck. There is no established methodology available to incorporate the effect of downstream bottleneck into the HCM reliability methodology. Due to the constraint of not being able to incorporate the effect of a downstream bottleneck into the reliability methodology in L08, the FREEVAL-RL tool may not provide reliable and accurate performance measure estimates in the presence of a downstream bottleneck.

The FREEVAL-RL is a corridor-level tool which can analyze multiple homogeneous segments together. But this tool cannot identify downstream bottleneck or rapid changes in roadway geometry outside the study corridor. This bottleneck investigation also illustrates how the L02 tool contributes to a corridor analysis. A prior investigation of the extended corridor using L02 tool can provide additional information about traffic pattern and existence of downstream bottleneck. Wisconsin does not have a professional software tool to produce bottleneck heatmaps; however the heatmaps can be manually produced with other commercial software such as MS Excel when

data are available. Such investigation allows the user to identify the effect of upstream or downstream bottlenecks on a study corridor and take appropriate measures to minimize the impact. Based on the speed profile comparison, it was decided to extend the corridor to incorporate the downstream bottleneck location with the assumption that the extended corridor may provide reliable performance measures from the FREEVAL-RL tool.

### 7.4 Study Corridor Extension

The study corridor was extended to incorporate the location of the downstream bottleneck. The extended study corridor is 7.4 miles long, starting at Forward Dr. and ending at the South Town Rd entrance on US 12/14. Now, there are 21 segments, including 10 basic segments, 2 on-ramp segments, 2 off-ramp segments and 7 weaving segments. The weaving segment intensity is high along the extended study corridor as the study corridor is located in an urban area and the spacing between the consecutive on-ramp and off-ramp segments is relatively small. A map of the extended study corridor is presented again here in Figure 7-10.



**Figure 7-10: Extended Study Site for L08 FREEVAL-RL Tool.**

A “before-after” comparison was conducted for the study corridor to evaluate the effectiveness of the capacity improvement. The changes in geometry due to construction are provided in Table 11.

**Table 7-11 Changes in Roadway Geometry on Extended Study Corridor.**

Segment	Segment Label	Before Period			After Period		
		Type	Length (ft)	No. of Lanes	Type	Length (ft)	No. of Lanes
1	S01	Basic	1700	2	Basic	1700	2
2	S02	Off Ramp	1500	2	Off Ramp	1500	2
3	S03	Basic	2900	2	Basic	2900	3
4	S04	Weaving	3400	3	Weaving	3400	4
5	S05	Basic	2500	2	Basic	2500	3
6	S06	On Ramp	1500	3	On Ramp	1500	4

7	S07	Basic	1150	3	Basic	1150	4
8	S08	Weaving	2000	4	Weaving	2000	4
9	S09	Basic	4450	3	Basic	4450	3
10	S10	Weaving	1500	4	Weaving	1500	4
11	S11	Off-Ramp	850	4	Off-Ram	850	4
12	S12	Basic	1270	3	Basic	1270	3
13	S13	Weaving	1300	4	Weaving	1300	4
14	S14	Basic	700	3	Basic	700	3
15	S15	On Ramp	1500	4	On Ramp	1500	4
16	S16	Weaving	2200	4	Weaving	2200	4
17	S17	Basic	1500	3	Basic	1500	3
18	S18	Weaving	2100	4	Weaving	2100	4
19	S19	Basic	800	3	Basic	800	3
20	S20	Weaving	1900	4	Weaving	1900	4
21	S21	Basic	2300	3	Basic	2300	3

To evaluate the extended study corridor, required data items were collected and processed for the extended portion of the study corridor and combined with the data from the previously selected study corridor. To collect real-time traffic demand data on the corridor extension, the traffic detector database was investigated. Unfortunately, traffic detectors are only available on a few ramp segments on the extended section. To compensate for the missing demand, the Wisconsin hourly traffic count portal was used. Since traffic demand data is available on an hourly basis on the hourly traffic data portal, the same traffic demand values were used for all four 15-minute time slices within the same hour. Similar to crash data collection for the previous study segments, the crash data for the extended section were collected from the Safety table in Meta-Manager and the average annual crash rate for the extended corridor was estimated using Equation 1.

The extended study corridor was evaluated in the FREEVAL-RL tool using site-specific input values. In the previous investigation, multiple scenarios were generated to obtain FREEVAL-RL outputs that were similar to field conditions. For the extended corridor, it was assumed that CAF or SAF will not be required as the downstream bottleneck location was already incorporated in the study corridor. Thus, only three scenarios were proposed using the different demand multiplier and crash rates as shown in Table 12. The national default crash rate provided in the FREEVAL-RL FSG was used along with the site-specific crash rate as the site-specific value is comparatively smaller.

**Table 7-12 FREEVAL-RL Scenarios for Extended Study Site.**

Scenario	Demand Multiplier	Crash Rate (Per MVMT)
Scenario 1	State-specific <sup>a</sup>	104.7 <sup>c</sup>
Scenario 2	State-specific <sup>a</sup>	153.8 <sup>d</sup>
Scenario 3	Site-specific <sup>b</sup>	104.7 <sup>c</sup>

a: Provided by WisDOT (Figure 7-4); b: Calculated from the field data (Figure 7-5); c: Site-specific crash rate estimated using Equation 2; d: National default crash rate provided in FREEVAL-RL

The FREEVAL-RL outputs for the generated scenarios are provided in Table 13. A value of 0.01 percent was used for the threshold for the base scenario probability in the FREEVAL-RL scenario generation. This threshold probability covers 99.64 percent of the distribution of events that occurred on the study corridor.

**Table 7-13 FREEVAL-RL Output in the "Before" period for Extended Study Corridor.**

Particular	Scenario 1	Scenario 2	Scenario 3	NPMRDS
Mean TTI	1.35	1.44	1.5	1.38
50th Percentile	1.14	1.15	1.18	1.15
80th Percentile	1.18	1.23	1.58	2.75
95th Percentile	1.79	2.32	2.2	5.00
Semi-Standard Deviation	50.6	45.39	60.76	17.77
Misery Index	4.74	6.09	5.05	6.87
Total Vehicle Hour Delay	261,678	343,571	561,164	x

x: Estimate not available

Note: The FREEVAL-RL tool was run with a total of 660 scenarios: Number of Demand scenarios: 8; Number of Demand and Incident scenarios: 384; Number of Demand and Weather scenarios: 82; Number of Demand, Incident and Weather Scenarios: 186.

The results provided in Table 13 show that the FREEVAL-RL estimated mean TTI for the three scenarios range between 1.35 and 1.5 whereas the estimated TTI using NPMRDS data was 1.38. The 50<sup>th</sup> percentile TTI or median TTI from all scenarios were almost the same as 50<sup>th</sup> percentile TTI estimated using NPMRDS. The estimated FREEVAL-RL TTI values were drastically different for the 60<sup>th</sup> percentile and above. The estimated 95<sup>th</sup> percentile TTI values range between 1.79 to 2.32 whereas the 95<sup>th</sup> percentile TTI value for field condition is 5. The semi-standard deviation and misery index indicate that the travel time estimates for the worse trips that occurred on the study corridor were different. One possible reason may be due to the tool constraint of using a maximum value of 10 percent capacity drop whereas the field data suggested that the capacity drop on this corridor is more than 20 percent during the afternoon peak hour period. A smaller capacity drop means faster queue dissipation and a shorter duration of the congested period. The limitation on the capacity drop input value should be removed in the revised version of FREEVAL-RL tool to mimic the actual travel conditions.

## 7.5 Before-After Study

A “before-after” analysis was conducted to quantify the improvement in travel time reliability due to the corridor capacity improvement. In Table 7-14, the reliability and congestion outputs from the FREEVAL-RL tool and the NPMRDS data were respectively calculated. For consistency, the

NPMRDS data for the “after period” were collected from January to September 2017. The state-specific demand multiplier with default crash rate of 153.8 per MVMT was used for both before and after conditions, without considering the change of travel demand.

Initially, the site-specific crash rate of 104.7 per MVMT was considered but according to Table 7-13, the NPMRDS value is much higher in the end tail of TTI distribution (80<sup>th</sup> percentile or more) than the FREEVAL-RL outputs. Thus, the national default crash rate of 153.8 per MVMT was used to increase the TTI on the high end of its distribution from FREEVAL-RL. It is worth noting that a) the crash rate was kept same in both before and after condition to make the comparison informative; and b) demand was kept same in both before and after conditions. However, the NPMRDS performance measures reflect the change in both travel demand and delays before and after the capacity improvement.

**Table 7-14 Before-After Study Using FREEVAL-RL and NPMRDS.**

Particular	FREEVAL-RL		NPMRDS	
	Before	After	Before	After
Mean TTI	1.44	1.46	1.38	1.36
50th Percentile	1.15	1.14	1.15	1.25
80th Percentile	1.23	1.22	2.75	2.5
95th Percentile	2.32	2.49	5	3.92
Semi-Standard Deviation	45.39	47.98	17.77	16.82
Misery Index	6.09	6.39	6.87	6.11
Reliability Rating	62.36%	85.06%	52.62%	52.12%
Percent VMT at TTI>2	6.58%	6.08%	x	x
% Time with Queue	58.60%	31.44%	x	x
Total Vehicle Hour Delay	343,571	340,189	x	x

x: Estimates not available

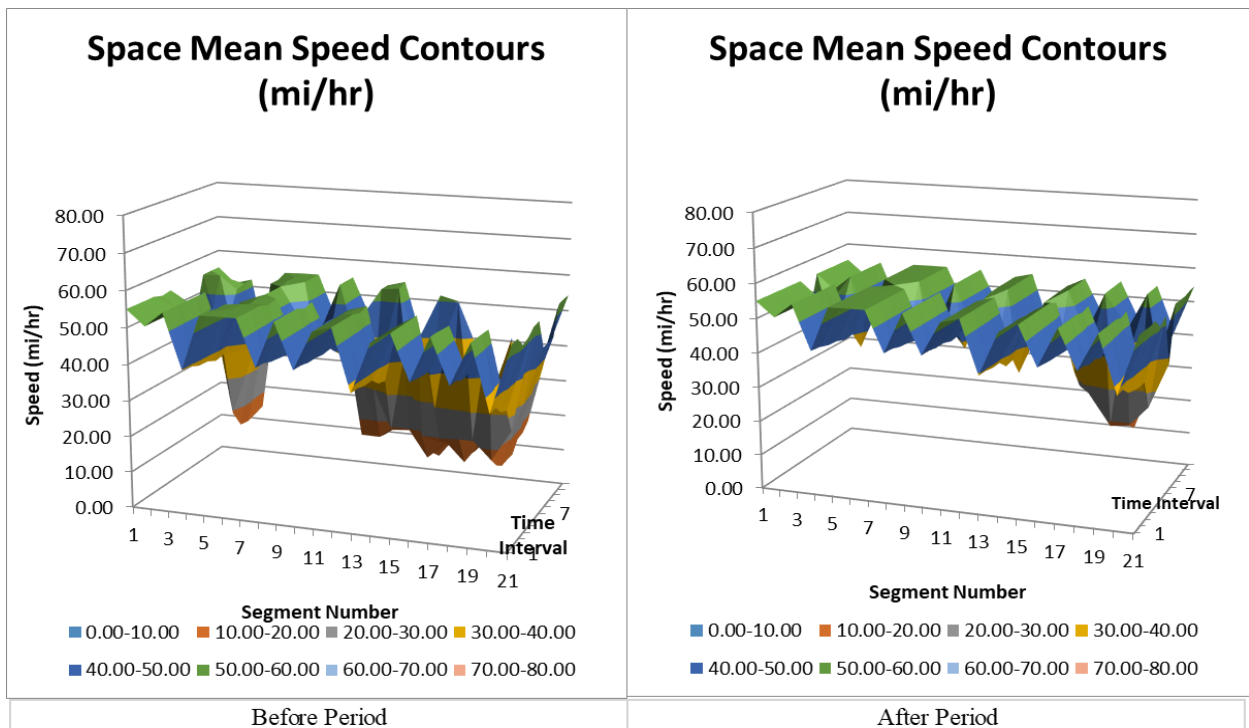
Note: The FREEVAL-RL tool was run with a total of 832 scenarios: Number of Demand scenarios: 8; Number of Demand and Incident scenarios: 384; Number of Demand and Weather scenarios: 80; Number of Demand, Incident and Weather Scenarios: 360.

In Table 7-14, it can be noted that the FREEVAL-RL TTI estimates of different percentiles for both before and after conditions are similar. In the after condition, all percentile performance measures are slightly lower than the before condition except for 95<sup>th</sup> percentile. The 95<sup>th</sup> percentile or higher TTI estimates from FREEVAL-RL suggests that the travel condition gets slightly worse for trips experiencing extremely long travel time after the improvement. Nevertheless, other performance measures such as reliability rating, percent VMT at TTI>2, % Time with Queue and Total Vehicle Hour Delay all show a positive improvement in travel time reliability

In Table 7-14, NPMRDS data also show positive improvement in all performance measures except for 50<sup>th</sup> percentile, suggesting trips between 50<sup>th</sup> percentile and 80<sup>th</sup> percentile may experience longer travel time in the after condition. However, for trips experiencing longer delay (e.g., 95<sup>th</sup>

percentile), the improvement is substantial. Again, the performance measures estimated using the NPMRDS data incorporates change in site-specific travel pattern, demand, crash, and incident information. Thus, the comparison between FREEVAL-RL with NPMRDS may not be reliable but shed the light on the size of the differences as well as the overall effectiveness of the corridor capacity improvements on travel time reliability.

To illustrate a different before-after comparison from FREEVAL-RL outputs, a speed contour from FREEVAL-RL was plotted. Figure 7-11 shows that the speed profile is improved due to the capacity improvement in the after condition.



**Figure 7-11: A Comparison of Space Mean Speed for Before and After Conditions.**

# CHAPTER 8 TESTING AND RESULTS OF SHRP 2 C11 PRODUCT

## 8.1 Introduction

The C11 Reliability module was applied to three corridors to assess output results across different facility types and traffic conditions. For each evaluation, it was of interest to compare results to observed conditions from other data sources (e.g. NPMRDS), as well as assess the impacts theoretical improved conditions would have on existing congestion. The tool interface, as shown in Figure 8-1, was used to perform the C11 evaluations. Key inputs for the analyses included:

- Forecast year (time horizon)
- Analysis period
- Highway type
- Segment length
- Number of lanes
- Free-flow speed
- Annual average daily traffic (AADT)
- Annual growth rate
- Truck percentage
- Segment capacity
- Segment terrain

Much of the information was readily available through Google Earth or provided by WisDOT.

Figure 8-1: C11 Graphical User Interface.

## 8.2 Analysis and Discussion

### 8.2.1 I-41 Corridor

The first analysis corridor was I-41, near Appleton, Wisconsin, as illustrated in Table 8-1. **Error! Reference source not found.** C11 evaluations were performed for an existing and forecast year (20-year horizon), and the existing four-lane facility and an improved six-lane facility. Roadway geometrics and traffic volumes were collected for the analysis segments, and default segment capacities were determined based on methodologies in the C11 guidance. The C11 results for this corridor are shown in Table 8-1.

**Table 8-1 I-41 Travel Time / Delay Summary.**

		C11 - Delay Output		
	Year	4-lane VHD	6-lane VHD	Reduction
<b>Total Hours</b>	<b>2016</b>	7,583	0	<b>7,583</b>
	<b>2035</b>	13,960	578	<b>13,382</b>
<b>Nonrecurring Hours</b>	<b>2016</b>	77	0	<b>77</b>
	<b>2035</b>	141	0	<b>141</b>
<b>Nonrecurring Proportion</b>	<b>2016</b>	1.0%	-	<b>1.0%</b>
	<b>2035</b>	1.0%	0.0%	<b>1.1%</b>

In addition to the C11 test, an analysis was also performed using WisDOT’s travel time analysis tool which estimates a reduction in vehicles hours of travel under recurring and non-recurring conditions. The WisDOT travel time analysis was performed for the same corridor so that it could be used as a reasonableness check of the C11 outputs, particularly nonrecurring congestion. The WisDOT travel time tool produced a reduction in travel time that was 24 times greater for 2016 and 53 times greater for 2035, than the C11 reduction in delay, for the same improvements.

There were several differences between the two toolsets that likely accounted for large discrepancies in the results. Functionalities that are unique to the WisDOT travel time tool include: direct inclusion of nonrecurring events, assessment of travel time (rather than delay), region-specific demand and capacity parameters, and several other factors. Thus, it was not expected for the C11 methods, which were intended for high-level planning assessments, to capture all user delay associated with real-life travel conditions. However, the order of magnitude between the delay and travel time reductions were significantly different when they should theoretically be similar based on the methodologies describing the C11 delay estimates.

The C11 results for travel time index (TTI) are shown in Table 8-2. These results were compared to year 2016 NPMRDS travel time data to assess the C11 travel time distribution with respect to sensor data. Travel time index measures were extracted using the NPMRDS Analytics toolset for a similar analysis period used in the C11 evaluation (i.e. 6 am to 7 pm). Outcomes from the annual sensor data assessment displayed an average travel time index of 1.08 and a 95th percentile TTI

of 1.19, compared to the C11 values of approximately 1.00 and 1.06 for the existing conditions scenario, respectively. This result further suggests that the C11 Reliability tool is underestimating travel time delay. If the tool is to be intended for reasonably estimating recurring and nonrecurring travel time delays, calibration factors would be beneficial for enhancing the accuracy of results.

**Table 8-2 I-41 Travel Time Index Summary.**

		C11		
	Year	4-Lane	6-Lane	Reduction
TTI - 50th	2016	1.00	1.00	0.00
	2035	1.00	1.00	0.00
TTI - 80th	2016	1.01	1.00	0.01
	2035	1.02	1.00	0.02
TTI - 95th	2016	1.06	1.00	0.05
	2035	1.08	1.01	0.07

### 8.2.2 I-39/90 Corridor

The second corridor evaluated was I-39/90, with analysis extents spanning the 45-mile portion from the southern Wisconsin state line to the city of Madison. The I-39/90 corridor can be characterized as a rural freeway facility that experiences relatively high volumes of recreational traffic, as compared to urban freeway traffic trends observed on the previously tested I-41. It was of interest to observe how reasonably the C11 Reliability module would estimate delay and possibly identify sources of error or areas for tool enhancement for such an analysis. Similar evaluations to I-41 were performed for I-39/90 – existing and improved conditions for an existing year and forecast year.

Initial results using default segment capacities yielded significantly low delay values produced by C11 relative to the travel time reduction magnitudes output from the WisDOT travel time tool. It was observed that base capacity values applied in the WisDOT travel time tool were lower than the default values used in the C11 analysis. Thus, the link capacities in C11 were modified to mirror those assumed in the WisDOT travel time tool to better reflect local conditions and to provide a more consistent comparison. Results of the C11 assessment are shown in Table 8-3.

**Table 8-3 I-39/90 Travel Time / Delay Summary.**

		C11 - Delay Output		
	Year	4-lane VHD	6-lane VHD	Reduction
Total Hours	2016	218,147	3,077	215,070
	2035	784,204	37,794	746,410
Nonrecurring Hours	2016	8,013	6	8,006

	<b>2035</b>	25,846	39	<b>25,807</b>
<b>Nonrecurring Proportion</b>	<b>2016</b>	3.7%	0.2%	<b>3.7%</b>
	<b>2035</b>	3.3%	0.1%	<b>3.5%</b>

Even with the capacity adjustments, the C11 delay reduction was roughly five times and nine times lower than the travel time reduction from the WisDOT tool for years 2016 and 2035, respectively. An additional finding worth noting is in regards to the nonrecurring congestion proportion, particularly in the improved alternative. The C11 nonrecurring delay values drop well below one percent of total delay. These values, along with the delay magnitudes of six and 39 hours for years 2016 and 2035, respectively, seem low considering nonrecurring events are likely to be prevalent over a year-long analysis period.

**Table 8-4 I-39/90 Travel Time Index Summary.**

	<b>Year</b>	<b>C11</b>		
		<b>4-Lane</b>	<b>6-Lane</b>	<b>Reduction</b>
<b>TTI - 50th</b>	<b>2016</b>	1.02	1.00	0.02
	<b>2035</b>	1.07	1.00	0.07
<b>TTI - 80th</b>	<b>2016</b>	1.05	1.00	0.05
	<b>2035</b>	1.16	1.01	0.16
<b>TTI - 95th</b>	<b>2016</b>	1.15	1.00	0.15
	<b>2035</b>	1.37	1.03	0.34

Annual corridor travel times were also evaluated using NPMRDS Analytics for comparison purposes with the C11 values shown in Table 8-4. The observed average TTI was 1.09, which lies above both the 50th and 80th percentiles output for the four-lane facility from C11. Interestingly, the 95th percentile travel time index collected from the sensor data was 1.16, which was near the C11-generated value. In this case, the C11 Reliability module appeared to underestimate vehicle delay during normal or slightly congested conditions but did a decent job of estimating travel times under relatively more severe congestion. However, since the C11 tool counts delay as travel times above the free-flow travel time but below the 80th percentile (for conservativeness), the calculated delay values are likely to be underestimated considering the empirical 80th percentile TTI is greater than the free-flow TTI by nearly double of what C11 is estimating (1.09 compared to 1.05).

An additional source for potential discrepancies between travel time estimates from the C11 tool and the NPMRDS data is recreational traffic. Vehicle volumes during recreational peaks are known to be higher than typical commuter peak volumes on several portions of I-39/90. Using AADTs and the C11 tool's fixed daily volume profiles, traffic conditions associated with the

higher recreational volumes are unable to be captured using the conventional C11 analysis methodologies. Flexibility in altering the volume profiles could remediate this volume gap.

### 8.2.3 US-14 Corridor

The third and final corridor for reliability testing was US 14 from Cross Plains to Middleton. This corridor is a rural two-lane facility that primarily serves commuter traffic going to and from Madison. In addition to freeway facilities, it was of interest to assess how recurring and nonrecurring delay magnitudes for rural undivided facilities compared between the C11 Reliability tool and other analysis methods.

Evaluations were initially performed using both the C11 tool and the WisDOT travel time tool. Similar to the previous tests, scenarios were analyzed for existing and forecast years, and for existing and an improved four-lane divided conditions. For comparison, capacity values assumed in the WisDOT tool were used in the C11 assessment to reflect local traffic characteristics. Table 8-5 summarizes the recurring and nonrecurring delay outputs from the C11 test.

**Table 8-5 US 14 Travel Time / Delay Summary.**

		C11 - Delay Output		
	Year	2-Lane VHD	4-lane VHD	Reduction
<b>Total Hours</b>	<b>2016</b>	5,919	0	<b>5,919</b>
	<b>2035</b>	16,131	178	<b>15,953</b>
<b>Nonrecurring Hours</b>	<b>2016</b>	77	0	<b>77</b>
	<b>2035</b>	205	0	<b>205</b>
<b>Nonrecurring Proportion</b>	<b>2016</b>	1.3%	-	<b>1.3%</b>
	<b>2035</b>	1.3%	0.0%	<b>1.3%</b>

A notable characteristic of the C11 results is the small magnitude of total delay. The delay reduction between alternatives corresponded to about six to twelve percent of the travel time reduction produced from the WisDOT tool. Additionally, the nonrecurring congestion proportion is very low, which is a common theme amongst the three analyses. A possible cause for the C11 methodologies underestimating the existing facility delay is the combining of demand and capacity for both travel directions to determine facility saturation (note this is only the case for two-lane highways). If there are heavy directional flows, this could result in lower demand-to-capacity ratios in peak directions than what exists in real-life conditions. Relatively uncongested travel times from the C11 test are also depicted by assessing the travel time index measures, as shown in Table 8-6.

**Table 8-6 US 14 Travel Time Index Summary.**

		C11		
	Year	2-Lane	4-Lane	Reduction
<b>TTI - 50th</b>	<b>2016</b>	1.00	1.00	0.00

	<b>2035</b>	1.01	1.00	0.01
<b>TTI - 80th</b>	<b>2016</b>	1.01	1.00	0.01
	<b>2035</b>	1.03	1.00	0.03
<b>TTI - 95th</b>	<b>2016</b>	1.05	1.00	0.05
	<b>2035</b>	1.10	1.01	0.10

An attempt was made to collect NPMRDS Analytics performance measures for this corridor. However, the extents of the analysis segments within the tool covered additional signalized intersections adjacent to the study corridor. This resulted in TTI measures that were significantly higher than the outputs from C11 and the WisDOT travel time tool; thus, they were disregarded as an appropriate comparison measure.

## **CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS**

This section provides a summary of the findings based on the evaluation results of the products. Some tool limitations are described and recommendations are proposed.

### **9.1 L02 Guide to Establishing Monitoring Programs for Travel Time Reliability**

WisDOT is very well situated for further implementation of the L02 product. The test confirmed that all the necessary data types are available – both from traffic sensors and other systems and including travel times, incidents, work zones, etc. – and are generally ubiquitous on the interstate, though of decreasing availability on lower volume segments.

The pilot effort as part of this project was for proof of concept and inherently manual or relied on web interfaces, but a great deal of automation should be achievable. In several cases, data are able to be extracted from databases in automated ways, e.g., SQL queries against the WisTransPortal database for incidents (TIA) and lane closures (WisLCS). Unfortunately, collection of certain other data types is going to remain mostly manual, e.g., special events weather.

The project also demonstrated the process taken for cleaning and conflating the data sources, computing the PDF and CDF plots, which is also automated to a large extent by using standards-based scripts in commonly available computational platforms. Each of the two pilot segment evaluations led to a report of results, and the recommendation for this is to generate web-based report results.

In summary, the concept for further implementation and automation of the L02 TTRMS would allow a user to request the PDF/CDF output from a given road segment over a given date range.

### **9.2 L05 Handbook for Incorporating Reliability Performance Measures into Transportation Planning and Programming**

Reliability has been incorporated into Wisconsin's Traffic Management Center Standard Operating Procedures. Testing SHRP 2 RDAT products with WisDOT sites allows for demonstration of Reliability applications on projects and treatments familiar to staff involved in the planning, programming and evaluation of financial investments. These measures and their results contribute to new tool applications in comparative performance results and established documentation of agency policies.

A Fact Sheet developed by our project team provides an overview of the RDAT products and how they have been applied. It is intended for staff exploring opportunities to incorporate reliability into the planning or evaluation process. Adding the application to more processes including program support and justification has been recognized and is increasing by program managers

### 9.3 L07 Reliability by Design

The FST service was explored as an improvement treatment in the L07 excel-based analysis tool. The treatment was treated as “Custom Incident Treatment” considering that the FST service only affects the duration of an incident. The key findings of the L07 tool output can be summarized as below:

- The tool provides operational and safety benefits separately along with travel time reliability performance measures.
- The benefit output from the tool with long-term work zone information is unreasonably high. Sensitivity analysis needs to be conducted to evaluate the effect of input variables in estimating operational and safety benefits.
- The reliability benefit output obtained from the test run is low compared to the delay benefit. An in-depth exploration of tool methodology needs to be conducted to identify the key contributors of reliability benefits.
- The L07 reliability outputs need to be compared with existing conditions to evaluate the tool accuracy. The Columbia and Brown County test sites are located on Interstates included in Wisconsin statewide performance measures. Historic performance data is available for further evaluation of these corridors.
- The analysis of FST by the L07 product complements another product, FHWA’s Traffic Incident Management Benefit-Cost Tool, for estimating benefits of freeway service patrols. Data inputs are similar to L07 treatment inputs but allow for detailed service patrol information to estimate program costs. The program’s output includes reduction of vehicle hours for trucks and passenger cars, fuel consumption of passenger cars and secondary incidents.

Some limitations of the L07 tool have been identified through the testing. Some seem to be an easy fix, most likely script bugs in the spreadsheet tool, but others are more of methodological issues.

- The reliability outputs from “Results” tab cannot be exported from the tool for further exploration.
- The tool cannot run if there are zero crashes on a segment.
- The tool inputs cannot be saved until the cursor from the input cell is removed.
- The total “Demand Flow Rate” in the Demand tab is a fixed value of “159,690”. Although this value does not change with changing demand input, this information does not seem to affect the tool’s analysis process.
- The safety benefit estimated values are switched between PDO and Fatal Crash types in “Benefit due to treatment effect” in the Treatment tab.
- The “Benefit-Cost Ratio” value cannot be estimated with Custom treatments.

## 9.4 L08 Incorporation of Travel Time Reliability into the Highway Capacity Manual

In this study, we tested the FREEVAL-RL tool by evaluating the HCM-based travel time reliability methodologies and performance measures for a freeway corridor. The key findings of the exploration of FREEVAL-RL can be summarized as below:

- The tool has a user-friendly interface. The input values are easy to understand. However, this tool requires a significant amount of data to properly execute compared to the other SHRP 2 reliability tools. The manual entry of a large number of data items is also very time-consuming.
- The testing of the FREEVAL-RL tool indicates that the tool can provide reasonable reliability output using the tool's default values, but the output may not resemble field conditions.
- The detailed evaluation of FREEVAL-RL with site-specific input values suggests that the tool may not provide reliable output in the presence of a downstream bottleneck.
- Apart from the effects of downstream bottleneck, the results with multiple scenarios indicate that the tool over-estimates the reliability measures in the lower portion (until 80<sup>th</sup> percentile) of the TTI distribution and under-estimates in the upper portion (over 80<sup>th</sup> percentile) of the TTI distribution. The disparities can also be observed from the estimated misery index and semi-standard deviation.
- The detailed evaluation of FREEVAL-RL with the extended corridor indicates that the tool is able to estimate mean and/or median TTI values similar to field conditions. But FREEVAL-RL underestimates travel time in the congested traffic condition. The limitation of capacity drop may play a significant role in estimating travel times for trips with excessive delay in the corridor.
- The reliability outputs are very sensitive to CAF values compared with SAF and with standard deviation of incident duration. Caution should be exercised while using any CAF value different from 1.

Based on the key findings and other relevant observations, we summarized the strengths and limitations of the L08 tool.

### 9.4.1 Tool Strengths

FREEVAL-RL provide some distinctive benefits by enhancing the FREEVAL model (8; 15). The strengths of this tool are listed below:

#### *User-friendly Interface*

The tool has a user-friendly interface. The worksheets in the tool are sequentially linked and highlight the required input values that need to be entered.

### *Incorporation of SAF*

The tool allows the user to calibrate the FREEVAL model using SAF. In HCM2010, the effects of weather and incidents on freeway facilities are modeled through a CAF. It is noted in literature that weather and incidents also affect the free-flow speed (8). Therefore, the FREEVAL-RL enhanced the HCM methodology by incorporating SAF to adjust speed to calibrate non-recurrent congestion scenarios.

### *National Defaults for CAF and SAF for Incident*

The FHWA research team for the L08 project incorporated national default values for CAF and SAF for incident and weather events on freeways in the HCM reliability analysis methodology through extensive literature review. The outputs from detailed analysis with Wisconsin data showed that the national default values can replicate weather or incident events with lower severities and provide reasonable reliability outputs.

### *Incorporation of Capacity Drop*

The FREEVAL-RL incorporates the capacity drop phenomenon which is not included in HCM 2010 (15). Past research has demonstrated that the incorporation of the capacity drop phenomenon in freeway analysis will result in nontrivial impacts on performance measures such as queue lengths, queue formation and dissipation times, speed and travel time, and facility levels of service (8).

## **9.4.2 Tool Limitations**

Some limitations of FREEVAL-RL were found based on the experiment with the Wisconsin data. The limitations of this tool and suggestions on the future improvements are listed below.

### *Visualization of the Highway Network*

FREEVAL-RL does not have a graphical interface. It is easy to make mistakes when entering network geometries for a large network, such as sequence of segment type, segment length, etc. A simple solution is to develop a computer-aided design (CAD) interface to assist with data entry.

### *Input Limitation in Creating Seed File*

- The amount of time to enter the data for creating seed files depends on the number of segments and length of the study period. The demand data need to be manually entered for each segment and for each 15-minute period. This process is time-consuming and it is easy to make mistakes.
- The user must define at least 3 segments when creating the seed file. While the number of segments in FREEVAL-RL starts with 1, the tool does not show any error message until the final step if the user defines fewer than 3 segments in a seed file.
- The ramp meter control must be specified to allow the tool to run properly. If the user forgets to specify the ramp meter control in the seed file management startup page, the tool does not warn the user until the final step of the seed file management.

- FREEVAL-RL allows the user to define a mainline segment with up to six lanes in one direction. Wisconsin has very few sites that would require additional mainline segments; however other users may find this restricting.
- FREEVAL-RL does not allow the user to use a capacity drop of more than 10 percent.

These restrictions in tool inputs should be highlighted in the user manual. Validating input cells with pre-defined values or providing warning information during data input can help the user to avoid some of the data entry errors. Copying and pasting roadway geometry and demand values or allowing the user to import from other tables into FREEVAL-RL will significantly reduce the required time to run the tool and increase data entry accuracy.

#### *Changes in Seed File*

The seed file cannot be changed once it is created with the required input information. The following limitations can occur due to inability to change the seed file:

- Once the seed file is generated with the defined study period, the timeline cannot be changed.
- The number of segments cannot be changed.

The user should be allowed to revise the seed file based on application requirements, such as adding flexibility to change seed file once it is created. Allowance need to be provided to extend study corridor and/ or time period. This improvement may help to test alternative scenarios.

#### *Weaving Segment*

When running a seed file, a dialogue box called the “Weaving Volume Calculator” appears for the defined weaving segments. The user can either manually define site-specific parameters to adjust the weaving volume or use the FREEVAL-RL tool provided default values. If the user decides to use site-specific values, the input information cannot be saved for the future use. This means the user needs to define the parameters every time when re-running the seed file. This procedure is very time-consuming and inefficient. The tool needs to be modified to enable the user to save and modify the weaving segment input values.

#### *Result Limitation*

There are two ways to generate a result file in FREEVAL-RL. The first is to run a seed file. The second is to run generated scenarios from FSG. The results generated after running the seed file are not accurate. The result file does not change with different input data. This might be a bug in the computer codes. The results generated from running the seed file need to be fixed in the future version. This may allow for easier calibration of the base scenario.

The L08 report and/or the FREEVAL-RL user manual do not provide examples of how to model a network in the tool. It would be useful to document a few examples of model networks to provide users with a better understanding about coding a network in the tool. Neither the L08 report nor the user manual have any discussion on the development of different scenarios in FSG. A discussion on scenario development is needed for tool implementation and calibration. Each scenario generated from FSG takes around 40 seconds to run in FREEVAL-RL tool. A discussion on sensitivity of the base probability threshold value and number of generated scenarios is needed for tool execution timeline planning and understanding the accuracy of tool output with different number of scenarios. Lastly, a guide on how to calibrate FREEVAL-RL to the field observations will be helpful.

### **9.5 C11 Development of Tools for Assessing Wider Economic Benefits of Transportation**

The C11 Reliability tool was tested on multiple corridors that have different functional characteristics (e.g. urban and rural). The C11 tool is intended to provide a high-level review for corridor reliability and can be used to test corridor sensitivity to capacity, volume, and crashes. Key findings from preliminary testing of the C11 tool are as follows:

- Minimal inputs are required for the C11 reliability tool. The most difficult input to obtain data was for incident duration, and any potential reduction under a build scenario. L02 monitoring could be used to increase the accuracy of the assumptions used as inputs for C11.
- The C11 tool delay outputs were significantly lower than expected. C11 results were compared to other tools developed by WisDOT to quantify nonrecurring effects. In most cases the delay results from C11 were lower by multiple orders of magnitude, and nonrecurring delay hours were minimal.
- If the computation methodology and underlying assumptions could be adjusted, a higher level of accuracy could be obtained.

In summary, through this IAP, WisDOT has demonstrated reliability applications on projects and treatments that are familiar to WisDOT staff who are involved in the planning, programming and evaluation of financial investments. The high degree of relevance and familiarity promotes active participation and dialogues among users and researchers. A better understanding of the data needs, strengths and limitations of the L38 bundle has been gained; and consensus regarding the future application and implementation of the L38 bundle has been effectively communicated.

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