FINAL REPORT

to

THE FLORIDA DEPARTMENT OF TRANSPORTATION
SYSTEMS PLANNING OFFICE

on Project

Multimodal and Corridor Applications of Travel Time Reliability

FDOT Contract BDK77 977-10

TRANSPORTATION RESEARCH CENTER
TRC
UNIVERSITY OF FLORIDA

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METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	Inches	25.4	Millimeters	mm
ft	Feet	0.305	Meters	m
yd	Yards	0.914	Meters	m
mi	Miles	1.61	Kilometers	km

METRIC (SI) UNITS TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	Millimeters	0.039	Inches	in
m	Meters	3.28	Feet	ft
m	Meters	1.09	Yards	yd
km	Kilometers	0.621	Miles	mi

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16. Abstract

Five previous Florida Department of Transportation (FDOT) research projects on travel time reliability (FDOT Contracts BD545-48, BD545-70, BD545-75, BDK77 977-02, and BDK77 931-04) developed tools for predicting travel time reliability for freeways, to assist in the project prioritization and selection process. However, there is also a need to use these tools for annual reporting to the Legislature. To accomplish this, the tools should be able to provide all performance measures related to travel time reliability that are of interest for these purposes. Furthermore, they need to provide travel time reliability measures for the arterial portion of the Strategic Intermodal System (SIS) and also consider reliability across all modes (including the auto, rail, transit, etc.) Therefore, this research project made improvements in the freeway travel time reliability method, developed a new arterial travel time reliability method, and proposed a framework for considering travel time reliability in a multimodal context.

Improvements in the freeway travel time method include the inclusion of two additional performance measures, the Travel Time Index (TTI) and the Planning Time Index (PTI) to estimate reliability. Also, an improved method for evaluating weather effects was developed and incorporated into the calculations.

Arterial travel time estimation models were developed using the simulation program CORSIM, considering a total of 1200 scenarios. A spreadsheet similar to that previously developed for freeway sections was developed to obtain travel time reliability measures along arterials, based on the results of the developed travel time estimation models.

Lastly, a conceptual framework for conducting multimodal travel time reliability analysis was developed considering single mode travel and multiple mode travel.

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EXECUTIVE SUMMARY

Traditionally, agencies have concentrated on mitigating recurring congestion by comparing demand and capacity during the peak periods and by removing those bottlenecks. However, congestion is often due to other sources, such as crashes, work zones, and adverse weather conditions. Therefore, new approaches and performance measures are needed to mitigate congestion considering those non-recurring events.

Travel time reliability has been proposed as a new concept that allows agencies to evaluate the performance of a facility beyond just the peak hour, and to consider operations over a longer period of time considering non-recurring events. Furthermore, the concept of travel time reliability has been widely recognized as one of, if not the, most important performance measures to evaluate highway traveler perceptions. Five previous Florida Department of Transportation (FDOT) research projects on travel time reliability (FDOT Contracts BD545-48, BD545-70, BD545-75, BDK77 977-02, and BDK77 931-04) developed and implemented tools for estimating travel time reliability for freeways. These can predict travel time reliability along the entire freeway portion of the Strategic Intermodal System (SIS) as a function of various changes in the system, such as incident removal times and work zone occurrences, as well as selected Intelligent Transportation Systems (ITS) programs and initiatives (such as the Road Rangers). However, there is also a need to use these tools developed for FDOT's project selection process for annual reporting to the Legislature. To accomplish this, the tools should be able to provide all performance measures related to travel time reliability that are of interest for these purposes. Furthermore, they need to provide travel time reliability measures for the arterial portion of the SIS and also consider reliability across all modes, including the auto, rail, transit, etc.

This research project made improvements in the freeway travel time reliability method, developed a new arterial travel time reliability method, and proposed a framework for considering travel time reliability in a multimodal context.

Improvements in the freeway travel time reliability method are the following:

1) The Travel Time Index (TTI) and the Planning Time Index (PTI) were incorporated into the method as two additional performance measures for reliability and variability.

2) The process for evaluating the impacts of weather on traffic operations was enhanced by considering three (instead of two) regions in Florida (represented by zipcodes in Tallahassee, Orlando, and Miami), and by analyzing weather data over five years (instead of only one year).
3) Travel time measures based on estimated and observed data were compared, focusing on sections with congested conditions. It was concluded that the estimated travel times are higher than the observed ones; however, there are some fundamental differences in the methods used to obtain the two sets of values. One of the most important differences is that the estimated values calculate the travel time over the entire section, while the observed values are based on spot speed measurements *extrapolated* to the entire section. Depending on the location of the detector, the conditions may or may not be representative of the entire section.

The arterial travel time estimation method was developed based on simulated data (using the CORSIM microsimulator). The following factors were used to develop the travel time estimation models: number of signals per mile, free-flow speed, demand, percent of turning movements, cycle length, *g/C* ratio, quality of progression, incident duration, and percent of lanes closed during an incident. These factors were selected because of their potential effect on travel time, and also because they are generally available to analysts in Florida. Two travel time estimation models were developed using results from a total of 1200 scenarios: one model for non-congested scenarios and one model for congested scenarios. A spreadsheet similar to that previously developed for freeway sections was developed to obtain travel time reliability measures along arterials, based on the results of the developed travel time estimation models.

Lastly, a conceptual framework for conducting multimodal travel time reliability analysis was proposed. For travel using a single mode, travel time and travel time reliability can be estimated separately for each mode. Comparisons can be made across modes as long as the travel time definitions are consistent across modes and the travel times are estimated in a consistent manner. For travel time using multiple modes, travel times and travel time reliability need to be estimated considering the entire trip including the interconnections between modes.

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1. INTRODUCTION

1.1. Background

The goal of the Strategic Intermodal System (SIS) is to provide a transportation system that efficiently serves Florida's citizens, businesses and visitors: a transportation system that helps Florida become a worldwide economic leader, enhances economic prosperity and competitiveness, enriches quality of life, and reflects responsible environmental stewardship. The SIS consists of transportation facilities and services of statewide and interregional significance, including both freeways and arterials. Traditionally, agencies have concentrated on mitigating recurring congestion by comparing demand and capacity during the peak periods and by removing those bottlenecks. However, congestion is often due to other sources, such as crashes, work zones, and adverse weather conditions. Therefore, new approaches and performance measures are needed to mitigate congestion considering those non-recurring events.

Travel time reliability has been proposed as a new concept that allows agencies to evaluate the performance of a facility beyond just the peak hour and to consider operations over a longer period of time considering non-recurring events. Furthermore, the concept of travel time reliability has been widely recognized as one of, if not the, most important performance measure to evaluate highway traveler perceptions. However, determining how to measure, quantify, predict, and report travel time reliability has proved to be elusive.

Five previous Florida Department of Transportation (FDOT) research projects on travel time reliability (FDOT Contracts BD545-48, BD545-70, BD545-75, BDK77 977-02, and BDK77 931-04) developed and implemented tools for estimating travel time reliability for freeways. These can predict travel time reliability along the entire freeway portion of the SIS as a function of various changes in the system, such as incident removal times, and work zone occurrences, as well as selected Intelligent Transportation Systems (ITS) programs and initiatives (such as the Road Rangers). However, there is also a need to use the tools developed in FDOT's project selection process for annual reporting to the Legislature. To accomplish this, the tools should be able to provide all performance measures related to travel time reliability that are of interest for these purposes. Furthermore, they need to provide travel time reliability measures for the arterial portion of the SIS and also consider reliability across all modes, including the auto, rail, transit, etc.

1.2. Objectives

The objectives of this research are: a) to identify the performance measures desired to be obtained from this tool (for annual reporting to the legislature, for project prioritization, for interchange approvals, etc.) and modify the tool accordingly; b) to develop new models and expanded methods for obtaining travel time reliability measures in arterials and multimodal corridors; and c) to develop a framework for expanding the travel time reliability estimation methods to all modes (rail, transit, water, aviation).

1.3. Organization

This report is organized as follows: Chapter 2 discusses the inclusion of additional performance measures to assess reliability, provides an overview of recommended changes to account for weather impacts, and presents the results of comparisons between model estimates and field travel time data. Chapter 3 develops travel time estimation models for arterials using simulation and develops methods for obtaining travel time reliability measures along arterial sections. Chapter 4 develops a framework for expanding the travel time reliability estimation methods to all modes (rail, transit, water, aviation). Chapter 5 provides conclusions and recommendations.

2. IMPROVEMENTS IN THE FREEWAY ANALYSIS METHOD

2.1. Performance Measures for Reliability

Two additional performance measures have been identified as potential measures of reliability: the Travel Time Index (TTI) and the Planning Time Index (PTI). The TTI is defined as the average travel time during the hour(s) of interest divided by the travel time under low flow conditions (i.e., the travel time corresponding to free-flow speed.) The PTI is defined as the 95% average travel time during the hour(s) of interest divided by the travel time under low flow conditions (i.e., the travel time corresponding to free-flow speed.) TTI has been incorporated into the database calculations for years 2005 – 2009, while PTI has been added as a performance measure in the spreadsheet applications used for initial development.

2.2. Weather Impacts

Weather impacts were previously considered based on two regions within Florida, and using one-year weather data. This revised procedure considers three regions in Florida (Tallahassee, Orlando, Ft. Lauderdale) and five years of data. The revised method and models are presented below, along with an example application.

The effects of weather are estimated for each freeway section based on the probability of occurrence for a particular rainfall category (none or trace, light rain, and heavy rain) for each of the 24 hours of analysis. This probability of occurrence is obtained using a calibrated relationship between rainfall intensity and frequency. Figure 2.1 illustrates conceptually such a relationship and the probabilities of occurrence for each of the three rainfall categories. The areas of each of the three categories specified in the figure represent the respective probabilities of occurrence. These three probabilities of occurrence are used in the reliability estimation to obtain the likelihood of each of the three rainfall categories for each analysis freeway section.

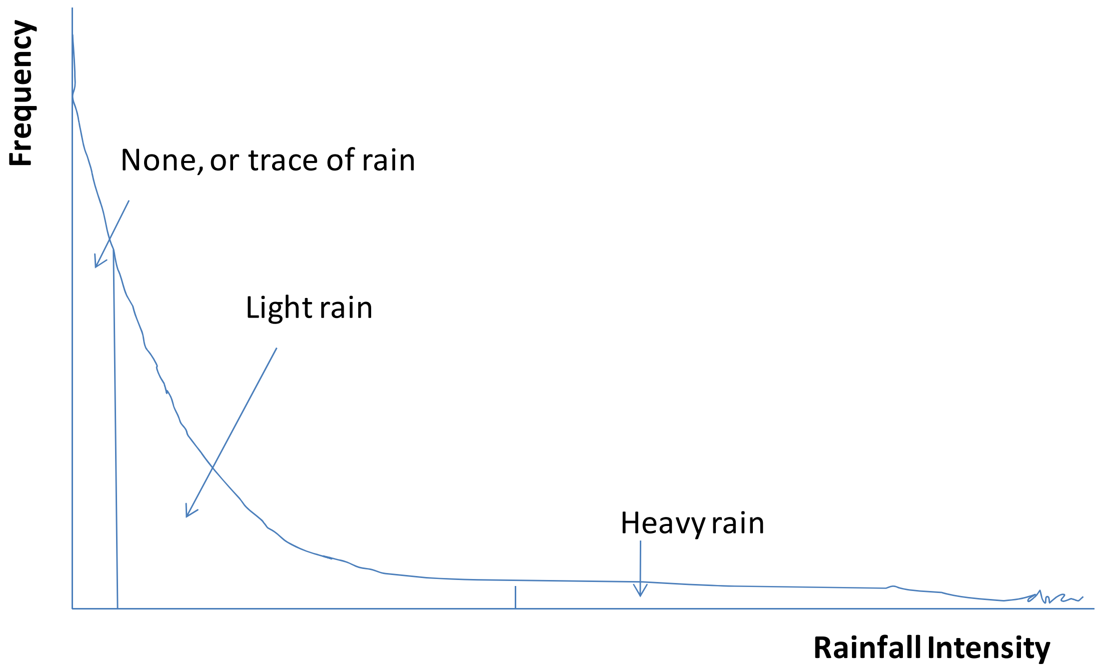


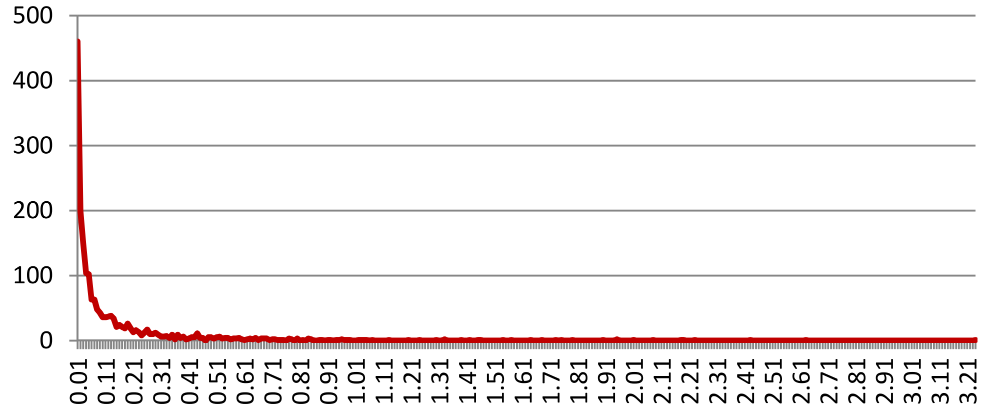
Figure 2.1 Relationship between Frequency and Rainfall Intensity

To obtain the three probabilities, first, a curve such as the one shown in Figure 2.1 is developed for each freeway segment. Three different curve types (or distribution models) were developed based on a five-year-period dataset (January, 2006 – December, 2010) for Tallahassee, Orlando, and Miami. The weather data were collected through the Weather Underground website (http://www.wunderground.com). Based on the location of the study segment, one of these three types is selected to develop the freeway section curve as a function of the average rainfall for that particular freeway section.

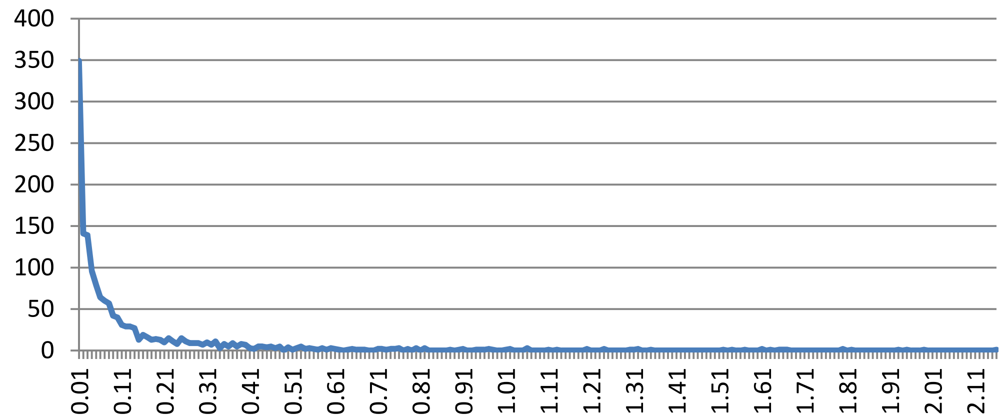
The remainder of this section describes the development of the three curve types and provides an example application for a freeway section.

2.2.1. The Three Types of Rainfall Intensity vs. Frequency Curves

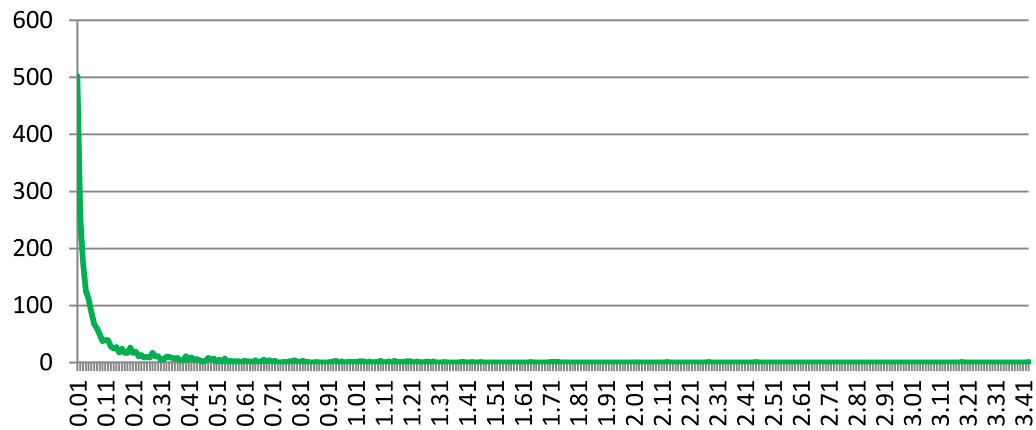
Three distribution models were developed based on a five-year-period dataset (January, 2006 – December, 2010) for Tallahassee, Orlando, and Miami. The weather data were collected through the Weather Underground website (http://www.wunderground.com). Figure 2.2 provides the frequency of rainfall intensity at these three representative locations. Based on its shape, the relationship between rain intensity and its corresponding frequency is assumed to be a Gamma distribution.



a) Rainfall Intensity Distribution for Tallahassee 32301
(Mean = 0.1425 inches/hour, Variance = 0.073 $\text{inches}^2/\text{hour}^2$)



b) Rainfall Intensity Distribution for Orlando 32801
(Mean = 0.1444 inches/hour, Variance = 0.064 $\text{inches}^2/\text{hour}^2$)



c) Rainfall Intensity Distribution for Miami 33127
(Mean = 0.1418 inches/hour, Variance = 0.070 $\text{inches}^2/\text{hour}^2$)

Figure 2.2 Rainfall Intensity Distribution of Three Representative Locations

Equations 1, 2 and 3 are the cumulative Gamma distribution functions for the three representative regions (1 for Tallahassee, 2 for Orlando, and 3 for Miami) in Figure 2.2:

$$k = 0.2782, \theta = 0.5123$$

$$F_N(x; 0.2782, 0.5123) = \frac{\gamma(0.2782, x/0.5123)}{\Gamma(0.2782)} == \frac{\int_0^{x/0.5123} t^{0.2782-1} e^{-t} dt}{\Gamma(0.2782)} \quad (1)$$

$$k = 0.3258, \theta = 0.4432$$

$$F_S(x; 0.3258, 0.4432) = \frac{\gamma(0.3258, x/0.4432)}{\Gamma(0.3258)} == \frac{\int_0^{x/0.4432} t^{0.3258-1} e^{-t} dt}{\Gamma(0.3258)} \quad (2)$$

$$k = 0.2872, \theta = 0.4937$$

$$F_N(x; 0.2872, 0.4937) = \frac{\gamma(0.2872, x/0.4937)}{\Gamma(0.2872)} == \frac{\int_0^{x/0.4937} t^{0.2872-1} e^{-t} dt}{\Gamma(0.2872)} \quad (3)$$

The two key parameters, the shape parameter k and the scale parameter θ, for each model were obtained by regression based on the five years of hourly rainfall data.

Figure 2.3 is a map of Florida's annual precipitation averaged over the period 1961-1990. From this map, it can be observed that the three cities discussed above (Tallahassee, Orlando and Miami) are located in the northwest extremely high precipitation area, central low precipitation area and southeast high precipitation area, respectively. Therefore, Florida was divided into three areas to reflect these differences in precipitation patterns. For each part of the state, the rainfall frequency distribution of one location (Tallahassee in the northwest area, Orlando in the central area, and Miami in the southeast area) was used to represent the frequency characteristics of rainfall intensity of the respective part of Florida. Table 2.1 and Figure 2.4 present the recommended categorization of counties to the three rainfall distribution regions.

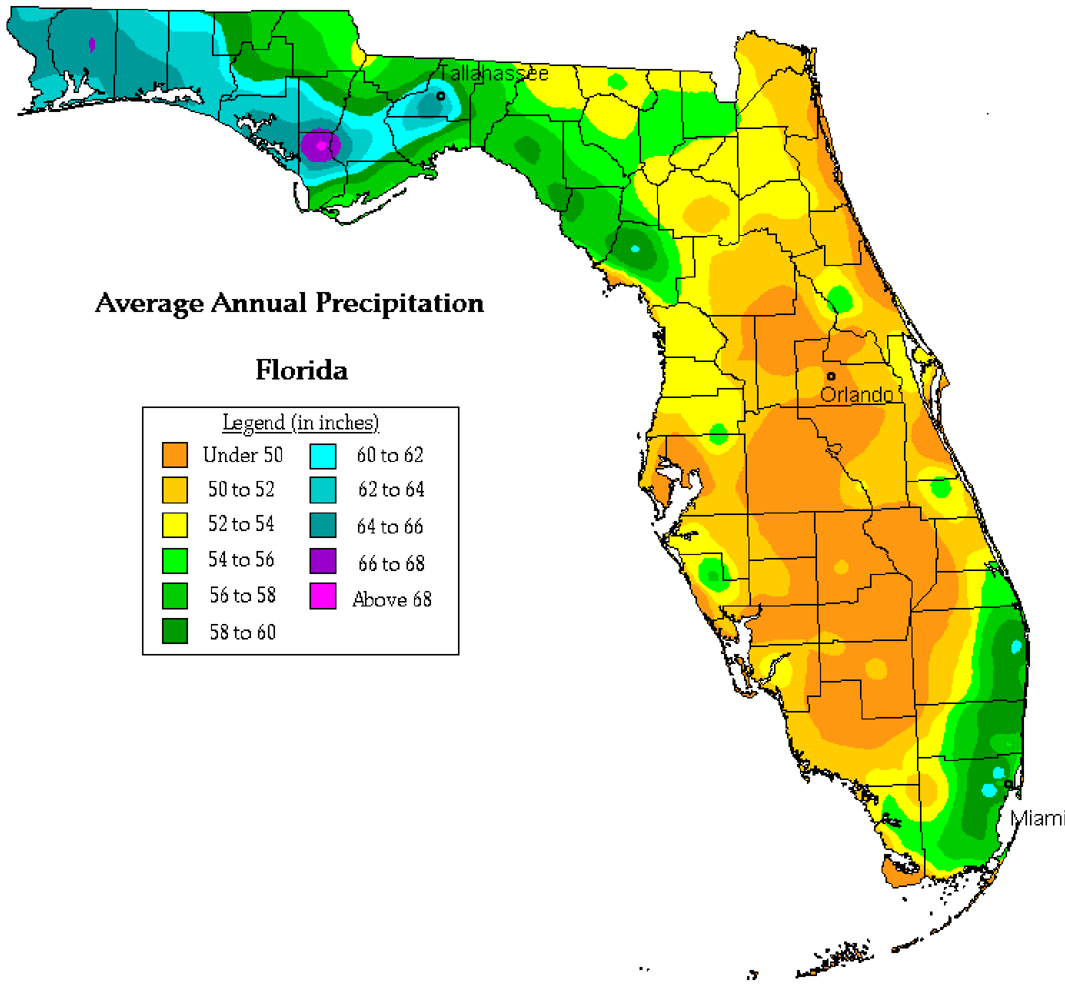


Figure 2.3 Florida Average Annual Precipitation Map
(Source:Spatial Climate Analysis Service, Oregon State University, 2000)

Table 2.1 Rainfall Distribution Regions

	Representative Location	Counties	Description
Region 1	Tallahassee	Escambia, Santa Rosa, Okaloosa, Walton, Holmes, Washington, Bay, Jackson, Calhoun, Gulf, Franklin, Liberty, Gadsden, Leon, Wakulla, Jefferson, Madison, Taylor, Hamilton, Suwannee, Lafayette, Dixie, Columbia, Baker, Union, Levy, Gilchrist	northwest extremely high precipitation area
Region 2	Orlando	Nassau, Duval, Clay, St. Johns, Putnam, Bradford, Alachua, Marion, Flagler, Volusia, Seminole, Lake, Citrus, Sumter, Hernando, Pasco, Pinellas, Hillsborough, Polk, Orange, Osceola, Brevard, Indian River, Okeechobee, Highlands, Hardee, Desoto, Manatee, Sarasota, Charlotte, Glades, Hendry, Lee, Collier	central low precipitation area
Region 3	Miami	St. Lucie, Martin, Palm Beach, Broward, Miami-Dade, Monroe	southeast high precipitation area

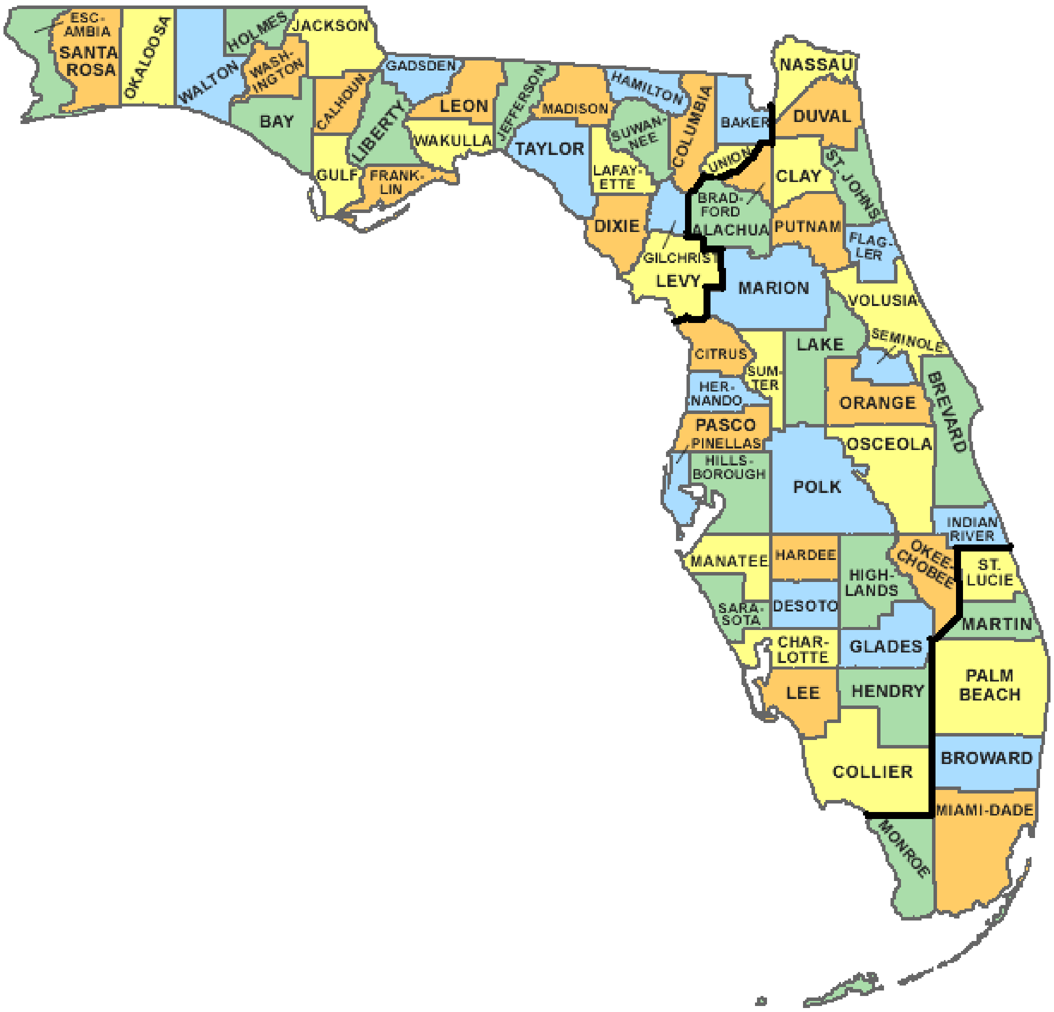


Figure 2.4 Division of the Rainfall Distribution Regions

All the rainfall frequency distributions in one rainfall distribution region are assumed to have the same shape parameter k. However, the second parameter of the distribution is estimated using the average rainfall of the specific freeway section. Using the specified shape parameter k in Equation 1, 2 or 3 (which represents the region of the state) and the mean of the rainfall data for each hour (which represents the freeway section), we obtain the specific rainfall distribution for each freeway section. We finally obtain the probability for each of the three rainfall scenarios (trace or none, light rain, or heavy rain) for each freeway section from these distributions, as shown in Figure 2.1.

The calculation algorithm for the probability of rain (light and heavy rain) for each location, as well as the split between light rain and heavy rain are the same as those described previously.

2.2.2. Example

An example is presented below to illustrate the method in more detail. The freeway segment used in this example is a section of I-95/SR 9 between Broward Blvd and Sunrise Blvd. The zip code for this area is 32819.

Step 1. Data Assembly

Rainfall data were obtained for a 72-day sample that included the 1st, 6th, 11th, 16th, 21st and 26th day of each month. The number of rainy days and the average rainfall for each hour of the rainy days were estimated. Figure 2.5 shows the respective calculation table in the "Rain" tab of the worksheet. The orange-highlighted columns indicate the required user inputs in the procedure.

RAIN										
Hour	Average Rainfall (in.)	Number of Rainy Days	Shape Parameter k	Scale Parameter θ	Probability of Trace	Probability of Light Rain	Probability of Heavy Rain	Probability of Rain	Ratio of Light Rain to Light+Heavy Rain	Ratio of Heavy Rain to Light+Heavy Rain
12-1	0.0530	2	0.2872	0.1845	0.476	0.516	0.009	0.028	0.984	0.016
1-2	0.0150	3	0.2872	0.0522	0.664	0.336	0.000	0.042	1.000	0.000
2-3	0.0050	0	0.2872	0.0174	0.844	0.156	0.000	0.001	1.000	0.000
3-4	0.0167	2	0.2872	0.0581	0.646	0.354	0.000	0.028	1.000	0.000
4-5	0.0467	3	0.2872	0.1626	0.492	0.502	0.006	0.042	0.989	0.011
5-6	0.0388	3	0.2872	0.1351	0.518	0.479	0.003	0.042	0.994	0.006
6-7	0.0050	0	0.2872	0.0174	0.844	0.156	0.000	0.001	1.000	0.000
7-8	0.0139	2	0.2872	0.0484	0.676	0.324	0.000	0.028	1.000	0.000
8-9	0.0150	3	0.2872	0.0522	0.664	0.336	0.000	0.042	1.000	0.000
9-10	0.0050	0	0.2872	0.0174	0.844	0.156	0.000	0.001	1.000	0.000
10-11	0.0283	2	0.2872	0.0985	0.564	0.436	0.001	0.028	0.999	0.001
11-12	0.0083	1	0.2872	0.0289	0.762	0.238	0.000	0.014	1.000	0.000
12-1	0.0179	2	0.2872	0.0623	0.635	0.365	0.000	0.028	1.000	0.000
1-2	0.0350	4	0.2872	0.1219	0.532	0.466	0.002	0.056	0.996	0.004
2-3	0.0221	2	0.2872	0.0769	0.601	0.398	0.000	0.028	1.000	0.000
3-4	0.0721	2	0.2872	0.2510	0.437	0.542	0.021	0.028	0.963	0.037
4-5	0.1415	9	0.2872	0.4927	0.361	0.560	0.078	0.125	0.877	0.123
5-6	0.0882	12	0.2872	0.3071	0.413	0.554	0.034	0.167	0.943	0.057
6-7	0.2171	9	0.2872	0.7559	0.320	0.545	0.135	0.125	0.801	0.199
7-8	0.0814	9	0.2872	0.2834	0.422	0.550	0.028	0.125	0.951	0.049
8-9	0.0305	7	0.2872	0.1062	0.552	0.447	0.001	0.097	0.998	0.002
9-10	0.0263	4	0.2872	0.0916	0.575	0.425	0.000	0.056	0.999	0.001
10-11	0.0500	3	0.2872	0.1741	0.483	0.510	0.007	0.042	0.986	0.014
11-12	0.1050	4	0.2872	0.3656	0.393	0.559	0.048	0.056	0.922	0.078

Figure 2.5 Calculation Example for the "Rain" Tab

Step 2. Determine Shape Parameter k and Scale Parameter θ

The location of the freeway segment is used in this step to determine the shape of the rainfall intensity distribution. The subject freeway segment is in rainfall distribution region 3; therefore, the value used for the shape parameter k of the Gamma distribution is 0.2872. The other descriptive parameter for the Gamma distribution, the scale parameter θ, is determined using the average rainfall for this location. For example, for the hour of 4 to 5 PM (or 16:00 to 17:00), the scale parameter θ is calculated using the following equation:

$$\theta = \frac{mean}{k} = \frac{0.1415}{0.2872} = 0.4927 \tag{4}$$

The results of this step are presented in the fourth and fifth columns of Figure 2.5.

Step 3. Probability of Rain

Since the "Trace" category does not have any impact on speed reduction, the probability of rain includes the sum of the probability of light and heavy rain. Based on the results of Step 1, the probability of rain for each hour is calculated by dividing the number of days that rained (precipitation is greater than 0.01 inches/hour) during this particular hour by 72 (the total number of days in the sample). For cases when the number of rainy days in the sample is zero, it is assumed that the probability of rain for this hour is 0.001. The results of this step are presented in the ninth column of Figure 2.5.

Step 4. Estimate the Probability for Three Rainfall Scenarios

Using the cumulative Gamma distribution function developed in step 2, the probability of each of the three rainfall scenarios for the hour of 4 to 5 PM (or 16:00 to 17:00) at this location can be identified.

Based on Equation (1), the probability for the "Trace" condition is as follows:

$$P(Trace) = F_S(0.01; 0.2872, 0.4927) = \frac{\gamma(0.2872, 0.01/0.4927)}{\Gamma(0.2872)} = 0.361 \tag{5}$$

The probability for "Light Rain" is calculated as follows:

$$\begin{aligned} P(Light\ Rain) &= F_S(0.5; 0.2872, 0.4927) - F_S(0.01; 0.2872, 0.4927) \\ &= \frac{\gamma(0.2872, 0.5/0.4927)}{\Gamma(0.2872)} - \frac{\gamma(0.2872, 0.01/0.4927)}{\Gamma(0.2872)} = 0.560 \end{aligned} \tag{6}$$

The probability for "Heavy Rain" is:

$$P(Heavy\ Rain) = 1 - P(Trace) - P(Light\ Rain) = 0.078 \tag{7}$$

The results of this step are presented in the sixth to eighth columns of Figure 2.5.

Step 5. Estimate the Ratio of Light and Heavy Rain

The ratio of the two rain levels is used to estimate the probability of occurrence for the two levels. The ratio of Light Rain to Light+Heavy Rain is calculated as follows:

P(Ratio of Light Rain) = P(Light Rain)/[P(Light Rain)+P(Heavy Rain)] = 0.877 (8)

The ratio of Heavy Rain to Light + Heavy Rain is as follows:

$$P(Ratio\ of\ \ Heavy\ Rain) = 1 - P(Ratio\ of\ \ Light\ Rain) = 1 - 0.877 = 0.123 \quad (9)$$

The results of this step are presented in the last three columns of Figure 2.5.

Step 6. Estimate the Equivalent Free-Flow Travel Time for the Rain Scenario

The three columns with blue headers shown in Figure 2.5 are used in the SR tab of the worksheet to calculate the travel time under rain-related scenarios. The hour of 16:00 to 17:00 is used as an example in the calculations below.

The free-flow speed of the subject freeway segment is 65 mph under normal conditions. As discussed previously, the free-flow speed reduction for light rain and heavy rain are assumed to be 6% and 12% respectively. Therefore, the adjusted free-flow speed for light rain is:

$$\begin{aligned} F(Light\ Rain) &= FFS \times (1 - FFS\ \ reduction\ for\ \ light\ \ rain) \\ &= 65 \times (1 - 0.06) = 61.1 \end{aligned} \quad (10)$$

Similarly, the adjusted free-flow speed for heavy rain is:

$$\begin{aligned} F(Heavy\ Rain) &= FFS \times (1 - FFS\ \ reduction\ for\ \ heavy\ rain) \\ &= 65 \times (1 - 0.12) = 57.2 \end{aligned} \quad (11)$$

Then, given that the length of this freeway segment is 1.022 miles, the equivalent free-flow travel time for the rain scenario is estimated as the weighted (based on frequency) average of the two rain conditions:

$$\begin{aligned} &Equivalent\ \ Free - flow\ \ Travel\ \ Time\ for\ \ Rain \\ &= (Ratio\ of\ \ Light\ \ Rain \times (3600 / FFS\ for\ \ Light\ \ Rain) \\ &\quad + Ratio\ of\ \ Heavy\ \ Rain \times (3600 / FFS\ for\ \ Heavy\ Rain)) \times Length \\ &= (0.877 \times (3600 / 61.1) + 0.123 \times (3600 / 57.2) \times 1.022 \\ &= 60.37 \end{aligned} \quad (12)$$

The results of the calculation for the equivalent free-flow travel time for the rain scenario are shown in column AI of the "SR" tab in the example worksheet. Using this travel time and the probability of rain obtained in step 3, the hourly adjusted travel time of each segment is obtained for each rain-related scenario.

2.3. Comparison to Field Data

Previous comparisons of the travel time reliability model estimates showed that generally travel times from sections with a small probability of congestion were estimated reasonably well by the models developed. This comparison focuses on comparisons for sections that have a high probability of congestion. The research team identified several congested sections (see Table 2.2) and obtained field data from the STEWARD database (traffic data clearinghouse developed by FDOT and UF, and currently maintained by UF) in order to compare the field data to model estimates. Due to the availability and quality of the field data, data from only five of these sections (Sections 1, 4, 6, 9, and 13) were used. These five sections are highlighted in red in Table 2.2, along with thei location and characteristics.

Field data were obtained for each of these sections in 5-min intervals, from 4 pm to 7 pm. For sections 1, 9 and 13 field data were obtained for the entire 2010 year (Jan. 1, 2010 to Dec. 31); however the other two sections had some missing data due to detector malfunctions, and thus field data were obtained between May 1 to Dec. 16, 2010, for section 4 and between Jan. 1 and Sept. 30, 2010, for section 6.

For these sites, three travel time-related measures were compared for the evening peak period (4-7 pm): average speed, 95% speed, and TTI (travel time index). When estimating averages, values weighted by frequency and volume were both calculated. The comparisons conducted for each of the measures are provided and discussed in the following sections.

Table 2.2 Evaluation of Selected Congested Sections

OrderID	Year	ROADWAY	BEGIN_POST	END_POST	USROUTE	CNTYNAME	DISTRICT	RLANES	LLANES	SECTADT	TOTLanes	AverageADT
1	2010	86070000	7.614	9.669	I 95	BROWARD	4	4	4	296000	8	37000
2	2010	10190000	1.746	2.09	I 275	HILLSBOROUGH	7	2	2	147000	4	36750
3	2010	87200000	11.558	11.784	I 395	MIAMI-DADE	6	2	2	145000	4	36250
4	2010	86095000	9.64	10.38	I 595	BROWARD	4	3	2	179000	5	35800
5	2010	10190000	2.613	2.762	I 275	HILLSBOROUGH	7	3	2	176500	5	35300
6	2010	87270000	3.221	5.228	I 95	MIAMI-DADE	6	3	3	210000	6	35000
7	2010	72020000	0	0.491	I 95	DUVAL	2	3	2	172000	5	34400
8	2010	10190000	7.342	7.444	I 4	HILLSBOROUGH	7	3	2	169000	5	33800
9	2010	86070000	14.892	15.093	I 95	BROWARD	4	4	4	267000	8	33375
10	2010	87004000	0.569	0.793	I 195	MIAMI-DADE	6	1	2	96000	3	32000
11	2010	10190000	5.126	5.632	I 275	HILLSBOROUGH	7	3	3	192000	6	32000
12	2010	86095000	4.191	5.82	I 595	BROWARD	4	3	3	185000	6	30833
13	2010	86070000	10.287	11.312	I 95	BROWARD	4	5	5	306000	10	30600
14	2010	10320101	0	0.41	I 275	HILLSBOROUGH	7	2	0	60500	2	30250
15	2010	86095000	6.68	6.825	I 595	BROWARD	4	4	3	211000	7	30143

2.3.1. Comparison of Average Speed

Table 2.3 provides the model-estimated speeds and the field average speeds, weighted by both frequency and volume. As shown, the differences between the frequency-weighted average speed and the volume-weighted average speed are very small. However, the differences between estimated and observed speeds are significant.

Table 2.3 Model-estimated and Observed Average Speeds

Segment Order ID	Field Data (mph)			Estimated Avg. Speed (mph)		
	Weighted by Frequency	Weighted by Volume	Percent of Difference	Weighted by Frequency	Weighted by Volume	Percent of Difference
1	66.84	66.49	0.52%	37.50	36.82	1.83%
4	72.43	72.26	0.23%	42.21	41.61	1.41%
6	52.60	52.31	0.55%	41.80	41.32	1.15%
9	63.20	62.28	1.46%	33.00	32.32	2.04%
13	66.94	66.12	1.22%	45.94	45.43	1.10%

Figures 2.6 and 2.7 display the estimated and observed speeds for each of the five sections, and show that the observed speeds are consistenty higher than the estimated ones for all five sections. In other words, the reliability model underestimates the average speeds (or overestimates the travel time) for sections that have high congestion frequency. Sections 6 and 13 have relatively smaller differences than the other sections. Examining the data it was found that these two sections have slightly higher volumes than the other three sections. However, all five of the selected sections appear to have moderate volumes (1250 veh/h to 1550 veh/h).

2.3.2. Comparison of 95% Speed

Similar to the average speeds, the frequency-based and volume-based 95% speeds are within 2 mph of each other. Also, the differences between the estimated and the observed speeds show similar trends to the average speeds. Sections 6 and 13 have relatively smaller differences than the other three sections.

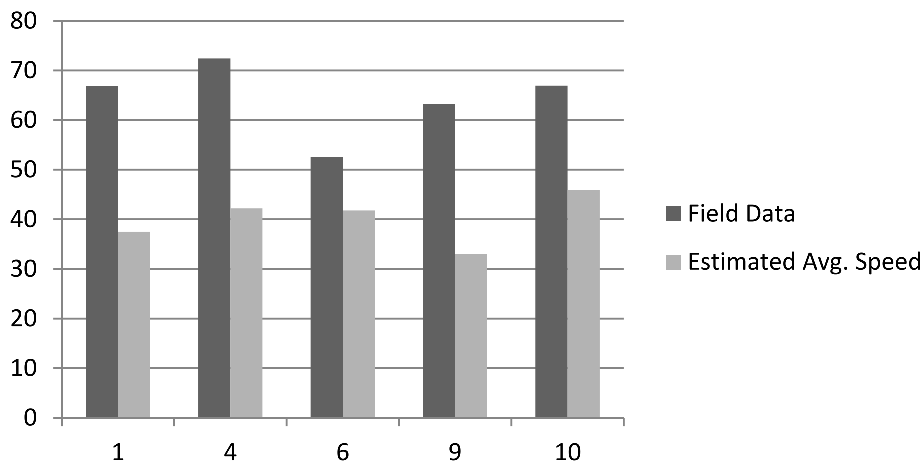


Figure 2.6 Comparison of Estimated and Observed Speeds (Weighted by Number of Hours)

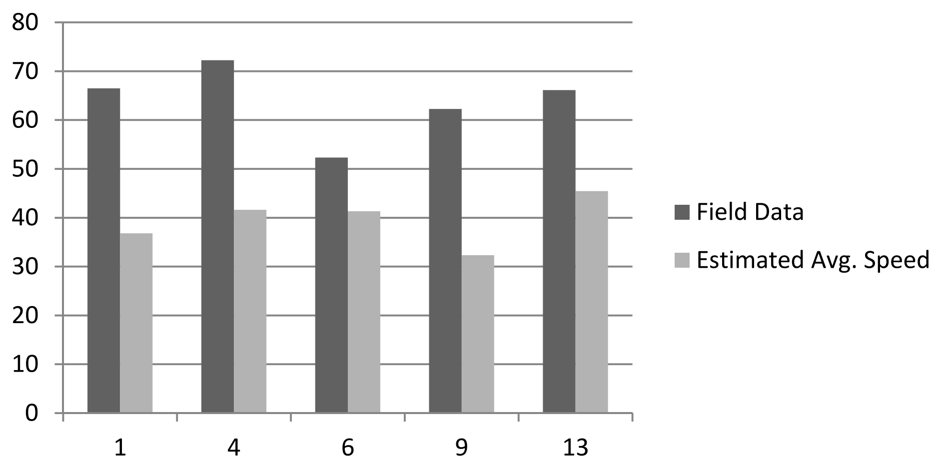


Figure 2.7 Comparison of Estimated and Observed Speeds (Weighted by Volume)

Table 2.4 Comparison of Estimated and Observed 95% Speeds

Segment Order ID	Field Data (mph)			Estimated 95% Speed (mph)		
	Based on Frequency	Based on Volume	Percent of Difference	Based on Frequency	Based on Volume	Percent of Difference
1	45.91	45.64	0.588%	28.39	28.78	1.385%
4	68.09	67.95	0.206%	26.48	26.69	0.816%
6	41.93	42.04	0.262%	19.51	19.51	0.000%
9	38.34	38.49	0.391%	8.46	9.94	17.606%
13	43.57	43.6	0.069%	34.31	34.94	1.830%

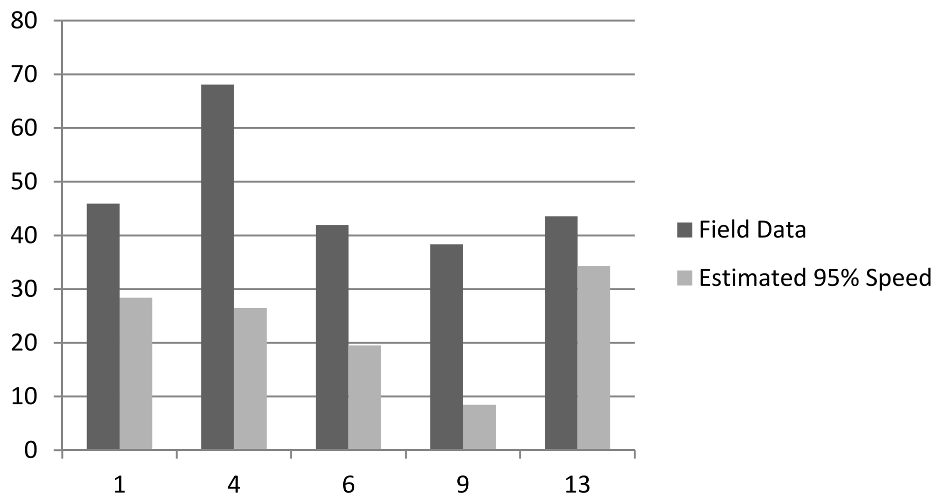


Figure 2.8 Comparison of Estimated and Observed 95% Speeds (Based on Frequency)

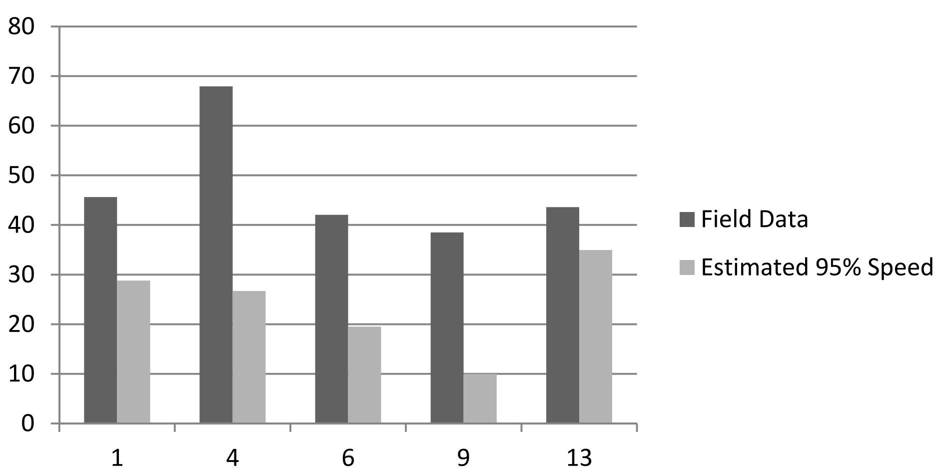


Figure 2.9 Comparison of Estimated and Observed 95% Speeds (Based on Volume)

2.3.3. Comparison of Travel Time Index (TTI)

The Travel Time Index (TTI) is the ratio of travel time in the peak period to the travel time at free-flow conditions:

$$\textit{Travel Time Index} = \textit{Average Travel Time} / \textit{Free-flow Travel Time} \qquad (12)$$

In this project, free-flow speed was assumed to be the speed limit plus 5 miles per hour. The TTI estimates are shown in Table 2.5. As with the other two measurements, calculation results based on frequency and volume are very similar. However, there are significant differences between the field and estimated values. The estimated TTI values are consistantly higher than the field data. This result is consistant with the average speed calculation since TTI is calculated based on the average travel time. As shown in Table 2.5, the values of TTI calculated based on field data are very close to 1. For section 4, the TTI is lower than 1.0 (0.97 for both the frequency-weighted and volume-weighted values), which indicates that the average speed is close to the free-flow speed.

Figures 2.10 and 2.11 present graphically the TTI values for the estimated and the observed speeds, weighted by number of hours and by volume respectively.

Table 2.5 Comparison of Estimated and Observed TTI

Segment Order ID	Field Data			Estimated TTI		
	Weighted by Frequency	Weighted by Volume	Percent of Difference	Weighted by Frequency	Weighted by Volume	Percent of Difference
1	1.08	1.09	0.93%	1.73	1.77	1.86%
4	0.97	0.97	0.00%	1.54	1.56	1.43%
6	1.09	1.09	0.00%	1.56	1.57	1.17%
9	1.18	1.19	0.85%	2.12	2.17	2.08%
13	1.09	1.11	1.83%	1.41	1.43	1.12%

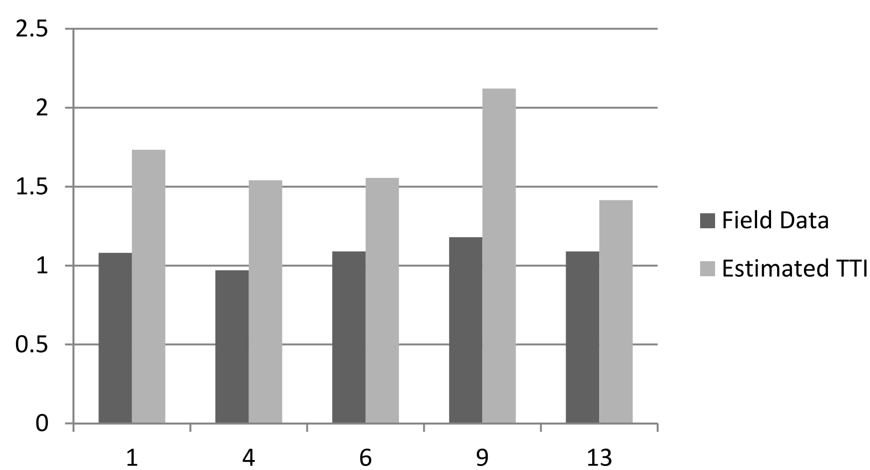


Figure 2.10 Comparison of Estimated and Observed TTI (Weighted by Number of Hours)

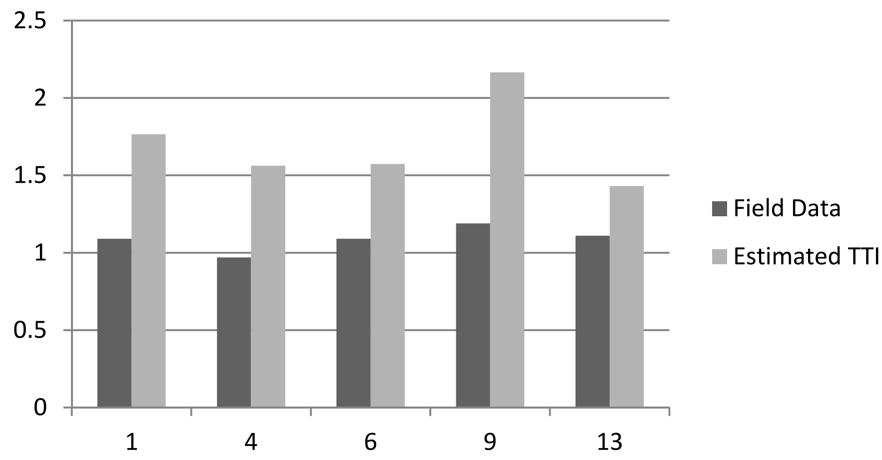


Figure 2.11 Comparison of Estimated and Observed TTI (Weighted by Volume)

2.3.4. Summary of the Comparison Results

From the above comparisons of the three reliability results, it can be concluded that the travel time reliability model appears to overestimate the congested condition, especially for the less congested freeway sections.

One of the key differences between the estimated and the observed values is that the estimated values calculate the travel time over the entire section, while the observed values are based on spot speed measurements extrapolated to the entire section. Thus, for locations where the sensor location is frequently congested the speed will generally lower and the travel time for the entire section will generally be higher. For locations where the sensor location is upstream or downstream of the queue the speed will generally be higher and the travel time lower. It is recommended that any further comparisons between the estimated travel times and field data are based on actual section travel times rather than speeds extrapolated to the entire section.

A second difference between the estimated and the observed values is that the estimates are based on the incident data from the 2007 CARS database, while the volumes are based on 2010 field data. The observed speeds were obtained in 2010. It is recommended that the annual incident data be used in future calculations to estimate travel time reliability for each year.

Lastly, in the current travel time reliability model, we used several assumptions (for example, work zone frequency) which may not be suitable for all segments. These assumptions contribute to the differences between estimated and observed data. It is recommended that the existing database be updated as additional data become available.

3. ESTIMATION OF ARTERIAL TRAVEL TIME USING SIMULATION

This section describes the development of travel time estimation models for arterials and their use in obtaining travel time reliability metrics. The CORSIM traffic microsimulator was used to develop the travel time estimation models. The first part of this chapter describes the development of the CORSIM network and the factors considered in the models developed. The second part summarizes the results of the simulated scenarios, while the third part presents the proposed travel time estimation models which were developed based on the simulation results. The fourth part evaluates the regression models developed, and the last part provides an overview of the spreadsheet developed to estimate travel time reliability for arterial sections.

3.1. Travel Time Estimation Using CORSIM

Several factors affect travel time along arterials (i.e., cycle length, distance between signals, presence of left turns, etc.). There is a very large number of potential combinations of such factors, which would lead to many different arterial configurations. However, there is a more limited set of factors that are typically available to FDOT, and they can readily be used in arterial travel time estimation. FDOT's Quality of Service Handbook (2009) uses the following input variables: number of signals per mile, posted speed, number of through lanes, left turn lanes, roadway class, median presence, terrain, *AADT, K, D*, cycle length, and *g/C*. To achieve the project objectives, eight factors were considered to investigate their effects on arterial travel time and eventually develop analytical models that predict travel time as a function of the most important ones. These factors are: number of signals per mile, free-flow speed (*FFS*, which can be assumed to relate to the posted speed), demand (which corresponds to *AADT, K, and D*), percent of turning movements, cycle length, *g/C* ratio, incident duration, and quality of progression. These factors were selected because of their potential effect on travel time, and also because they are available to be used as input factors later in evaluating travel time reliability for a particular arterial facility. Another factor, 'percent of lanes blocked by incidents' is also included to account for the effects of incidents. This subsection discusses these nine factors and the corresponding scenarios to be evaluated.

1. <u>Number of Signals Per Mile</u>

A simulated arterial section with length 1.07 miles was developed in CORSIM. It was assumed that there are two through lanes per direction at each intersection; sections with three lanes per direction were also tested to evaluate incident conditions. The number of signals per mile can have a significant effect on travel time. Therefore, the scenarios for considering the number of signals per mile are: 1, 4, 7, with one of those being a major intersection and the others minor intersections. The layouts of the arterial for the three scenarios are shown in Figure 3.1. It was assumed that 250-ft left-turn pockets are provided at each intersection approach.

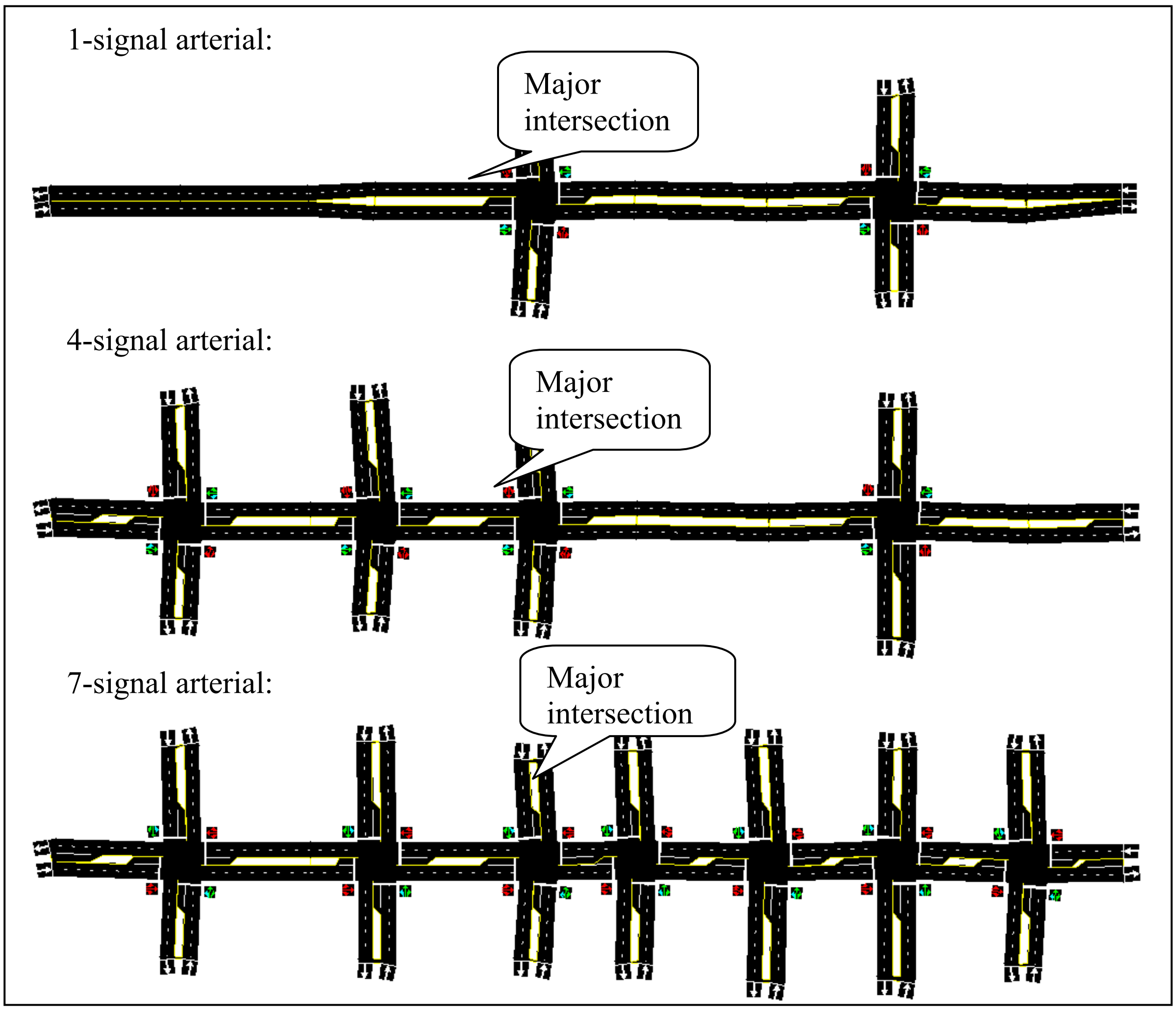


Figure 3.1 Arterial Layouts as a Function of the Number of Signals per Mile

2. FFS (mph)

FFS can have a significant effect on travel time, particularly for the non-congested scenarios. Two scenarios were used for the main arterial: 35 mph and 45 mph. It was assumed that all side streets have 35 mph FFS.

3. Demand (vphpl)

Demand can have a very significant effect on travel time. The following scenarios were tested:

- For the main arterial: 100, 500, 800, 1200 vphpl
- For side streets: 500 vphpl for minor intersections and 800 vphpl for major intersections

It was assumed that the percent of heavy vehicles for the entire network is zero.

4. Percent of turning movements (%)

This variable can have an important effect on travel time; however such data are typically not available for specific locations. Therefore, the following are assumed for all scenarios:

- For the main arterial: Major intersection: Right: 15%, Left 15% ; Minor intersection: Right: 5%, Left 5%
- For the side streets: Major intersection: Right: 15%, Left 15%; Minor intersection: Right: 5%, Left 5%

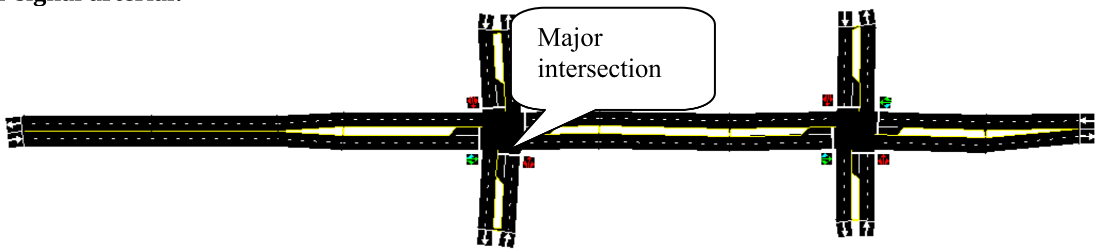
5. Cycle length (sec)

It was assumed that each signal is pre-timed. Minor intersections were assumed to have two phases, while major intersections were assumed to have four phases (including dual lefts for both the NS and the EW directions). Two scenarios were tested: 100 sec and 140 sec.

6. Weighted *g/C* ratio

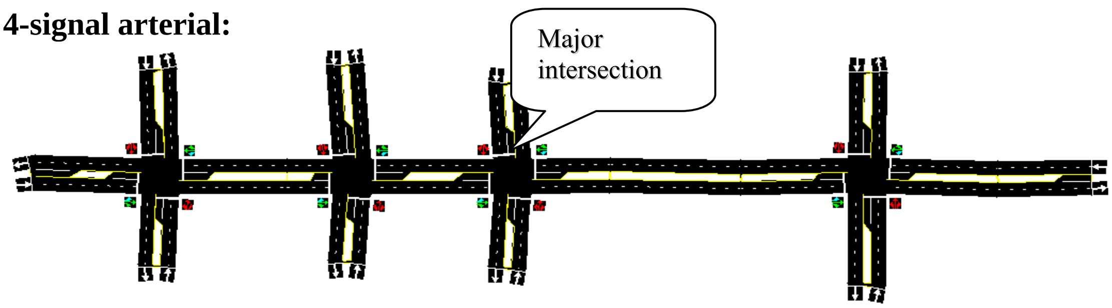
According to the 2009 FDOT Quality and Level of Service Handbook, "the weighted *g/C* of an arterial is the average of the sum of the critical intersection's through *g/C* with the average of the other intersections' through *g/Cs*. Essentially the worst intersection is given equal weight as all the other intersections combined". Thus, an overal *g/C* ratio can be obtained for the arterial according to FDOT's procedures. It was assumed that the arterial approaches of the major intersection has *g/C* ratio not exceeding 0.4, and the arterial approaches of minor intersections have a *g/C* as high as 0.7. The following scenarios of the weighted *g/C* ratio were tested: 0.4, 0.45, 0.5. The research team also tested *g/C* ratios of 0.3 and 0.6 for non-congested non-incident conditions. The scenarios tested are illustrated in Figure 3.2. The figure shows the weighted *g/C* as well as the individual *g/Cs* corresponding to each intersection under each scenario.

1-signal arterial:



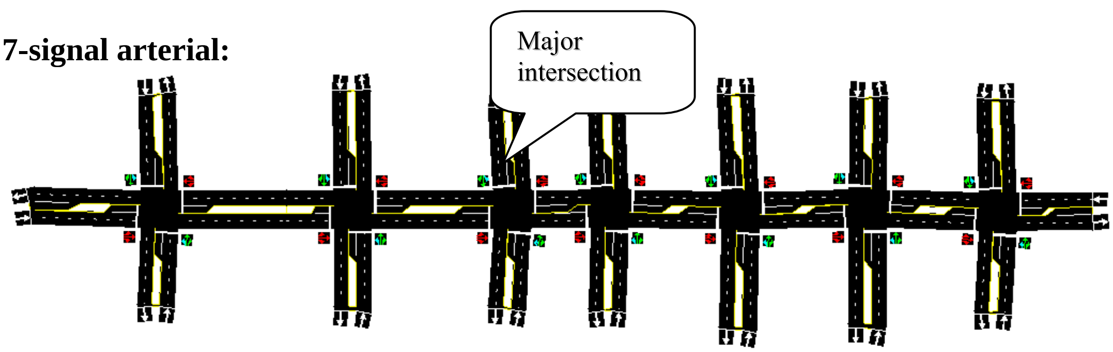
(g/C=0.3):	**g/C=0.3**	**g/C=0.3**
(g/C=0.4):	**g/C=0.3**	**g/C=0.5**
(g/C=0.45):	**g/C=0.35**	**g/C=0.55**
(g/C=0.5):	**g/C=0.4**	**g/C=0.6**
(g/C=0.6):	**g/C=0.5**	**g/C=0.7**

4-signal arterial:



(g/C=0.3):	g/C=0.35	g/C=0.3	g/C=0.25	g/C=0.3
(g/C=0.4):	g/C=0.55	g/C=0.4	g/C=0.35	g/C=0.4
(g/c=0.45):	g/C=0.5	g/C=0.5	g/C=0.35	g/C=0.45
(g/C=0.5):	g/C=0.5	g/C=0.5	g/C=0.4	g/C=0.6
(g/C=0.6):	g/C=0.65	g/C=0.65	g/C=0.4	g/C=0.7

7-signal arterial:



(g/C=0.3):	g/C= 0.35	g/C=0. 3	g/C=0. 25	g/C=0. 3	g/C=0.3	g/C=0.3	g/C=0.3
(g/C=0.4):	g/C= 0.4	g/C=0. 45	g/C=0. 3	g/C=0. 4	g/C=0.35	g/C=0.4	g/C=0.5
(g/C=0.45):	g/C= 0.45	g/C=0. 5	g/C=0. 35	g/C=0. 45	g/C=0.4	g/C=0.55	g/C=0.45
(g/C=0.5):	g/C= 0.5	g/C=0. 55	g/C=0. 4	g/C=0. 45	g/C=0.45	g/C=0.5	g/C=0.65
(g/C=0.6):	g/C= 0.65	g/C=0. 65	g/C=0. 4	g/C=0. 6	g/C=0.6	g/C=0.7	g/C=0.6

Figure 3.2 Weighted and Intersection *g/C* Scenarios for Each Arterial Layout
(Note: *g/C* values in parentheses provide the weighted *g/C* ratios)

7. Incident duration

The following incident durations were tested: no incidents (base case), 15 min, and 30 min. The incident was assumed to occur on one link near the major intersection at time 100 sec (the total simulation time is 3600 sec).

8. Percent of lanes blocked by incident

Three lane closure scenarios were tested: single lane closure along a 2-lane arterial, single lane closure along a 2-lane arterial, and a 2-lane closure along a 3-lane arterial. To incorporate the number of lanes blocked into the travel time estimation models, the following index was employed:

$$\text{Lane Blockage Index} = \frac{\text{\# lanes blocked by incidents}}{\text{total \# lanes per direction}}$$

The following indices of lanes blocked by incident were tested: 1/2 (incident blocks one lane on a 2-lane arterial), 1/3 (incident blocks one lane on a 3-lane arterial), and 2/3 (incident blocks two lanes on a 3-lane arterial).

9. Quality of progression/ offsets

Given the very high number of possible scenarios related to offsets, two categories of progression were tested: favorable progression and unfavorable progression. A preliminary analysis was conducted for the 88 basic scenarios shown in Table 3.1, to determine which set of offsets would result in favorable and unfavorable progression.

Table 3.1 Preliminary Tests for Determining Offset

	FFS (mph)	Demand (vphpl)	Cycle (sec)	# Signals and g/C ratio	Incident duration (min)	# Lanes blocked	# Scenarios
Range of factors 1	35, 45	100, 500, 800, 1200	100, 140	1 signal & g/C=0.4, 4 signal &g/C=0.45, 7 signal & g/C=0.5	0	0	2*4*2*3 = 48
Range of factors 2	35, 45	100, 500, 800	100, 140	1 signal & g/C=0.3, 4 signal & g/C=0.6,	0	0	2*3*2*2 = 24
Range of factors 3	45	100, 500, 800, 1200	100, 140	1/4 signal & g/C=0.4, 7 signal & g/C=0.5	15	1 or 2 lanes blocked on a 3-lane arterial	1*4*2*2*1 *1 = 16

For each of the 88 scenarios shown in Table 3.1, different offsets (0%, 5%, 10%, 15%, 20%, and 30% percent of the cycle length) were tested. For example, for the 4-signal arterial, and 100 sec cycle length, the scenario with offsets as 10% of the cycle length has offset values of 0, 10, 20, 30 sec. at each of the four intersections respectively. Based on the test results, one set of offsets was selected to represent favorable progression, and another one was selected to represent non-favorable progression. The remaining scenarios employed the same offsets as their respective basic scenarios. Thus, the same set of offsets was used for all scenarios with the same geometric and traffic control characteristics but with differing *g/C* and incident durations.

Table 3.2 summarizes the results of the preliminary CORSIM runs for each of the first 48 scenarios shown in Table 3.1 and for each of the 6 offset options. CORSIM was run for 10 times for each scenario and offset case and the corresponding average arterial travel times are summarized in Columns 7 to 12 of Table 3.2. For each scenario, the offset resulting in the lowest arterial travel time was selected as the favorable progression and is marked in red. The offset resulting in the highest arterial travel time was selected as the unfavorable progression and is marked in blue.

Table 3.2 Determining Offsets for Favorable and Unfavorable Progression

Scenario	Arterial Demand (vphpl)	Cycle (sec)	Arterial g/C ratio	Signals/mile	Arterial FFS (mph)	Arterial Travel Time (min)					
						Offset = 0%C	Offset = 5%C	Offset = 10%C	Offset = 15%C	Offset = 20%C	Offset = 30%C
1	100	100	0.4	1	35	2.61	2.59	2.63	2.65	2.67	2.73
2	100	100	0.4	1	45	2.23	2.22	2.26	2.30	2.35	2.31
3	100	100	0.45	4	35	3.07	3.00	2.97	2.97	2.97	3.10
4	100	100	0.45	4	45	2.59	2.56	2.53	2.54	2.60	2.80
5	100	100	0.5	7	35	3.29	3.17	3.16	3.24	3.50	3.76
6	100	100	0.5	7	45	2.78	2.72	2.82	2.98	3.26	3.51
7	100	140	0.4	1	35	2.95	3.01	3.09	3.14	3.10	2.91
8	100	140	0.4	1	45	2.60	2.67	2.74	2.68	2.57	2.43
9	100	140	0.45	4	35	3.40	3.38	3.39	3.46	3.58	3.86
10	100	140	0.45	4	45	2.94	2.97	3.04	3.15	3.28	3.36
11	100	140	0.5	7	35	3.69	3.70	3.86	4.09	4.18	4.71
12	100	140	0.5	7	45	3.23	3.32	3.55	3.78	3.87	4.50
13	500	100	0.4	1	35	3.13	3.13	3.12	3.04	2.95	2.81
14	500	100	0.4	1	45	2.69	2.61	2.51	2.43	2.37	2.32
15	500	100	0.45	4	35	3.73	3.60	3.40	3.31	3.23	3.16

Table 3.2 (continued) Determining Offsets for Favorable and Unfavorable Progression

Scenario	Arterial Demand (vphpl)	Cycle (sec)	Arterial g/C ratio	Signals/mile	Arterial FFS (mph)	Arterial Travel Time (min)					
						Offset = 0%C	Offset = 5%C	Offset = 10%C	Offset = 15%C	Offset = 20%C	Offset = 30%C
16	500	100	0.45	4	45	3.18	2.96	2.78	2.68	2.64	2.77
17	500	100	0.5	7	35	3.89	3.55	3.26	3.11	3.30	3.82
18	500	100	0.5	7	45	3.21	2.89	2.68	2.78	3.10	3.66
19	500	140	0.4	1	35	3.46	3.33	3.21	3.15	3.12	3.02
20	500	140	0.4	1	45	2.82	2.73	2.71	2.66	2.60	2.54
21	500	140	0.45	4	35	4.18	3.79	3.56	3.45	3.46	3.78
22	500	140	0.45	4	45	3.36	3.13	2.96	2.99	3.13	3.43
23	500	140	0.5	7	35	4.13	3.74	3.61	3.82	4.09	5.01
24	500	140	0.5	7	45	3.50	3.18	3.26	3.59	3.90	4.89
25	800	100	0.4	1	35	6.70	6.65	6.66	6.67	6.73	6.98
26	800	100	0.4	1	45	6.47	6.25	6.24	6.22	6.13	6.33
27	800	100	0.45	4	35	4.21	4.18	4.05	3.85	3.66	3.59
28	800	100	0.45	4	45	3.76	3.59	3.34	3.10	3.04	3.14
29	800	100	0.5	7	35	4.48	4.10	3.71	3.45	3.46	4.02
30	800	100	0.5	7	45	3.82	3.39	3.06	2.98	3.26	3.92
31	800	140	0.4	1	35	8.95	8.91	8.85	8.58	8.67	8.43
32	800	140	0.4	1	45	8.14	8.19	8.16	7.96	8.14	8.07
33	800	140	0.45	4	35	5.14	4.80	4.39	4.02	3.92	4.16
34	800	140	0.45	4	45	4.40	3.93	3.68	3.44	3.56	3.83
35	800	140	0.5	7	35	5.01	4.43	4.07	4.04	4.37	5.62
36	800	140	0.5	7	45	4.34	3.83	3.60	3.85	4.22	5.49
37	1200	100	0.4	1	35	10.11	10.04	10.06	10.09	10.09	9.90
38	1200	100	0.4	1	45	9.84	9.75	9.67	9.61	9.70	9.55
39	1200	100	0.45	4	35	7.87	7.93	7.89	7.59	7.58	7.44
40	1200	100	0.45	4	45	7.73	7.17	7.50	6.87	7.01	7.40
41	1200	100	0.5	7	35	6.54	6.26	5.81	5.44	5.74	6.36
42	1200	100	0.5	7	45	5.86	5.68	5.66	5.28	6.03	6.23
43	1200	140	0.4	1	35	10.99	10.88	10.80	10.72	10.70	10.50
44	1200	140	0.4	1	45	10.62	10.39	10.40	10.37	10.26	10.27
45	1200	140	0.45	4	35	10.17	10.22	9.46	9.18	8.31	8.91
46	1200	140	0.45	4	45	9.90	9.65	8.59	8.43	8.50	8.11
47	1200	140	0.5	7	35	8.63	8.89	8.40	7.83	7.77	8.65
48	1200	140	0.5	7	45	8.12	8.55	7.96	8.47	8.08	8.79

Note: Red color - favorable progression
Blue color – unfavorable progression

Based on the nine factors discussed above, a total of 1200 scenarios were tested, as described in Table 3.3.

Table 3.3 Final Set of Scenarios Tested

	# Signals	FFS (mph)	Demand (vphpl)	Cycle (sec)	*g/C* ratio	Incident duration (min)	# Lanes blocked by incident	Offset	Scenarios
Range of factors 1	1 4 7	35 45	100 500 800 1200	100 140	0.4 0.45 0.5	0, 15 30	1 lane blocked on a 2-lane arterial	1-favorable 0-neutral	3*2*4*2*3*3*2=864
Range of factors 2	1 4 7	35 45	100 500 800	100 140	0.3 0.6	0	N/A	1-favorable 0-neutral	3*2*3*2*2*1*2=144
Range of factors 3	1 4 7	45	100 500 800 1200	100 140	0.4 0.5	15 30	1 or 2 lanes blocked on a 3-lane arterial	1-favorable	3*1*4*2*2*2*2*1=192
Total # scenarios									**1200**

For statistical purposes, multiple runs are needed for each scenario. Based on the standard deviation of speed under various conditions it was determined that the number of runs for scenarios with arterial demand 100 veh/h/ln and 500 veh/h/ln would be 5, while the number of runs for scenarios with demand 800 veh/h/ln and 1200 veh/h/ln would be 15. The higher scenario demands have higher variability and thus a higher number of runs is needed to estimate the average.

3.2. Travel Time Estimates

For illustrative purposes, travel times for both the subject direction and the opposing direction of the arterial for the first 37 scenarios are summarized in Table 3.4.

Table 3.4 Results for the First 37 Scenarios

	incduration	demand	cycle	numinter	gcratio	FFS	offset	Average TT (min/mile)	
Scenario	Incident duration (min)	Demand (vphpl)	Cycle (sec)	# signals /mile	g/C ratio	FFS (mph)	Offset	Subject Direction	Opposing Direction
1	0	100	100	1	0.4	35	favorable	2.41	2.50
2	0	100	100	1	0.4	35	neutral	2.55	2.53
3	0	100	100	1	0.4	45	favorable	2.07	2.01
4	0	100	100	1	0.4	45	neutral	2.19	2.22
5	0	100	100	1	0.45	35	favorable	2.31	2.34
6	0	100	100	1	0.45	35	neutral	2.44	2.46
7	0	100	100	1	0.45	45	favorable	1.97	1.89
8	0	100	100	1	0.45	45	neutral	2.08	2.05
9	0	100	100	1	0.5	35	favorable	2.22	2.22
10	0	100	100	1	0.5	35	neutral	2.34	2.39
11	0	100	100	1	0.5	45	favorable	1.88	1.82
12	0	100	100	1	0.5	45	neutral	1.99	1.86
13	0	100	100	4	0.4	35	favorable	2.86	3.10
14	0	100	100	4	0.4	35	neutral	2.90	3.40
15	0	100	100	4	0.4	45	favorable	2.48	2.56
16	0	100	100	4	0.4	45	neutral	2.64	3.02
17	0	100	100	4	0.45	35	favorable	2.76	2.95
18	0	100	100	4	0.45	35	neutral	2.89	3.32
19	0	100	100	4	0.45	45	favorable	2.35	2.43
20	0	100	100	4	0.45	45	neutral	2.61	3.03
21	0	100	100	4	0.5	35	favorable	2.57	2.67
22	0	100	100	4	0.5	35	neutral	2.78	3.13
23	0	100	100	4	0.5	45	favorable	2.21	2.24
24	0	100	100	4	0.5	45	neutral	2.43	2.80
25	0	100	100	7	0.4	35	favorable	3.29	4.50
26	0	100	100	7	0.4	35	neutral	3.72	5.44
27	0	100	100	7	0.4	45	favorable	2.92	3.48
28	0	100	100	7	0.4	45	neutral	3.59	5.18
29	0	100	100	7	0.45	35	favorable	3.13	3.88
30	0	100	100	7	0.45	35	neutral	3.62	4.54
31	0	100	100	7	0.45	45	favorable	2.77	3.10
32	0	100	100	7	0.45	45	neutral	3.43	4.07
33	0	100	100	7	0.5	35	favorable	2.95	3.35
34	0	100	100	7	0.5	35	neutral	3.50	4.26
35	0	100	100	7	0.5	45	favorable	2.54	2.79
36	0	100	100	7	0.5	45	neutral	3.27	3.66
37	0	100	140	1	0.4	35	favorable	2.71	2.88

3.3. Arterial Travel Time Estimation Models

This section presents the travel time estimation models developed based on the results of the simulation runs. After all scenario runs were completed the researchers developed several plots illustrating the relationships between various sets of parameters to identify trends and potential relationships. It was observed that the relationship between demand and travel time is not linear, and that the relationship is different for non-congested vs. congested conditions. Thus, separate models were developed to estimate the arterial travel time for these two conditions .

To categorize each scenario as representing congested vs. non-congested conditions, the research team examined the CORSIM simulation output and animation. It was concluded that congested conditions would include all scenarios with demand of 1,200 veh/h/ln, some scenarios with demand of 500 veh/h/ln and *g/C* ratio of 0.3, and some scenarios with demand of 800 veh/h/ln. Table 3.5 provides an overview of the scenarios with congested conditions.

Table 3.5 Overview of the Congested Scenarios

Incident Duration (min)	Demand (vphpl)	Cycle (sec)	# Signals	*g/C* ratio
0	500	100	7	0.30
		140	7	0.30
	800	100	7	0.40
		140	1/4/7	0.40
		all	all	0.30
	1200	all	all	all
15	800	100	1/7	0.40
		140	1/4/7	0.40
			7	0.45
	1200	all	all	all
30	800	100	1	0.40
			7	0.4, 0.45
		140	1/4/7	0.40
			7	0.45, 0.5
	1200	all	all	all

The development of the two models as well as their final form are provided below.

1. Model for non-congested scenarios

A total of 819 scenarios belong to this condition. A multiple linear regression model was developed that estimates travel time as a function of various arterial characteristics. A minimum travel time of 60/FFS minutes (calculated as 1 mile divided by FFS), which would occur when demand=0, incident duration =0, and no signal, is included in the model as the intercept. This model is valid for cycle lengths longer than 60 seconds and *g/C* ratios larger than 0.3. All the factors included in the model are continuous variables except for progression, which is categorized as favorable or unfavorable. The model developed based on the CORSIM runs is:

$$TT = \frac{60}{FFS} + 0.001603\ X\ t + 0.084618\ X\ laneclose + 0.001413\ X\ D + 0.012962\ X\ C_{(act-60)} \qquad (13)$$

$$+0.204141\ \mathrm{X}\ \mathrm{N} - 4.70594\ X\ gc_{(act-0.3)} - 0.52147\ X\ O\ (min/mile)$$

where:

FFS= Free-Flow Speed (mph)

t = incident duration (min)

laneclose = percent of lanes blocked by incidents (= lanes blocked by incidents / total lanes)

D = demand (veh/h/ln)

$C_{(act-60)}$ = cycle length - 60 (sec)

N = number of signals per mile

$gc_{(act-0.3)}$ = *g/C ratio* - 0.3

O = 0 if favorable progression, -1 if unfavorable progression

The resulting R-square value is 0.93, indicating a good fit of the model to the simulated data. According to the equation, when demand is approaching zero, and there are no signals along the arterial, the travel time would be (60/FFS) minutes per mile. Travel time increases linearly with incident duration, percent of lanes blocked by incident, demand, and the number of signals. It also increases as the cycle length increases above 60 seconds, while it decreases with the average *g/C*. The travel time also increases when the progression becomes unfavorable.

Note that the variables ‘t’ and ‘laneclose’ are included in the model to consider the effects of incident duration and closed lanes on travel time, although they are not statistically significant. One of the early versions of the models included two separate models, one for scenarios with incidents and another for scenarios without incidents. However, if the two models are developed separately, their results are not consistent. For example, the models sometimes resulted in lower travel times when an incident was present with all other variables being identical. Therefore the researchers combined all data in one model to avoid those discrepancies.

2. Model for congested scenarios

A total of 349 scenarios belong to this condition. Similar to the model for non-congested scenarios, a minimum travel time of 60/FFS minutes (calculated as 1 mile divided by free flow speed) is set for ideal conditions. The model is as follows:

$$TT = \frac{60}{FFS} + 0.030626\ X\ t + 0.727794\ X\ laneclose + 0.005191\ X\ D + 0.037972\ X\ C_{(act-60)} \qquad (14)$$
$$+0.136407\ \mathrm{X}\ \mathrm{N} - 24.1586\ X\ gc_{act-0.3} - 0.82938\ X\ O\ (min/mile)$$

where:

FFS= Free-Flow Speed (mph)

t = incident duration (min)

laneclose = percent of lanes blocked by incidents (= lanes blocked by incidents / total lanes)

D = demand (veh/h/ln)

C_{act-60} = cycle -60 (sec)

N = number of signals per mile

$gc_{act-0.3}$ = *g/C ratio* - 0.3

O = 0 if favorable progression, -1 if unfavorable progression

The resulting R-square value is 0.97, which indicates very good agreement with the simulated data. As for the equation for non-congested conditions, when demand is approaching zero, and there are no signals along the arterial, the travel time would be (60/*FFS*) minutes per mile. Travel time increases linearly with incident duration, percent of lanes blocked by incident, demand, and the number of signals. It also increases as the cycle length increases above 60 seconds, while it decreases with the average *g/C*. In this case however, the increase is steeper for all variables, compared to the non-congested non incident case. The only exception is the number of signals per mile, as its impact appears less pronounced for congested conditions. Similarly to the model for non-congested conditions, the variable 'laneclose' is included in this model to consider the effects of closed lanes on travel time, although it is not significant.

To apply the models, the following should be observed, to be consistent with the data used in model development:

(1) The cycle length should be more than 60 sec.

(2) The *g/C* ratio should be larger than 0.3.

(3) When demand is below 300 veh/h/ln, use the developed models with caution. This is because the estmated travel time could be lower than the free-flow travel time given a very high *g/C* ratio (above 0.5) and low demand (below 300 veh/h/ln).

3.4. Evaluation of Travel Time Estimation Models

The models developed are evaluated by testing their results under various input values. These evaluation values were obtained under a variety of conditions, to ensure the results are reasonable under a broad range of conditions. Table 3.6 provides some of the results of this evaluation (a total of 30 scenarios). As shown, the results are reasonable for the scenarios tested.

3.5. Development of Spreadsheet to Estimate Arterial Travel Time

A spreadsheet similar to that previously developed for freeway sections was developed to obtain travel time reliability measures along arterials, based on the results of the travel time estimation models described above. The literature review on the impacts of rain on arterial travel time is presented in Appendix A, while the guide to the spreadsheet is provided in Appendix B.

In summary, the spreadsheet was developed with the following assumptions:

1) Light rain reduces the free-flow speed by 10%, and heavy rain reduces the free-flow speed by 17%.
2) Only blocking incidents are considered.
3) Incident data and workzone data along arterial streets are not presently available to the research team, therefore assumptions were made with respect to the probability of incidents and workzones as well as their duration.

Table 3.6 Results of Model Evaluation

Scenario	Incident Duration (min)	Percent of Lanes Blocked by Incident	Demand (veh/h/ln)	Cycle (sec)	Number of Signals	g/C Ratio	FFS (mph)	Progression (0-favorable, -1-neutral)	Estimated Travel Time (min/mile)
1	NO	N/A	300	70	2	0.5	50	1	1.2
2	NO	N/A	300	100	2	0.6	50	0	1.7
3	NO	N/A	600	70	4	0.5	40	1	2.4
4	NO	N/A	600	100	4	0.6	40	0	2.8
5	NO	N/A	1500	70	8	0.5	30	1	6.4
6	NO	N/A	1500	100	8	0.6	30	0	6.0
7	20	0.5	300	80	2	0.4	50	1	1.9
8	20	0.5	300	130	2	0.5	50	0	2.6
9	20	0.5	600	80	4	0.4	40	1	3.0
10	20	0.5	600	130	4	0.5	40	0	3.7
11	20	0.5	1500	80	8	0.4	30	1	10.2
12	20	0.5	1500	130	8	0.5	30	0	10.5
13	40	0.333	300	90	2	0.3	50	1	2.5
14	40	0.333	300	150	2	0.5	50	0	2.9
15	40	0.333	600	90	4	0.3	40	1	3.6
16	40	0.333	600	150	4	0.5	40	0	4.0
17	40	0.333	1500	90	8	0.3	30	1	13.5
18	40	0.333	1500	150	8	0.5	30	0	11.8
19	60	0.667	300	100	2	0.3	50	1	2.7
20	60	0.667	300	160	2	0.5	50	0	3.1
21	60	0.667	600	100	4	0.3	40	1	3.8
22	60	0.667	600	160	4	0.5	40	0	4.2
23	60	0.667	1500	100	8	0.3	30	1	14.7
24	60	0.667	1500	160	8	0.5	30	0	13.0
25	45	0.5	600	120	5	0.45	45	1	3.4
26	45	0.33	600	120	5	0.45	45	1	3.4
27	45	0.67	600	120	5	0.45	45	1	3.4
28	45	0.5	1500	120	5	0.45	55	1	10.0
29	45	0.33	1500	120	5	0.45	55	1	9.8
30	45	0.67	1500	120	5	0.45	55	1	10.1

4. FRAMEWORK FOR EXPANDING THE TRAVEL TIME RELIABILITY ESTIMATION TO ALL MODES

This chapter discusses the conceptual framework for conducting multimodal travel time reliability analysis. The first section summarizes the literature review findings, while the second section develops a conceptual framework for estimating travel time reliability across multiple modes.

4.1. Literature Review

Travel time reliability for the following modes was explored in the literature: transit, intercity transportation, bicycles, and pedestrians. The findings are summarized in the remainder of this section.

1. Transit

Transit service reliability is complex in that there is no single measure that can comprehensively gauge service quality. The most common measures of service reliability generally relate to schedule adherence, running times, and headways (Victoria et al., 2008).

Schedule adherence is an important reliability measure for infrequent users, timed transfers, and long headway service. Traditionally, transit agencies use on-time performance (OTP) as a measure of schedule adherence. OTP is expressed as the percentage of buses that depart a certain location within a predetermined range of time, generally no more than one minute early or five minutes late (Bates, 1986). When vehicles conform to the schedule, passengers are able to coordinate their arrivals with those of the bus better, resulting in average wait times that are less than one-half the scheduled headway. OTP is a measure that is particularly useful for evaluating system reliability from a transit agency's standpoint. However, a measure such as departure delay is more relevant to a passenger's experience of delay. Another limitation of OTP from the passenger's perspective is that it assumes that all early and late departures are of equal consequence, regardless of the delay's severity or the time of day (Kimpel, 2001).

For high-frequency service, which is typically defined as service operating at headways of 10 minutes or less, headway delay is reported as the most important indicator of reliability. Headway delay uses actual headway minus scheduled headway to measure the spacing between buses. A negative value for headway delay means that a bus is falling behind its leader, and a positive value means that the bus is gaining (Kimpel, 2001). Extreme variation in headway delay will result in bus bunching, which tends to propagate as vehicles travel along a route. The uneven passenger loading associated with bunching causes additional delay and requires the use of more vehicles to serve the same number of passengers (Victoria et al., 2008).

Running time is also an important measure of transit performance. Running time represents the time it takes a bus to travel from one location to another. Running time delay (actual running time minus scheduled running time) measures how well a bus is moving along each link. A positive value of running time delay means that a bus is having difficulty traversing the link. Running times are important to passengers to the extent that they affect in-vehicle travel time (Kimpel, 2001).

TCRP Report 100, the second edition of the Transit Capacity and Quality of Service Manual (Kittelson and Associates, 2003), is known as the primary document that incorporates research findings on transit capacity and quality of service. A set of six fixed-route transit service measures is provided to assist with the measurement of transit availability and comfort/convenience at the stop-level, route segment-level, and system-level. The six measures are presented along with level of service (LOS) grades from A to F (analogous to the highway LOS measures). One of the six measures is on-time performance. The on-time performance LOS defines "on time" as zero to five minutes late. For LOS A, the on-time percentage is 95 to 100 percent or, from the perspective of the passenger, approximately one late transit vehicle every two weeks (not including transfers). For LOS F, the on-time percentage is less than 75 percent or, from the passengers' perspective, at least one late transit vehicle on a daily basis (also not including transfers).

2. Intercity Travel Time

There has been only a limited amount of research on intercity travel time reliability. In one of the most relevant papers, Chang and Hsu (2003) developed a mathematical model to analyze the passenger waiting time in an intermodal station in which the intercity transit system was served via feeder buses. The model relates the passenger waiting time to the reliability of feeder bus services and the capacity of the intercity transit system.

Also, the California High-Speed Rail Authority and the Federal Railroad Administration (2008) completed an environmental impact evaluation of the High-Speed Train (HST) program between the Bay Area and the Central Valley. To evaluate the relative differences in travel conditions that would result from the No Project or HST alternatives, they considered travel time and reliability as performance measures. Travel time was measured as the total (door-to-door) travel time for the example city pairs and compared between different alternatives. The report didn't provide the travel time calculation method for the corridor, but it mentioned that the travel time for the air travel mode and the HST mode both include access time, terminal time, wait time, line-haul time and arrival time (not only the time spent on the train or the plane). For the reliability analysis, the report indicated 8 factors that impact travel time reliability: incidents, inclement weather, construction, volume variation, special events, traffic control devices and procedures, base capacity and vehicle availability and routing. The extent to which these eight factors affect each travel mode is analyzed and compared on a qualitative basis. The susceptibility of each travel mode to each reliability factor is described and ranked into three levels: low, moderate and high. Because trips are composed of combinations of modal elements (including different modes for trip segments such as station or terminal access), modal rankings were combined, providing a qualitative understanding of the reliability of each alternative. They finally concluded that HST systems can provide shorter travel times and are more reliable than other travel modes and the conventional U.S. intercity rail services.

3. Bicycles

No research was found in the literature related to bicycle travel time reliability; however several papers were found reporting on the estimation of bicycle travel speed and the factors affecting bicycle travel time. In summary, the factors found to affect bicycling speed include type of facility (off-street facility, on-street facility and regular streets), gradient, trip length, number of signalized intersection, average daily traffic, time of day (peak or off-peak) and personal characteristics (age, gender, comfort in traveling in light and heavy traffic). The majority of the bicycling speeds reported in the literature fall between 7.5 mph to 15.5 mph.

4. Pedestrians

No studies were found in the literature related to reliability for pedestrian facilities, however, there are several studies related to the speed of pedestrians. In summary, the factors that have been reported to impact pedestrian speed include pedestrian age, gender, weather, season and type of walking facility. Most of the research articles have focused on the pedestrian crossing speed, which is the walking speed of pedestrians at intersections: the average crossing speed for all pedestrians ranges from 3.94 fps to 4.60 fps. Xiong et al. (2007) studied the pedestrian speed on sidewalk and concluded that the average walking speed of pedestrians on sidewalks is 4.0 fps. Both Daamen and Hoogendoorn (2006) and Xiong et.al. (2007) indicated that speeds of individuals follow a normal distribution. Lam and Cheung (2000) reported travel time estimates for pedestrians on different types of walking facilities in Hong Kong. They also produced a travel time function used to estimate pedestrian speeds as a function of free-flow travel speeds and volume-to-capacity relationships for congested pedestrian areas.

4.2. Multimodal Reliability Performance Measures

This section provides an overview of the framework developed regarding the consideration of reliability in a multi-modal environment.

Generally, multimodal travel time estimation can be performed at two levels:

1. Travel times and travel time reliability for travel by a single mode from a given origin to a given destination. In this case travel time and travel time reliability can be estimated separately for each mode. Comparisons can be made across modes as long as the travel time definitions are consistent across modes and the travel times are estimated in a consistent manner.
2. Travel times and travel time reliability for travel using multiple modes from a given origin to a given destination. In this case travel times and travel time reliability need to be estimated considering the entire trip including the interconnections between modes.

Figure 4.1 illustrates conceptually three alternative routes. In the cases of routes 1 and 2, each one is completed with one mode, and these belong in the first category. The third one involves three different modes. Each of these two types of comparisons is discussed in additional detail in the remainder of this chapter.

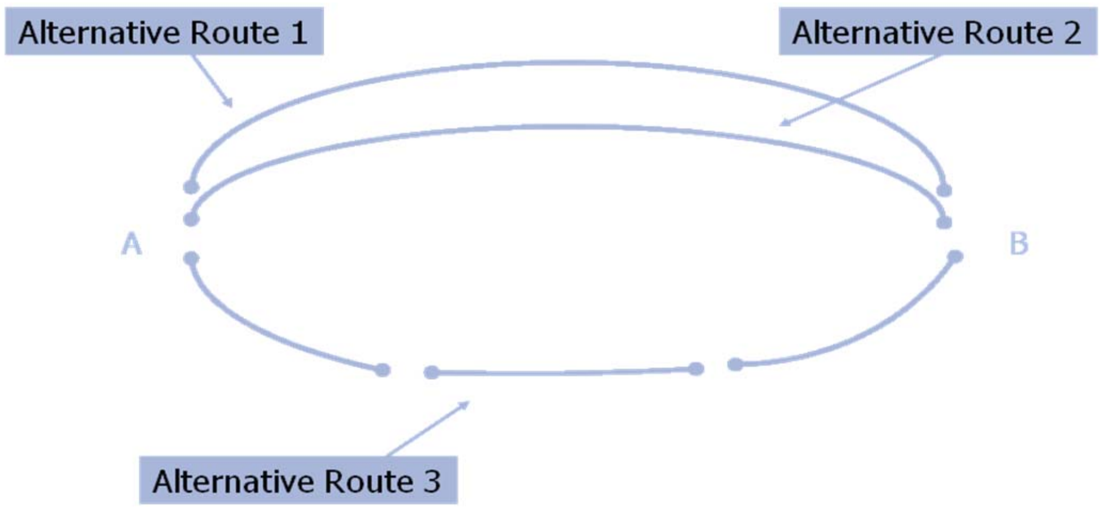


Figure 4.1 Travel Times for Alternative Routes and Multiple Modes

Travel time by a single mode

When travel between an origin and a destination is conducted by a single mode (air, rail, water, automobile, truck, transit, intercity transportation, bicycle, and walking) travel time can be obtained relatively easily (at least theoretically) by obtaining departure times and the arrival times during the hours of interest. The threshold for defining reliability however needs to be obtained differently for each mode. For modes that involve schedules, the threshold needs to be obtained as a function of the scheduled arrival time. For example, for transit service the TCRP Report 100, the second edition of the Transit Capacity and Quality of Service Manual (Kittelson and Associates, 2003), recommends considering arrivals within 5 minutes of the scheduled arrival time as being on-time. For modes that do not involve schedules (such as automobile and bicycles) the threshold should be set based on speeds during non-congested conditions, or based on average travel speed during free-flow conditions. Issues that need to be addressed in setting such thresholds across modes are the following:

- Should the reliability threshold vary between different modes? For example, if a 5-minute threshold is used for transit service, should the same threshold be used for bicycles?

- Should the reliability threshold be set as a function of the trip distance? For example should the threshold be 5 minutes for an anticipated 10 min trip as well as for a 60 min trip?

Travel time using multiple modes

Figure 4.2 illustrates a multi-modal route between origin A and destination B. The route consists of three links which represent three different modes. The figure also provides the average travel times for two different time periods along each link. As shown in this example, the average travel time for each link varies between time periods. Thus in this case it is important to consider the travel time for the entire trip and for each time period of interest. On the other hand, individual link travel times are also important, as they can provide information on bottleneck location and times.

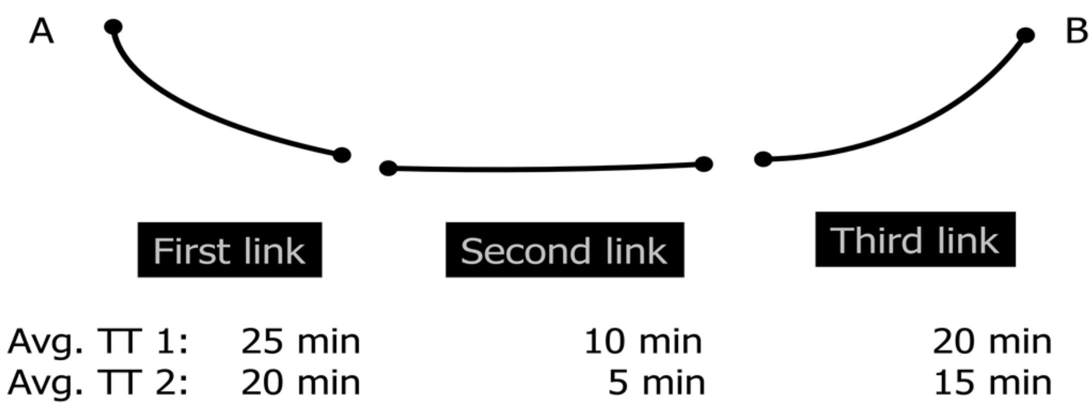


Figure 4.2 Travel Time Estimation for Multimodal Route

Note that the second link could represent the interconnection time between two modes. For example, if a traveler takes a bus to reach the train station and catch a train, then in Figure 4.2 the first link is the bus trip, the second link is the time between the bus arrival and the train departure, and the third link is the train trip.

Issues to be resolved under this category are the following:

- How should on-time performance be defined in this case? Should the threshold for the route be based on a combination of thresholds for each link? Should thresholds be set considering different alternative routes (as for example in the case of the three alternative routes in Figure 4.1)?

- How should connections between modes be handled? What threshold should be used for an “on-time” connection?

5. CONCLUSIONS AND RECOMMENDATIONS

This research project made improvements in the freeway travel time reliability method, developed a new arterial travel time reliability method, and proposed a framework for considering travel time reliability in a multimodal context.

Improvements in the freeway travel time reliability method are the following:

1) The Travel Time Index (TTI) and the Planning Time Index (PTI) were incorporated into the method as two additional performance measures for reliability and variability.
2) The process for evaluating the impacts of weather on traffic operations was enhanced by considering three (instead of two) regions in Florida (represented by Tallahassee, Orlando, and Miami), and by analyzing weather data over five years (instead of only one year).
3) Travel time measures based on estimated and observed data were compared, focusing on sections with congested conditions. It was concluded that the estimated travel times are higher than the observed ones; however there are some fundamental differences in the methods used to obtain the two sets of values. One of the most important differences is that the estimated values calculate the travel time over the entire section, while the observed values are based on spot speed measurements *extrapolated* to the entire section. Depending on the location of the detector, the conditions may or may not be representative of the entire section.

The arterial travel time estimation method was developed based on simulated data (using the CORSIM microsimulator). The following factors were used to develop the travel time estimation models: number of signals per mile, FFS, demand, percent of turning movements, cycle length, *g/C* ratio, quality of progression, incident duration, and percent of lanes closed during an incident. These factors were selected because of their potential effect on travel time, and also because they are generally available to analysts in Florida. Two travel time estimation models were developed using results from a total of 1200 scenarios: one model for non-congested scenarios, and one model for congested scenarios. A spreadsheet similar to that previously developed for freeway sections was developed to obtain travel time reliability measures along arterials, based on the results of the developed travel time estimation models.

Lastly, a conceptual framework for conducting multimodal travel time reliability analysis was proposed. For travel using a single mode, travel time and travel time reliability can be estimated separately for each mode. Comparisons can be made across modes as long as the travel time definitions are consistent across modes and the travel times are estimated in a consistent manner. For travel time using multiple modes, travel times and travel time reliability need to be estimated considering the entire trip including the interconnections between modes.

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APPENDIX A - Effects of Rain on Arterial Travel Time

This appendix presents the assumptions made for effects of rain on arterial travel time reliability based on previous research. The first few paragraphs summarize the key articles identified that examine weather effects on arterial travel time, and the appendix concludes with the list of recommendations .

Lamm et al. (1990) examined 24 curved road sections of rural two lane highways during both dry and wet conditions. They found no statistical difference in operating speed between those two conditions without the consideration of visibility. Therefore, they concluded that operating speeds are not affected by wet pavement until visibility is also impacted.

Gillam and Withill (1992) investigated weather impacts on adaptive traffic signal systems in four urban areas of the United Kingdom. They analyzed traffic flow under dry and wet pavement conditions from March to November 1991, and found that travel time delay and congestion increased by an average of 11% when roads were wet, and that saturation flow rate was reduced by 6% with wet pavement.

Mitretek Systems (2002) used a two-step regression analysis to analyze the impacts of adverse weather on travel time based on the combined data of reported travel time data and weather observation. The weather impacts on 15 arterial segments and 18 freeway segments in metropolitan Washington, D.C. from December 1999 to May 2001 were studied. They found that, the average impact of precipitation on peak-period traffic is at least an 11% increase in travel time. During the off-peak periods, travel time increases by approximately 13% due to an array of weather attributes including visibility (0->=0.25 miles, 1-<=0.25 miles), wind, and precipitation. Precipitation was found to cause a 3.5% increase in travel time. The report concluded that the value of 3.5% was likely to be lower than reality due to the limitation of data. However, the report did not distinquish between the effects of light rain and those of heavy rain.

Perrin and Martin (2002) analyzed the impacts of inclement weather on speed and saturation flow rate at two intersections in Salt Lake Valley, Utah, during the winter 1999/2000. Over 30 hours data were collected on 14 days with inclement weather. The authors found that rain reduced speed and saturation flow rate by 10% and 6% respectively.

Chin et al. (2004) used loop detector data from different regions of the United States to analyze the impacts of weather on operations. Weather conditions were classified into 5 categories: light rain, heavy rain, light snow, heavy snow, fog and ice. They assumed that rain or snow falling at a rate of 1 inch or more per hour to be heavy and lower amounts to be light. For both urban arterials and rural arterials, the estimated loss of capacity and speed are 6% and 10% respectively under light rain conditions. The same results were obtained for heavy rain conditions.

Chung et al. (2005) investigated the effects of rainfall on travel demand and travel time at Tokyo Metropolitan Expressway (MEX). The authors concluded that travel demand decreases for rainy days, especially during the weekend. Saturday is most sensitive to weather conditions, followed by Sunday. They also found that, at low density, there is no significant difference in travel time between rainy and dry conditions. However, at high density, travel time is significantly higher during rainy conditions than during dry conditions by 4.4 to 6.3%. In their study, the impact of light rain and heavy rain on travel time is not analyzed separately.

Abdalla and Abdel-Aty (2006) modeled travel time when drivers are equipped with real-time traffic information/advice, based on urban traffic networks consisting of several different arterials in Orlando. They considered three different weather conditions (clear sky, light rain, and heavy rain) in their model, and found that light and heavy rain conditions increase the travel time by 9.12% and 17%, respectively. However, they did not classify precipitation by intensity.

Athey Creek Consultants (2009) designed a real-time travel time estimation model for the Minnesota arterial travel time (MATT) project. They considered the impact of rain or snow on travel time in the calibrating process of the travel time estimation model. The travel time was increased if it was raining or snowing by a set number. However, it is not clear from the report what amount of increase in travel time was assumed.

In summary, most of the literature reported that rain resulted in a speed reduction of 9%-11% and saturation flow rate / capacity reduction of approximately 6%. However, most of the previous research did not classify precipitation by intensity. There is one paper indicating that light rain and heavy rain increase the travel time by 9% and 17%, respectively. Table A-1 provides a summary of the literature review regarding speed and capacity reductions caused by rain on arterials.

Table A-1 Summary of Literature on Speed and Capacity Reduction on Arterials Due to Rain

Authors (Year)	Rain Intensity Levels	Speed Reduction	Capacity Reduction
Lamm et al. (1990)	Dry and Wet Conditions	Operating speeds are not affected by wet pavement until visibility is also impacted.	--
Gillam and Withill (1992)	Dry and Wet Conditions	11%	6%
Mitretek Systems (2002)	Dry and Wet Conditions	causes more than 11% increase in travel time in peak period, 3.5% increase in off-peak period	--
Perrin and Martin (2002)	Dry and Wet Conditions	10%	6%
Chin et al. (2004)	Light (< 1 in/h)	10%	6%
	Heavy (≥1 in/h)	10%	6%
Abdalla and Abdel-Aty (2006)	Light	increase the travel time by 9.12%	--
	Heavy	increase the travel time by 17%	--

In conclusion, the recommended rainfall intensity categories and their impact on arterial operating speed and capacity reduction are shown in Table A-2.

Table A-2 Recommended Rainfall Intensity Classifications and Impacts on Arterial Speed Reduction

Rain Category	Rainfall Intensity (inch/hour)	Speed Reduction (%)	Capacity Reduction (%)
None	< 0.01	0	0
Light	0.01- 1	10	6
Heavy	>1	17	6

APPENDIX B - Guide to the Worksheet for Estimating Arterial Travel Time Reliability

Tab 1 – Facility Description

This tab is for informational purposes only and it defines the various types of facilities and their corresponding abbreviations that will be used in the rest of the worksheet. The example "SR 15/US 17/92 Orlando" consists of three facility types: "1art1c", "1art2c", and "1art3d", which are highlighted with light purple, olive green, and aqua in the tab.

Tab 2 – LOS Criteria

This tab presents the level of service (LOS) volume thresholds (columns C to G) according to facility type (column A), number of lanes (column B) and time period – peak, off-peak and midday (column I). The corresponding LOS data of "1art1c", "1art2c", and "1art3d" are highlighted with light purple, olive green, and aqua in the tab.

Tab 3 – HrlyK with Peak Hours Speed Table

This tab presents the average hourly K factors (column C) according to facility type (column A), hour of the day (column B) and time period (column D). The data for arterial road are highlighted with grey in the tab.

Tab 4 – SR15 Inputs

This tab has the basic information related to the example section. The orange-highlighted cells indicate user input. The grey column headers indicate information related to the characteristics of the example section. The blue-highlighted column headings indicate output that will be used as input in the intermediate calculations in other tabs.

Input

The characteristics of the example section are input (cells B3:M3), including the speed limit (cell AA3). From the 2009 FDOT Quality/Level of Service Handbook, the cycle length (cell W3) and g/c ratio (cell X3) can be obtained from the Generalized Service Volume Table 1. The speed threshold for different road types and different LOS can also be obtained from the same table, and the LOS C threshold is used as the free-flow speed for Reliability Calculation in Tab 10 and 11 (cell AB3). The number of signals (cell U3) is obtained from Google Earth.

The progression type (cell Y3), the probability of one/two lane blocked incident (column V) and work zone (column X), and the duration of one/two lane blocked incident (column W) and work zone (column Y), were not available through field data, thus the numbers shown are provided for illustrative purposes.

Calculations

Columns B,C,D,E,F,G,I,K,L,M:

They obtain their respective values from row 3.

Column H:

Length = END_POST - BEGIN_POST.

Column J:

LANES Adj = Integer (LANES/2).

Column N:

PD HourVol = AADT * 0.55 * Avg of HrlyK (from the HrlyK with Peak Hours tab, according to Facility type and hour of the day).

Column O:

OD HourVol = AADT * 0.45 * Avg of HrlyK (from the HrlyK with Peak Hours tab, according to Facility type and hour of the day).

Cells N33, O33:

Sums of their respective columns.

Columns P,Q,R,S,T:

LOSA, LOSB, LOSC, LOSD, LOSE are calculated from the lookup table "LOS Criteria" based on the LOSTABLE field for “1art1c”, “1art2c”, and “1art3d” type.

Cell V3:

Number of signals per mile = Number of signals / Length.

Cell Z3:

FFS for Travel Time Calculation = Speed Limit + 5.

Cells Z8:Z31:

Probability of 1 Lane Blocked Incident and Work Zone = Probability of 1 Lane Blocked Incident * Probability of 1 Lane Blocked Work Zone.

Cells AA8:AA31:

1 Lane Blocked Incident and Work Zone Duration = Maximum (1 Lane Blocked Incident Duration, 1 Lane Blocked Work Zone Duration).

Cells Z35:Z58:

Probability of 2 Lane Blocked Incident and Work Zone=

Probability of 1 Lane Blocked Incident * Probability of 2 Lane Blocked Work Zone

+ Probability of 2 Lane Blocked Incident * Probability of 1 Lane Blocked Work Zone

+ Probability of 2 Lane Blocked Incident * Probability of 2 Lane Blocked Work Zone

Cells AA35:AA58:

2 Lane Blocked Incident and Work Zone Duration = Maximum (2 Lane Blocked Incident Duration, 2 Lane Blocked Work Zone Duration).

Tab 5 – Rain

This tab includes all weather-related calculations. The orange-highlighted cells indicate user input fields, while the blue-highlighted column and row headings indicate output that will be used as input in other tabs.

Input

From the literature review, we concluded that the speed reduction for "None or Trace", "Light Rain" and "Heavy Rain" is 0, 10% (cell F2) and 17% (cell F3) respectively. The capacity reduction for both light and heavy rain is 6% (cell F4). The entire Florida is divided into three areas to reflect the differences in precipitation patterns. Table B-1 presents the three rainfall distribution regions.

Table B-1. Rainfall Distribution Regions

	Representative Location	Counties	Description
Region 1	Tallahassee	Escambia, Santa Rosa, Okaloosa, Walton, Holmes, Washington, Bay, Jackson, Calhoun, Gulf, Franklin, Liberty, Gadsden, Leon, Wakulla, Jefferson, Madison, Taylor, Hamilton, Suwannee, Lafayette, Dixie, Columbia, Baker, Union, levy, Gilchrist	Northwest extreme high precipitation area
Region 2	Orlando	Nassau, Duval, Clay, St. Johns, Putnam, Bradford, Alachua, Marion, Flagler, Volusia, Seminole, Lake, Citrus, Sumter, Hernando, Pasco, Pinellas, Hillsborough, Polk, Orange, Osceola, Brevard, Indian River, Okeechobee, Highlands, Hardee, Desoto, Manatee, Sarasota, Charlotte, Glades, Hendry, Lee, Collier	Central low precipitation area
Region 3	Miami	St. Lucie, Martin, Palm Beach, Broward, Miami-Dade, Monroe	Southeast high precipitation area

If the subject arterial section is located in Region 1, the value of Segment Location (cell F6) is 1; if it is located in Region 2, Segment Location is 2; and if it is located in Region 3, Segment Location is 3. The shape parameter k of the Gamma Distribution was estimated to be 0.2782, 0.3258, and 0.2872 for Region 1 (cell J5), Region 2 (cell J6), and Region 3 (cell J7), respectively.

Calculations

Column D:

Shape Parameter k of the Gamma Distribution = 0.2782 if Segment Location = 1; or Shape parameter k of Gamma Distribution = 0.3258, if Segment Location = 2; or Shape parameter k of Gamma Distribution = 0.2872, if Segment Location = 3.

Column E:

Scale Parameter θ of the Gamma Distribution = Average Rainfall/Shape Parameter k, if Average Rainfall is not 0; or Scale Parameter θ of the Gamma Distribution = 0.001/Shape Parameter k, if Average Rainfall equals to 0.

Column F:

Probability of Trace= GAMMADIST (0.01, k, θ, TRUE) (Returns the cumulative gamma distribution at 0.01 given values of k and θ). 0.01 is the upper bound of the rainfall intensity range for "Trace".

Column G:

Probability of Light Rain= GAMMADIST (0.5, k, θ, TRUE) - GAMMADIST (0.01, k, θ, TRUE). 0.01 and 0.5 are the lower and upper bounds of the rainfall intensity range for "Light Rain" respectively.

Column H:

Probability of Heavy Rain= 1- Probability of Light Rain - Probability of Trace

Column I:

Probability of Rain = Number of Rainy Days/72, (72 is the sample size of the rainfall data.) if Number of Rainy Days is not 0; or Probability of Rain = 0.001, if Number of Rainy Days equals to 0.

Column J:

Ratio of Light Rain to Light + Heavy Rain = Probability of Light Rain/(Probability of Light Rain + Probability of Heavy Rain).

Column K:

Ratio of Heavy Rain to Light + Heavy Rain = 1 - Ratio of Light Rain to Light + Heavy Rain.

Tab 6 and 7– Capacity-Demand 1 lane blocked / Capacity-Demand 2 lane blocked

These tabs include the 1 or 2 lane blocked calculations for different scenarios. The procedure followed is essentially the same in the two tabs, except the Number of Closed Lanes (Cells C12:C35) is 1 and 2 respectively, as indicated in the tab title, thus only Tab 6 (Capacity-Demand 1 lane blocked) is presented in this section.

The orange-highlighted cells indicate user input. The grey column headers indicate information related to the characteristics of the example section. The blue-highlighted column headings indicate output used as input in the intermediate calculations in other tabs.

Input

The capacity maintained for each lane under different number of lane blocked conditions for incident (cells C5:D7) and work zone (cells I5:J7) were not available. The numbers shown are provided for illustrative purposes only.

Seasonal Factors for arterial road for the 52 weeks of a year (cells AW38:CV38) were not available. FDOT Seasonal Factors for freeways were used here for illustrative purposes.

Calculations

Cells B12:B35:

The number of lanes per direction is obtained from the SR15 Inputs Tab (column J).

Cells C12:C35:

The Number of Closed Lanes is 1 as indicated in the tab title.

Cells D12:D35:

The LOS E, i.e. capacity without incident or work zone or rain, is obtained from the SR15 Inputs Tab (column T).

Columns E and F:

The peak and off-peak direction volume (vehicle per hour per direction) is obtained from the SR15 Inputs Tab (column N and O).

Cells H12:H35:

Capacity under no incident/no work zone (vphpd) = LOS E (Capacity without incident or work zone or rain).

Cells I12:I35:

Capacity under rain (vphpd) = LOS E (Capacity without incident or work zone or rain) * (1 - The capacity reduction from rain (Tab Rain Cell F4)).

Cells J12:J35:

If the Number of Lanes per direction is greater than the Number of Closed Lanes, the remaining capacity for the blocking incident is obtained from the Incident Capacity Table (cells C5:D7) as a function of the Number of Lanes per direction and the Number of Closed Lanes. Then Capacity under incident (vphpd) = LOS E * Remaining Capacity per lane for blocking incident * (Number of Lanes per direction - Number of Closed Lanes).

Cells K12:K35:

If the Number of Lanes per direction is greater than the Number of Closed Lanes, the remaining capacity for the blocking work zone is obtained from the Work Zone Capacity Table (cells I5:J7) as a function of the Number of Lanes per direction and the Number of Closed Lanes. Then Capacity under work zone (vphpd) = LOS E * Capacity Remains per lane for blocking work zone * (Number of Lanes per direction - Number of Closed Lanes).

Cells L12:L35:

Capacity under rain and incident (vphpd) = Capacity under incident * (1 - The capacity reduction from rain).

Cells M12:M35:

Capacity under rain and work zone (vphpd) = Capacity under work zone * (1 - The capacity reduction from rain).

Cells N12:N35:

Capacity under incident and work zone (vphpd) = Minimum (Capacity under incident, Capacity under work zone).

Cells O12:O35:

Capacity under rain, incident, and work zone (vphpd) = Capacity under incident and work zone * (1 - The capacity reduction from rain).

Columns AW to EV apply the FDOT seasonal factors (for the 52 weeks of the year) on both the peak and the off-peak direction volumes in order to obtain the average demand as well as the probability of demand over capacity for different scenarios. In particular:

Cells AW12:CV35:

Peak Direction Volume for each $week_i$ (vphpd) = Peak Direction Volume (vphpd)* FDOT Seasonal $Factors_i$, where i = the week #.

Cells CW12:EV35:

Off-peak Direction Volume for each $week_i$ (vphpd) = Off-peak Direction Volume (vphpd)* FDOT Seasonal $Factors_i$, where i = the week #.

Cells AW43:EV66:

Demand-Capacity $_{\text{no incident/no work zone}}$ = 0, if Direction Volume for each week < Capacity under no incident/no work zone (column H).

Demand-Capacity $_{\text{no incident/no work zone}}$ = 1, if Direction Volume for each week > Capacity under no incident/no work zone (column H).

Cells AW71:EV94:

Demand-Capacity $_{\text{rain}}$ = 0, if Direction Volume for each week < Capacity under rain (column I).

Demand-Capacity $_{\text{rain}}$ = 1, if Direction Volume for each week > Capacity under rain (column I).

Cells AW99:EV122:

Demand-Capacity $_{\text{incident}}$ = 0, if Direction Volume for each week < Capacity under incident (column J).

Demand-Capacity $_{\text{incident}}$ = 1, if Direction Volume for each week > Capacity under incident (column J).

Cells AW127:EV150:

Demand-Capacity $_{\text{work zone}}$ = 0, if Direction Volume for each week < Capacity under work zone (column K).

Demand-Capacity $_{\text{work zone}}$ = 1, if Direction Volume for each week > Capacity under work zone (column K).

Cells AW155:EV178:

Demand-Capacity $_{\text{rain and incident}}$ = 0, if Direction Volume for each week < Capacity under rain and incident (column L).

Demand-Capacity $_{\text{rain and incident}}$ = 1, if Direction Volume for each week > Capacity under rain and incident (column L).

Cells AW183:EV206:

Demand-Capacity $_{\text{rain and work zone}}$ = 0, if Direction Volume for each week < Capacity under rain and work zone (column M).

Demand-Capacity $_{\text{rain and work zone}}$ = 1, if Direction Volume for each week > Capacity under rain and work zone (column M).

Cells AW211:EV234:

Demand-Capacity $_{\text{incident and work zone}}$ = 0, if Direction Volume for each week < Capacity under incident and work zone (column N).

Demand-Capacity $_{\text{incident and work zone}}$ = 1, if Direction Volume for each week > Capacity under incident and work zone (column N).

Cells AW239:EV262:

Demand-Capacity $_{\text{rain, incident, and work zone}}$= 0, if Direction Volume for each week < Capacity under rain, incident, and work zone (column O).

Demand-Capacity $_{\text{rain, incident, and work zone}}$ = 1, if Direction Volume for each week > Capacity under rain, incident, and work zone (column O).

Column AS:

weeks Demand > Capacity = SUM of the Demand-Capacity cells.

Column AT:

% of weeks Demand > Capacity = (# weeks Demand > Capacity)/(2*52).

Column AU:

Demand Uncongested = Average of Directional Volumes of the weeks where Demand-Capacity = 0 / (Number of Lanes per direction - Number of Closed Lanes), if (# weeks Demand > Capacity) ≠ 104.

Demand Uncongested = blank, if (# weeks Demand > Capacity) = 104.

Column AV:

Demand Congested = Average of Directional Volumes of the weeks where Demand-Capacity = 1 / (Number of Lanes per direction - Number of Closed Lanes), if (# weeks Demand > Capacity) ≠ 0.

Demand Congested = blank, if (# weeks Demand > Capacity) = 0.

Columns Q,R,S,T,U,V,W,X:

Probability of demand over capacity = % of weeks Demand > Capacity (column AT), depending on the scenario.

Columns Z,AA,AB,AC,AD,AE,AF,AG:

Demand under uncongested conditions = Demand uncongested (column AU), depending on the scenario.

Columns AI,AJ,AK,AL,AM,AN,AO,AP:

Demand under congested conditions = Demand congested (column AV), depending on the scenario.

Tab 8 – Intermediate Scenario Calc

This tab calculates the average incident duration, average # lanes blocked by incidents/ total # lanes, Average Demand (vphpl), and Probability of Occurrence for different scenarios. These are shown in blue header columns and are subsequently used as input in the SR 15 Final Calc Tab.

Input from other Tabs

Column B:

Number of Lanes per direction is obtained from the SR 15 Inputs Tab (column J).

Cells C5:C28:

Probability of Rain is obtained from the Rain Tab (column I).

For One-Lane Blocked Scenario:

Cells C65:C88:

Number of Closed Lanes is obtained from the Capacity-Demand 1 lane blocked Tab (column C).

Cells E65:J88:

PROBABILITY & DURATION OF INCIDENT is obtained from the SR 15 Inputs Tab (cells V8:AA31).

Cells L65:S88:

PROBABILITY OF DEMAND OVER CAPACITY is obtained from the Capacity-Demand 1 lane blocked Tab (cells Q12:X35).

Cells U65:AB88:

DEMAND UNDER UNCONGESTED CONDITIONS is obtained from the Capacity-Demand 1 lane blocked Tab (cells Z12:AG35).

Cells AD65:AK88:

DEMAND UNDER CONGESTED CONDITIONS is obtained from the Capacity-Demand 1 lane blocked Tab (cells AI12:AP35).

For Two-Lane Blocked Scenario:

Cells C95:C118:

Number of Closed Lanes is obtained from the Capacity-Demand 2 lane blocked Tab (column C).

Cells E95:J118:

PROBABILITY & DURATION OF INCIDENT is obtained from the SR 15 Inputs Tab (cells V35:AA58).

Cells L95:S118:

PROBABILITY OF DEMAND OVER CAPACITY is obtained from the Capacity-Demand 2 lane blocked Tab (cells Q12:X35).

Cells U95:AB118:

DEMAND UNDER UNCONGESTED CONDITIONS is obtained from the Capacity-Demand 2 lane blocked Tab (cells Z12:AG35).

Cells AD95:AK118:

DEMAND UNDER CONGESTED CONDITIONS is obtained from the Capacity-Demand 2 lane blocked Tab (cells AI12:AP35).

Calculations

*If the probability of occurrence is equal to zero, this means the scenario will not occur at this specific time for this section. Thus the corresponding duration, # lanes blocked, and demand are shown as blank.

For Non-Congested Scenario:

Cells E5:E28:

Incident Duration = 0.

Cells F5:F28:

lanes blocked by incidents/ total # lanes = 0.

Cells G5:G28:

Demand (vphpl) = Uncongested Demand under no incident/no work zone (vphpl) (U65:U88).

Cells H5:H28:

Prob of Occurrence = (1- Probability of Rain)*(1- Probability of Demand over Capacity under no incident/no work zone), if Number of Lanes per direction = 1;

Prob of Occurrence = (1- Probability of 1 Lane Blocked Incident)*(1- Probability of 1 Lane Blocked Work Zone)*(1- Probability of Rain)*(1- Probability of Demand over Capacity under no incident/no work zone), if Number of Lanes per direction = 2;

Prob of Occurrence = (1- Probability of 1 Lane Blocked Incident- Probability of 2 Lane Blocked Incident)*(1- Probability of 1 Lane Blocked Work Zone- Probability of 2 Lane Blocked Work Zone)*(1- Probability of Rain)*(1- Probability of Demand over Capacity under no incident/no work zone), if Number of Lanes per direction = 3.

For Non-Congested with Rain Scenario:

Cells J5:J28:

Incident Duration = 0.

Cells K5:28:

lanes blocked by incidents/ total # lanes = 0.

Cells L5:L28:

Demand (vphpl) = Uncongested Demand under rain (vphpl) (V65:V88).

Cells M5:M28:

Prob of Occurrence = Probability of Rain*(1- Probability of Demand over Capacity under no incident/no work zone), if Number of Lanes per direction = 1;

Prob of Occurrence = (1- Probability of 1 Lane Blocked Incident)*(1- Probability of 1 Lane Blocked Work Zone)*Probability of Rain*(1- Probability of Demand over Capacity under no incident/no work zone), if Number of Lanes per direction = 2;

Prob of Occurrence = (1- Probability of 1 Lane Blocked Incident- Probability of 2 Lane Blocked Incident)*(1- Probability of 1 Lane Blocked Work Zone- Probability of 2 Lane Blocked Work Zone)*Probability of Rain*(1- Probability of Demand over Capacity under no incident/no work zone), if Number of Lanes per direction = 3.

For Non-Congested with Incident Scenario:

Cells O5:O28:

Incident Duration = blank, if Number of Lanes per direction = 1;

Incident Duration = 1 Lane Blocked Incident Duration, if Number of Lanes per direction = 2;

Incident Duration = (1 Lane Blocked Incident Duration*Probability of 1 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 1 lane blocked) + 2 Lane Blocked Incident Duration*Probability of 2 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 2 lane blocked)) / (Probability of 1 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 1 lane blocked) + Probability of 2 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 2 lane blocked)), if Number of Lanes per direction = 3.

Cells P5:P28:

lanes blocked by incidents/ total # lanes = blank, if Number of Lanes per direction = 1;

lanes blocked by incidents/ total # lanes = 1/2, if Number of Lanes per direction = 2;

lanes blocked by incidents/ total # lanes = (1*Probability of 1 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 1 lane blocked) + 2*Probability of 2 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 2 lane blocked)) / (Probability of 1 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 1 lane blocked) + Probability of 2 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 2 lane blocked)), if Number of Lanes per direction = 3.

Cells Q5:Q28:

Demand = blank, if Number of Lanes per direction = 1;

Demand = Uncongested Demand under incident for 1 lane blocked, if Number of Lanes per direction = 2;

Demand = (Uncongested Demand under incident for 1 lane blocked*Probability of 1 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 1 lane blocked) + Uncongested Demand under incident for 2 lane blocked*Probability of 2 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 2 lane blocked)) / (Probability of 1 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 1 lane blocked) + Probability of 2 Lane Blocked Incident*(1- Probability of Demand over Capacity under incident for 2 lane blocked)), if Number of Lanes per direction = 3.

Cells R5:R28:

Prob of Occurrence = 0, if Number of Lanes per direction = 1;

Prob of Occurrence = Probability of 1 Lane Blocked Incident*(1- Probability of 1 Lane Blocked Work Zone)*(1-Probability of Rain)*(1- Probability of Demand over Capacity under incident for 1 lane blocked), if Number of Lanes per direction = 2;

Prob of Occurrence = Probability of 1 Lane Blocked Incident*(1- Probability of 1 Lane Blocked Work Zone- Probability of 2 Lane Blocked Work Zone)*(1-Probability of Rain)*(1- Probability of Demand over Capacity under incident for 1 lane blocked) + Probability of 2 Lane Blocked Incident*(1- Probability of 1 Lane Blocked Work Zone- Probability of 2 Lane Blocked Work Zone)*(1-Probability of Rain)*(1- Probability of Demand over Capacity under incident for 2 lane blocked), if Number of Lanes per direction = 3.

For Non-congested with work zone, Non-congested with rain and incident, Non-congested with rain and work zone, Non-congested with incident and work zone, Non-congested with rain, incident, work zone, Congested, Congested with rain, Congested with incident, Congested with work zone, Congested with rain and incident, Congested with rain and work zone, Congested with incident and work zone, Congested with rain, incident, work zone Scenarios, the calculations are similar.

Tab 9 – SR 15 Final Calc

This tab calculates the travel time under different scenarios and the average travel time for the example section. The orange-highlighted cells indicate user input. The grey column headers indicate information related to the characteristics of the example section. The blue column headers are reserved for the travel times and probabilities of each scenario and the purple column headers and highlighted cells are the results (yearly averages).

Input

Cells F3:M4:

The coefficients of the travel time estimation models from the project report.

Calculations

Column B:

Length is obtained from the SR 15 Inputs Tab (column H).

Columns C and D:

The peak and off-peak direction volume is obtained from the SR15 Inputs Tab (column N and O).

Column F,G,H,I:

They obtain their respective values from the SR15 Inputs Tab (cells V3:Y3).

Column J:

Constant is used in the travel time estimation model calculation and given as 1.

Column L:

Free-Flow Speed is obtained from the SR 15 Inputs Tab (cell Z3).

Column M:

FFS adjusted for Light Rain = FFS*(1- Free-flow speed reduction for Light Rain).

Column N:

FFS adjusted for Heavy Rain = FFS*(1- Free-flow speed reduction for Heavy Rain).

Columns O,P:

Light and Heavy rain ratios are obtained from their corresponding columns on the Rain tab.

Column Q:

Equivalent Free-flow Travel Time for Rain = ((Ratio of Light Rain to Total Rain*(3600/FFS adjusted for Light Rain)) + (Ratio of Heavy Rain to Total Rain*(3600/FFS adjusted for Heavy Rain)))*Length.

Column R:

FFS adjusted for Rain = Length*3600 / Equivalent Free-flow Travel Time for Rain.

Columns U,W,Y,AA,AC,AE,AG,AI,AK,AM,AO,AQ,AS,AU,AW,AY:

Probability of occurrence for each scenario is obtained from the Intermediate Scenario Calc Tab.

Columns T,V,X,Z,AB,AD,AF,AH:

If the probability of occurrence is equal to zero, this means the scenario will not occur at this specific time for this section and the corresponding scenario travel time is shown as blank.

Non-congested scenarios travel time (sec) = (60/FFS (or FFS adjusted for Rain for scenarios with rain) + 0.001603*incident duration + 0.084618* # lanes blocked by incidents/ total # lanes + 0.001413*demand + 0.012962* Cycle Length + 0.204141* # Signals/mile – 4.70594*Arterial g/C Ratio – 0.52147*Progression + (-60*0.012962-03*(–4.70594))*1)*Length*60.

Columns AJ,AL,AN,AP,AR,AT,AV,AX:

If the probability of occurrence is equal to zero, this means the scenario will not occur at this specific time for this section and the corresponding scenario travel time is shown as blank.

Congested scenarios travel time (sec) = (60/FFS (or FFS adjusted for Rain for scenarios with rain) + 0.030626*incident duration + 0.727794* # lanes blocked by incidents/ total # lanes + 0.005191*demand + 0.037972* Cycle Length + 0.136407* # Signals/mile – 24.1586*Arterial g/C Ratio – 0.82938*Progression + (-60*0.037972-03*(–24.1586))*1)*Length*60.

Column BA:

Total Probability Check = the sum of all scenario probabilities (must be 100%).

Column BB:

Annual Expected TT = the sum of all scenario probability*scenario travel time.

Column BD:

Annual Average Speed = Length / (Annual Expected TT/3600).

Column BF:

Calculations for TT Weighted By Demand = Annual Expected TT*(PD HourVol + OD HourVol).

Cell BB33:

Avg. Annual TT = Average of the hourly Annual Expected.

Cell BD33:

Avg. Annual Speed = Length / (Avg. Annual TT/3600).

Cell BF33:

Avg. Annual TT/mile = Avg. Annual TT / Length.

Cell BB34:

Avg. Weighted by Hourly Demand TT = (the sum of Calculations for TT Weighted By Demand) / (Total of PD HourVol + Total of OD HourVol).

Cell BD34:

Avg. Weighted by Hourly Demand Speed = Length / (Avg. Weighted by Hourly Demand TT/3600).

Cell BF34:

Avg. Weighted by Hourly Demand TT/mile = Avg. Weighted by Hourly Demand TT / Length.

Tabs 10 and 11 – Reliability All Day / Reliability 4-7

In these tabs the results of the SR 15 Final Calc Tab are used to estimate reliability performance measures. The procedure followed is essentially the same in the two tabs, thus only Tab 10 (Reliability All Day) will be discussed here.

Input

There is no manual input in this tab, as everything is obtained from another tab. In cells AI11 and AI12 the total days in a year and the total hours in a year are found.

Calculations

Column C:

Travel Time is obtained from all the Travel Time columns of the SR 15 Final Calc Tab.

Column D:

Frequency (%) is obtained from all the Probability of Occurrence columns of the SR 15 Final Calc Tab.

Column E:

Average Speed = Length/(Travel Time/3600)

Column F:

Frequency (hours) = Frequency (%) * Total days in a year.

Column G:

Flow - Both Directions = PD HourVol + OD Hour Vol (from the SR 15 Final Calc Tab).

Column H:

Annual Hourly Volume = Frequency (hours) * Flow-Both Directions

Column I:

TT*Freq (%) = Travel Time * Frequency (%).

Cells F393, H393:

The sums of Frequency (hours), Annual Hourly Volume

Column K:

Free-flow Travel Time = Section Length / (Free-flow Speed (SR 15 Inputs Cell AB3) / 3600)

Column L:

Section Hourly Volume = Flow - Both Directions

Column M:

Hourly Avg. TT (Weighted by Freq) = Sum of TT*Freq(%) of each scenario

Column N:

Hourly Avg. Speed (Weighted by Freq) = Section Length/(Hourly Avg. TT/3600)

Column O:

Hourly Travel Time Index = Hourly Avg. TT/Free-flow Travel Time

Cell M36:

Daily Average TT (Weighted by Freq) = Average of Hourly Avg. TT (Column M)

Cell M37:

Daily Average TT (Weighted by volume) = Section Hourly Volume (Column L) Weighted Average of Hourly Avg. TT (Column M)

Cell M39:

Daily Average Speed (Weighted by Freq) = Average of Hourly Avg. Speed (Column N)

Cell M40:

Daily Average Speed (Weighted by volume) = Section Hourly Volume (Column L) Weighted Average of Hourly Avg. Speed (Column N)

Cell M42:

Daily TTI (Weighted by Freq) = Average of Hourly Travel Time Index (Column O)

Cell M43:

Daily TTI (Weighted by volume) = Section Hourly Volume (Column L) Weighted Average of Hourly Travel Time Index (Column O)

Columns P, Q, R:

These are columns C, E, F sorted by Travel Time.

Column S:

Cumulative Hours = the cumulative of the sorted Frequency (hours).

Column V:

Frequency (Hours) by brackets in order to be used in a Chart. Refers to column R.

Columns W, X, Y:

These are columns C, E, H sorted by Travel Time.

Column Z:

Cumulative Volume = the cumulative of the sorted Volume.

Column AC:

Total Vehicles by brackets in order to be used in a Chart. Refers to column Y.

Travel Time Reliability Calculations

Cell AI11, AI12:

Total days in a year and the total hours in a year.

Cell AI13:

Total Annual Volume = Sum of Column H.

Cell AJ17:

Travel time corresponding to 10 mph = Length*3600/10.

We seek the last travel time value on column Q and X less than 10 mph and we highlight that line in yellow.

Cell AI18:

Percent of time travel speed is above 10 mph = Highlighted cell (see above) in the Cumulative Hours column / Total hours in a year.

Cell AI19:

Percent of trips travel speed is above 10 mph = Highlighted cell (see above) in the Cumulative Volume column / Total Annual volume.

Cell AJ21:

Travel time corresponding to 15 mph = Length*3600/15.

We seek the last travel time value on column Q and X less than 15 mph and we highlight that line in yellow.

Cell AI22:

Percent of time travel speed is above 15 mph = Highlighted cell (see above) in the Cumulative Hours column / Total hours in a year.

Cell AI23:

Percent of trips travel speed is above 15 mph = Highlighted cell (see above) in the Cumulative Volume column / Total Annual volume.

Cell AI27:

95% of the Total Annual Volume = Total Annual Volume*95%

We seek the last cumulative volume value on column Z that is less than the 95% of total annual volume and we highlight that line in yellow.

Cell AK27:

Travel Time corresponding to 95% of time = The value of the highlighted cell (see above) on the sorted Travel Time column (Column W).

Cell AM27:

Travel Speed corresponding to 95% of time = The value of the highlighted cell (see above) on the sorted Average Speed column (Column X).

Cell AJ28:

Free-Flow (LOS C Threshold Speed) Travel Time = The value in Cell K8.

Cell AJ29:

Planning Time Index based on number of trips = Travel Time corresponding to 95% of trips / Free-flow Travel Time.

Cell AI31:

95% of the Total Hours in a Year = Total hours in a year*95%

We seek the last cumulative hours value on column S that is less than the 95% of total hours in a year and we highlight that line in yellow.

Cell AK31:

Travel Time corresponding to 95% of time = The value of the highlighted cell (see above) on the sorted Travel Time column (Column P).

Cell AM31:

Travel Speed corresponding to 95% of time = The value of the highlighted cell (see above) on the sorted Average Speed column (Column Q).

Cell AJ32:

Free-Flow (LOS C Threshold Speed) Travel Time = The value in Cell K8.

Cell AJ33:

Planning Time Index based on number of trips = Travel Time corresponding to 95% of hours / Free-flow Travel Time.

Cell AJ37:

Volume Weighted Daily Average TT = The value in Cell M37

Cell AJ41:

Daily Average TT Weighted by Frequency = The value in Cell M36

Cell AJ38, AJ42:

Free-Flow (LOS C Threshold Speed) Travel Time = The value in Cell K8.

Cell AJ39:

Travel Time Index based on number of trips = Volume Weighted Daily Average TT/ Free-flow Travel Time

Cell AJ43:

Travel Time Index based on frequency = Daily Average TT Weighted by Frequency/ Free-flow Travel Time