FINAL REPORT

to

THE FLORIDA DEPARTMENT OF TRANSPORTATION
SYSTEMS PLANNING OFFICE

on Project

"Travel Time Reliability Models"

FDOT Contract BD-545, RPWO #75 (UF Project 00063433)

August 31, 2008

The University of Florida

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Florida Department of Transportation.

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

Two previous FDOT research projects (FDOT Contracts BD-545-48 and BD-545-70) on travel time reliability developed models for predicting travel time reliability for freeways, using data from Philadelphia, PA. The objectives of this research are to implement the results of these projects to estimate travel time reliability on the Florida Strategic Intermodal System (SIS), to enhance the previously developed models based on Florida data, and to develop a framework for estimating travel time on arterial streets.

The first part of the report describes a methodology and the respective tools for estimating travel time reliability for a freeway section as well as for a freeway network, and it applies those tools to estimate various travel time reliability measures for a freeway section in South Florida.The second part of the report summarizes the data analysis conducted using data from Jacksonville, FL, to evaluate the travel time estimation models previously developed. It was concluded that the differences between model estimates and field observations are relatively low for non-congested conditions (less than 5%), while they are relatively large for congested conditions (as high as 23.7%). The discrepancies may be due to model limitations as well as sensor calibration issues. The third part of the report developed a framework for estimating arterial travel time and obtaining the related travel time reliability performance measures. It is recommended that a total of 16 scenarios be used to obtain travel time estimates for arterials.

Future work should focus on obtaining field data to calibrate the conceptual models provided in this report. Generally, it is recommended that the methodology developed and illustrated in this report be implemented to estimate travel time reliability for the SIS, and evaluate the model predictions for existing conditions. Such an evaluation will identify any atypical conditions for which adjustments to the existing models need to be made, and will identify any inconsistencies between predicted and observed travel times. Subsequently, the application can be used to test various project implementations, and estimate travel time reliability in the entire SIS, or in specific SIS sections as a function of various operational and design changes.

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EXECUTIVE SUMMARY

The goal of the Strategic Intermodal System (SIS) is to provide a transportation system that efficiently serves Florida's citizens, businesses and visitors; helps Florida become a worldwide economic leader; enhances economic prosperity and competitiveness; enriches quality of life; and reflects responsible environmental stewardship. The SIS is composed of transportation facilities and services of statewide and interregional significance, including both freeways and arterials. Much research on the SIS and its users is needed. Travel time reliability is widely recognized as one of, if not the, most important performance measure of highway traveler perceptions.

Two previous FDOT research projects (FDOT Contracts BD-545-48 and BD-545-70) on travel time reliability developed models for predicting travel time reliability for freeways, using data from Philadelphia, PA. The objectives of this research are to implement the results of these projects to estimate travel time reliability on the Florida SIS, to enhance the previously developed models based on Florida data, and to develop a framework for estimating travel time on arterial streets. Research under this project implemented the results of two previous FDOT-funded projects to estimate travel time reliability on the Florida SIS, evaluated the previously developed models based on Florida data, and developed a framework for estimating travel time on arterial streets.

The first part of the report describes a methodology and the respective tools for estimating travel time reliability for a freeway section as well as for a freeway network. Then, it applies those tools to estimate various travel time reliability measures for a freeway section in South Florida. The methods and tools developed can be used as follows:

- Project prioritization based on travel time reliability (either on-time arrival or buffer index) can be performed. Based on agency needs and priorities, travel time reliability can be estimated for given time periods in a year (seasonal or hourly estimates), and projects can be prioritized to improve sections with the lowest reliability.
- Impacts of various types of programs or improvements (such as road rangers, incident removal duration, work zones,) on the expected reliability for each

section as well as for the entire system can be estimated. Such improvements can be evaluated considering hours and days of operation, sections affected, etc.

- Travel time reliability can be reported annually to legislators and other decision makers, and can be monitored over time.
- Freight shippers may find the tool useful as an initial planning tool for routing and scheduling trips through major metropolitan areas. It could also serve as a major mobility performance measure for freight.

It should be stressed that the methods and results presented here are the first effort to estimate travel time reliability on a section and freeway network, and it is expected that many refinements will be added to improve accuracy and facilitate the use of the tool for additional applications. Suggested refinements include the following:

- Refinement of travel time estimation models based on a more extensive set of Florida data; as additional data become available in Florida, the travel time estimation models used here can be refined to better represent Florida conditions, and also to consider various types of freeways.
- Refinement of incident data based on section-by-section information; if additional, more detailed data become available to provide incident information on a section-by-section basis, these can be used to estimate more accurately the frequency of incidents by section, and also the resulting travel times during incidents.
- Data regarding work zones; the investigators were not able to locate work zone frequency information for the study area. If these data become available in the future, they can be entered into the existing tools to improve their accuracy.
- Improving spillover effects from one section to another; for example, the effects of a major incident are currently limited in time and space to individual sections and do not extend upstream. A related issue is the consideration of demand values, rather than flows, in estimating travel time. Current models are based on flows measured at detector locations, and they do not consider the queues developing upstream and the additional travel time spent in the upstream queue.

- Refinement of capacity values to account for capacity drop during oversaturated conditions.

The second part of the report summarizes the data analysis conducted using data from Jacksonville, FL, to evaluate the travel time estimation models previously developed. As shown, the differences between model estimates and field observations are relatively low for non-congested conditions (less than 5%), while they are relatively large for congested conditions (as high as 23.7%). These differences for congested conditions can be attributed to several reasons, including model limitations as well as sensor calibration issues. It is recommended that future research address travel time estimation upstream of bottlenecks, to refine the existing models.

The third part of the report developed a framework for estimating arterial travel time and obtaining the related travel time reliability performance measures. It is recommended that a total of 16 scenarios be used to obtain travel time estimates for arterials. Future work should focus on obtaining field data to calibrate the conceptual models provided in this report. Another possible alternative is the use of simulation to estimate travel times, at least for scenarios involving congested conditions, incidents and work zones; simulation cannot be used to replicate rain conditions.

Generally, it is recommended that the methodology developed and illustrated in this report be implemented to estimate travel time reliability for the SIS, and evaluate the model predictions for existing conditions. Such an evaluation will identify any atypical conditions for which adjustments to the existing models need to be made, and will identify any inconsistencies between predicted and observed travel times. Subsequently, the application can be used to test various project implementations, and estimate travel time reliability in the entire SIS, or in specific SIS sections as a function of various operational and design changes.

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I. BACKGROUND

Travel times fluctuate for various reasons, including times when demand exceeds capacity, and when there are incidents, work zones, adverse weather conditions, and special events. The study of travel time reliability aims to quantify the effects of such conditions on travel time along a section or facility over a long period of time, say a year. The results of such studies can be used for various purposes including: a) provision of travel time estimates to drivers so that they can plan their trips, and b) provision of a metric or group of metrics to transportation agencies, which can be used to make systems planning and project development decisions.

There has recently been a lot of research on travel time reliability through the SHRP2 program (http://www.trb.org/SHRP2/). In the SHRP2 program travel time reliability is generally defined as the variability of travel times over a long period of time. One of the major projects currently underway under that program (L03: "*Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies*", described in http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2179) aims to develop statistical relationships between highway improvements and travel time reliability. The project will collect a significant amount of field data, across the country, and it is expected to be completed in 2009. There are several additional projects underway and planned under the SHRP2 program that focus on reliability.

Several states (Minnesota, Virginia, Washington, and others) have also started conducting research and attempting to incorporate travel time reliability into their operations, planning, and decision making processes (Cambridge Systematics, Inc., 2004). The Florida Department of Transportation (FDOT) has taken a leadership role in developing mobility measures in general and reliability measures in particular. FDOT is interested in incorporating travel time reliability in its performance measurement program, and has been taking significant steps toward achieving that goal. FDOT senior management has taken the position that reliability will be included as a performance measure at both planning and operations levels. It is to be used to evaluate the effectiveness of the Florida's Intelligent Transportation System (ITS) program and for reporting on Florida's Strategic Intermodal System (SIS), roughly Florida's equivalent to the National Highway System.

The goal of the Strategic Intermodal System (SIS) is to provide a transportation system that efficiently serves Florida's citizens, businesses and visitors; helps Florida become a worldwide economic leader; enhances economic prosperity and competitiveness; enriches quality of life; and reflects responsible environmental stewardship. The SIS is composed of transportation facilities and services of statewide and interregional significance, including both freeways and arterials. Much research on the SIS and its users is needed.

Travel time reliability is widely recognized as one of, if not the, most important performance measure of highway traveler perceptions. The challenges of estimating travel times are daunting, considering that only a fraction of the SIS mileage can be used to directly measure travel times and estimate reliability. Two previous FDOT research projects (Elefteriadou and Cui, 2007, and Elefteriadou and Xu, 2007) on travel time reliability developed models for predicting travel time reliability for freeways, using data from Philadelphia, PA. The objectives of this research are to implement the results of these projects to estimate travel time reliability on the Florida SIS, to enhance the previously developed models based on Florida data, and to develop a framework for estimating travel time on arterial streets.

The next section summarizes the methodology used to estimate travel time reliablity on the SIS, and section three provides an example application for estimating travel time reliability on a freeway section in Broward County, FL. Section four discusses the data analysis conducted using field data from Jacksonville, FL to evaluate the previously developed travel time estimation models. Section five provides a recmmended framework for estimating travel time on arterial streets, while the last section summarizes the conclusions and recommendations of the research.

II. ESTIMATING TRAVEL TIME RELIABILITY ON THE SIS

This section provides an overview of the methodology developed to estimate travel time reliability for a freeway section, and then for a freeway network. The methodology was implemented using a Microsoft Excel spreadsheet, and will ultimately be implemented in conjunction with the FDOT Mobility Performance Measures Program. The following steps are followed (Figure 1):

First, the freeway network to be analyzed is segmented at a section level (interchange to interchange). Interchanges and beginning and ending milepost numbers are obtained from FDOT's Roadway Characteristics Inventory.

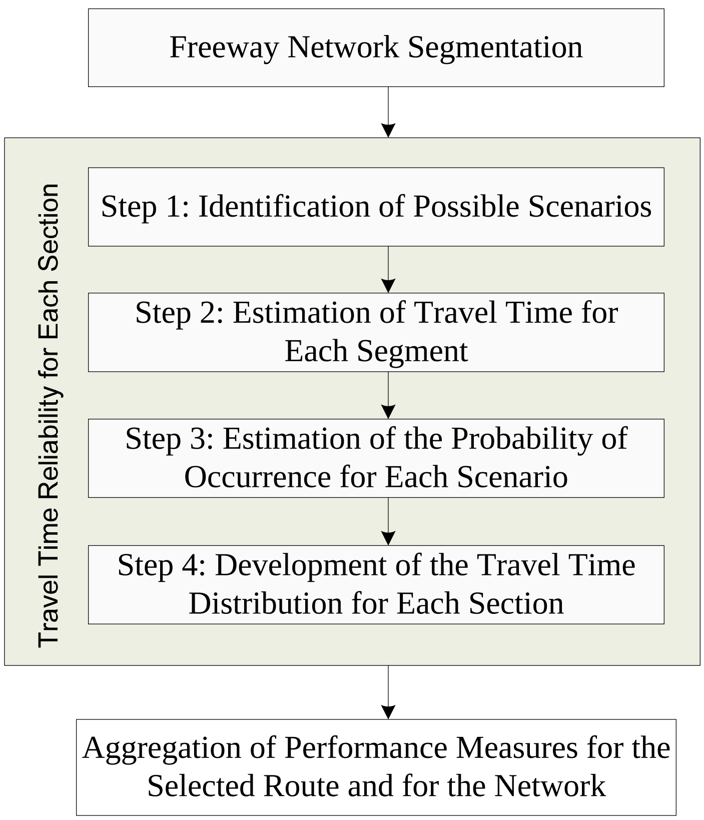


Figure 1 Methodology Overview

Second, travel time reliability measures are obtained for each freeway section in the network according to the following procedure:

Step 1: Identification of the possible scenarios that may occur on any given freeway section. For example, one scenario may be that the section is congested and in addition there is an incident occurring along its length. Another scenario may be that the section is not congested, but there is a work zone along its length.

Step 2: Estimation of travel time for each scenario identified in Step 1.

Step 3: Estimation of the probability of occurrence for each scenario identified in Step 1.

Step 4: Development of the travel time distribution for the section, and estimation of selected travel time reliability measures based on this distribution.

Finally, the travel time reliability for the entire freeway network is estimated by aggregating the respective measures for each of the sections analyzed. Each of those steps is discussed in more detail in the remainder of this section.

Freeway Network Segmentation

First, a freeway facility is segmented into sections at appropriate points, so that travel time estimates can be obtained along each section. Then, performance measures for consecutive freeway sections can be grouped together at a "facility" level for reporting purposes. FDOT statewide criteria for segmentation are based on the location of the following major points (provided in ranked order):

1. Strategic Intermodal System (SIS) freeway to SIS freeway interchanges
    a. Non-SIS freeways are also a major consideration; and
    b. Logical extensions of SIS freeways if a short gap of freeway is missing. (This scenario occurs if a freeway terminates, and a major arterial provides connection to another freeway)
2. Non-adjacent urbanized area boundaries

    a. Transitioning and rural boundaries are also considered as segmentation points.
3. SIS intersecting routes
4. Other special considerations
    a. Major downtown core areas; these are typically handled as one section
    b. SIS multimodal hubs (e.g., international airports); and
    c. State boundaries.
5. Length
    a. Consideration given to area type in which the freeway is located; and
    b. Short extension of freeways leading to the arterial network.

Figure 2 shows the facility aggregations used in this study for Broward County. Although these criteria were used to segment Florida's whole freeway network for reporting purposes, the facility lengths over which travel time reliability is estimated may be extended or shortened according to the desired analytical purposes. For example, if an analyst wanted to assess travel time reliability of I-95 from downtown Miami to downtown West Palm Beach extending all the way through Broward County, that can be readily done. Alternatively, if an analyst wanted to evaluate I-95 from Hollywood to Ft. Lauderdale, Broward County's two largest cities, that can also be easily done.

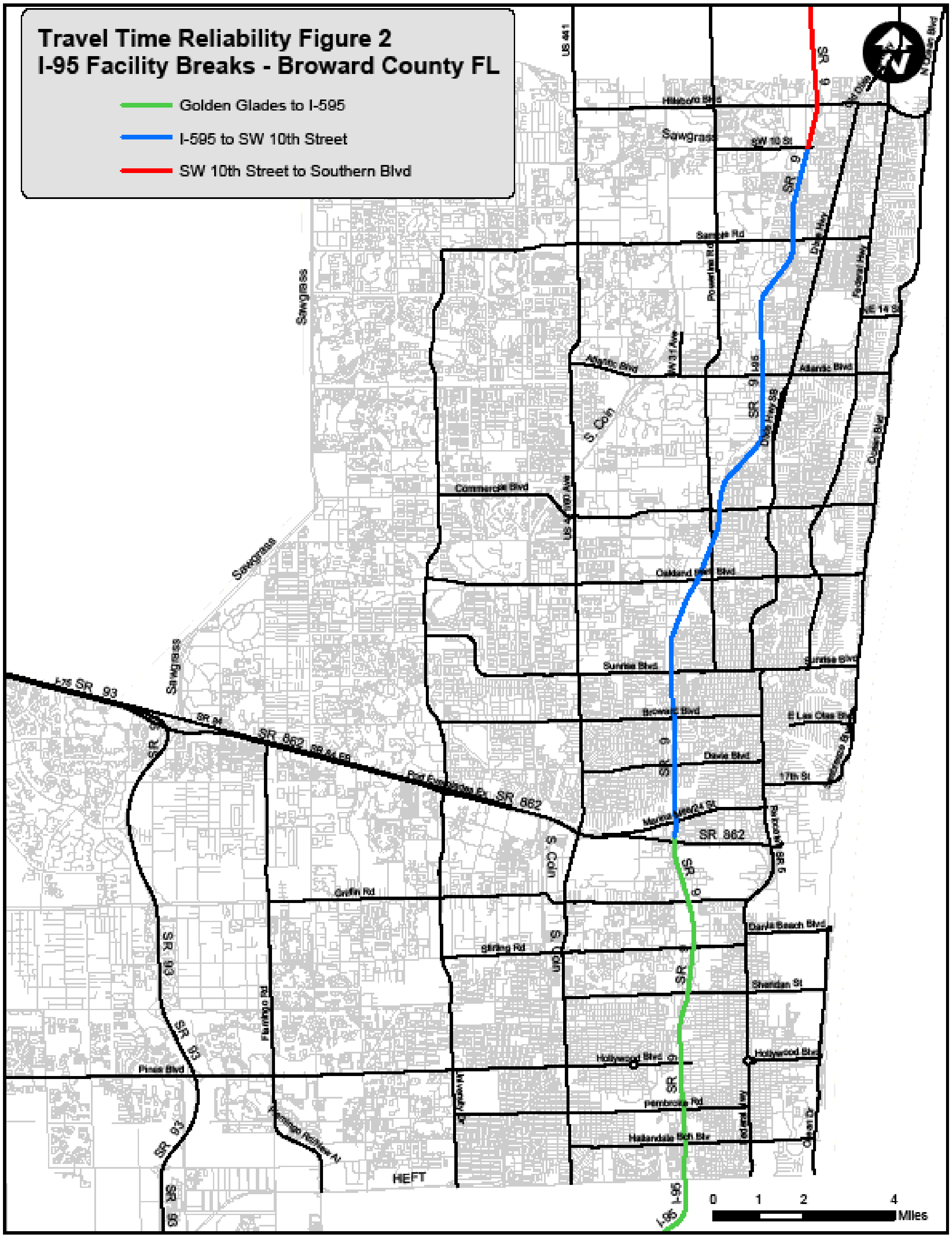


Figure 2 Facility Aggregations for Broward County

Estimating Travel Time Reliability for a Freeway Section

This subsection provides detailed information regarding each of the steps followed to estimate travel time reliability for a given freeway section. Data sources used in developing and applying this model are also provided here; however, agencies interested in applying this work in their own jurisdictions would have to rely on different data sources, and adjust the application of the methodology according to the data available to them.

Step 1: Identification of the possible scenarios that may occur on any given freeway section

In this research, the conditions considered are as follows:

- Recurring traffic congestion (due to high demand only)
- Incidents
    - Lane-blocking incidents
    - Non-lane blocking incidents
- Weather
    - Clear weather
    - Rain (average precipitation by hour)
- Work zones

There are a total of 24 scenarios which could occur as combinations of the above list of conditions. These conditions were selected based on the availability of information typically available from FDOT regarding those specific conditions, and also to maintain a reasonable number of scenarios for this initial effort. In future work, additional conditions may be identified as important; the tools developed here could be modified accordingly to incorporate them. Also, for other agencies interested in applying this method, the conditions selected may be different (for example, state agencies in the northern US would likely need to add snowfall-related scenarios).

Step 2: Estimation of travel time for each scenario identified in Step 1

The travel time estimates for each scenario are based on models developed in (4, 5). As described in those references, travel time estimation models were developed based on field data from Philadelphia, PA. At the time this research was initiated, there were no suitable data available in Florida; therefore, the data set used was from a relatively level freeway facility in Pennsylvania. The data were obtained over a period of four months (May-August 2004) from the Philadelphia Transportation Management Center (TMC), and Mobility Technologies, a traveler information provider. The data set included spot speeds, volume, and occupancy data for an 8.72 mile portion of US 202 located in Philadelphia, PA. There were eight data collection locations which recorded speeds and flows for 24 hours a day, seven days a week, in one-minute intervals. These data were collected by Mobility Technologies using Remote Traffic Microwave Sensors (RTMS). Five CCTV cameras installed along the study area were also used to obtain sample travel times for validation purposes.

For each scenario identified in Step 1, and based on the data set from Philadelphia, PA, a model was developed to predict travel time based on all relevant factors (i.e., congestion level, weather conditions, impact of work zone level, and impact of incident level). These models are of the form:

$$E(TT_{scenario}) = f(congestion, weather, work\_zone, incident)$$

Table 1 shows the developed travel time estimation models for each scenario. As shown, the database did not contain enough data to develop models for some of the scenarios, particularly for those involving work zones and incidents. In that project, models were not specifically developed for non-lane-blocking incidents. However, those types of incidents may also affect travel time, particularly for non-congested conditions. Therefore, the following assumptions had to be employed to estimate travel time under those conditions:

SCENARIO 1: NON-CONGESTED CONDITIONS

Travel time was estimated by using an upper boundary for the number of lanes, not allowing it to get higher than 3 lanes, which was the maximum for the Philadelphia data. Generally, the non-congested travel time should not be further reduced as the number of lanes increases beyond 3 lanes per direction. The probability of occurrence for this scenario was estimated as follows:

Probability of non-congested conditions = 1 - prob of demand over capacity - probability of occurrence of other non-congested scenarios

SCENARIOS 3A, 5A, 7A, 8A, : NON-CONGESTED CONDITIONS WITH A NON-LANE-BLOCKING INCIDENT

It was assumed that if a non-lane-blocking incident occurs, the travel time would increase relative to the respective scenario with out an incident by 8% (which corresponds to approximately a 5 mph speed drop for a 65 mph FFS).

SCENARIO 6: NON-CONGESTED CONDITIONS WITH RAIN AND WORK ZONE

It was assumed the travel time under this scenario would be equal to the scenario of non-congested conditions with rain and incident.

SCENARIO 7: NON-CONGESTED CONDITIONS WITH INCIDENT AND WORK ZONE

It was assumed the travel time under this scenario would be equal to the scenario of non-congested conditions with incident multiplied by 1.2.

SCENARIO 8: NON-CONGESTED CONDITIONS WITH INCIDENT, WORK ZONE AND RAIN

It was assumed the travel time under this scenario would be equal to the scenario of non-congested conditions with incident and work zone multiplied by 1.05.

SCENARIO 10: CONGESTED CONDITIONS WITH RAIN

It was assumed the travel time under this scenario would be equal to the scenario of congested conditions multiplied by 1.001.

SCENARIO 11: CONGESTED CONDITIONS WITH INCIDENT

It was assumed the travel time under this scenario would be equal to the scenario of congested conditions multiplied by 1.2.

Table 1 Travel Time Estimation Models By Scenario

	Congestion Level	Weather Level	Incident Level	Work Zone Level	Number of Data Points	Model
Scenario 1	Non-congested	No rain	No incident	No work zone	51947	TT/mile = 65.4 - 3.56 [Min (# lanes, 3)]
Scenario 2	Non-congested	Rain	No incident	No work zone	17179	TT/mile = 66.6 + 5.22 Rainfall - 3.51 # Lanes
Scenario 3	Non-congested	No rain	Incident	No work zone	334	TT/Mile = 61.1 - 4.27 Open # Lanes/Total # Lanes
Scenario 3A	Non-congested	No rain	Non-Blocking Incident	No work zone	None	No data
Scenario 4	Non-congested	No rain	No incident	Work zone	838	TT/Mile = 61.6 - 0.854 Open # Lanes
Scenario 5	Non-congested	Rain	Incident	No work zone	79	TT/Mile = 70.4 - 3.70 O/T - 4.34 # lanes + 10.5 Rainfall
Scenario 5A	Non-congested	Rain	Non-Blocking Incident	No work zone	None	No data
Scenario 6	Non-congested	Rain	No incident	Work zone	23	Not enough data
Scenario 7	Non-congested	No rain	Incident	Work zone	None	No data
Scenario 7A	Non-congested	No rain	Non-Blocking Incident	Work zone	None	No data
Scenario 8	Non-congested	Rain	Incident	Work zone	None	No data
Scenario 8A	Non-congested	Rain	Non-Blocking Incident	Work zone		No data
Scenario 9	Congested	No Rain	No incident	No work zone	563	TT/mile = - 62.4 + 987.6022 e^(-0.0008 Hourly Flow per Lane)
Scenario 10	Congested	Rain	No incident	No work zone	258	
Scenario 11	Congested	No rain	Incident	No work zone	15	Not enough data
Scenario 11A	Congested	No rain	Non-Blocking Incident	No work zone	None	No data
Scenario 12	Congested	No rain	No incident	Work zone	3	Not enough data
Scenario 13	Congested	Rain	Incident	No work zone	6	Not enough data
Scenario 13A	Congested	Rain	Non-Blocking Incident	No work zone	None	No data
Scenario 14	Congested	Rain	No incident	Work zone	None	No data
Scenario 15	Congested	No rain	Incident	Work zone	None	No data
Scenario 15A	Congested	No rain	Non-Blocking Incident	Work zone	None	No data
Scenario 16	Congested	Rain	Incident	Work zone	None	No data
Scenario 16A	Congested	Rain	Non-Blocking Incident	Work zone	None	No data

SCENARIOS 11A, 13A, 15A, 16A, : CONGESTED CONDITIONS WITH A NON-LANE-BLOCKING INCIDENT

It was assumed that if a non-lane-blocking incident occurs under congested conditions, the travel time would increase relative to the respective scenario with out an incident by 0.1%. It is expectted that under congested conditions the impact of a non-lane blocking incident would be relatively minor.

SCENARIO 12: CONGESTED CONDITIONS WITH WORK ZONE

It was assumed the travel time under this scenario would be equal to the scenario of congested conditions multiplied by 1.2.

SCENARIO 13: CONGESTED CONDITIONS WITH RAIN AND INCIDENT

It was assumed the travel time under this scenario would be equal to the scenario of congested conditions with an incident multiplied by 1.001.

SCENARIO 14: CONGESTED CONDITIONS WITH RAIN AND WORK ZONE

It was assumed the travel time under this scenario would be equal to the scenario of congested conditions with rain and incident.

SCENARIO 15: CONGESTED CONDITIONS WITH INCIDENT AND WORK ZONE

It was assumed the travel time under this scenario would be equal to the scenario of congested conditions multiplied by 1.3.

SCENARIO 16: CONGESTED CONDITIONS WITH INCIDENT, WORK ZONE, AND RAIN

It was assumed the travel time under this scenario would be equal to the scenario of congested conditions multiplied by 1.301 (or congested conditions with work zone and rain multiplied by 1.001).

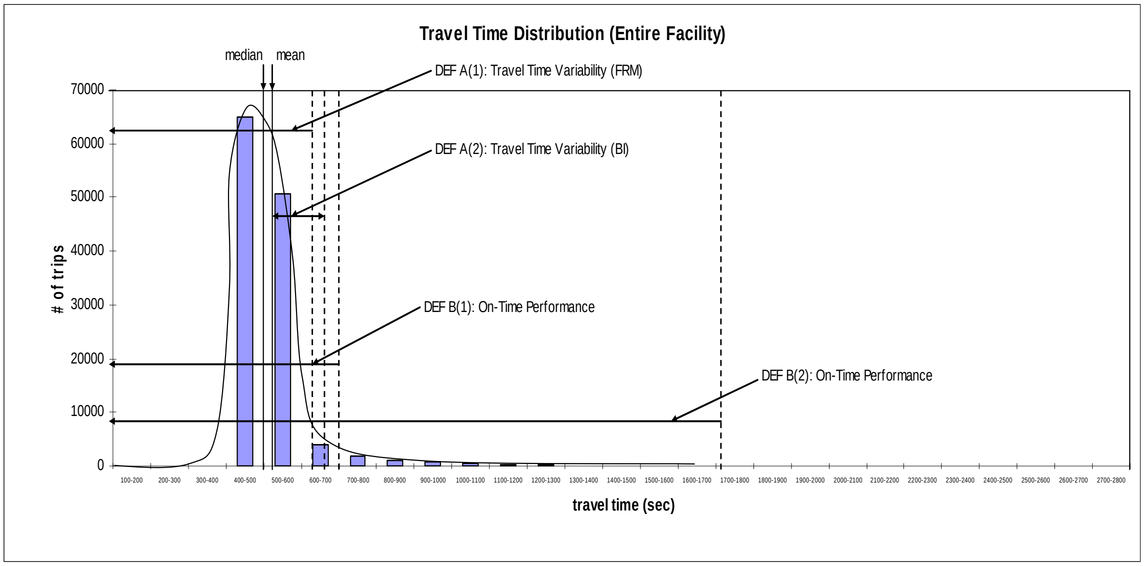
It is expected that as data become available from Florida freeways, these models would be refined, and the tools described in this paper would be improved accordingly. Again, other agencies interested in applying this method may want to use data from their own network, and considering their own set of scenarios, to develop the respective travel time estimation models.

Step 3: Estimation of the probability of occurrence for each scenario identified in Step 1

The methodology and application described here considers travel time by hour of the day throughout a year. Therefore, the probability of occurrence of each scenario was estimated by hour of day, using existing data regarding the frequency of certain occurrences. For example, in this research, the probability of recurring congestion was based on the probability of demand exceeding capacity for each hour in the day and by direction, using FDOT data. Over the last 10 years FDOT annually calculates and reports delay and levels of congestion for the entire State Highway System based on traffic (e.g., average annual daily traffic), roadway (e.g., lanes) and signalization characteristics, and typical hourly traffic distributions by roadway and area type. Traffic, roadway and signalization data, as well as roadway identifications are found in FDOT's traffic and roadway characteristic inventories. The probability of an incident (lane-blocking and non-lane blocking) by time of day was obtained based on data from FDOT District 4 Sunguide (http://www.smartsunguide.com/Reports/monthly_Broward-120107-123107_010408-102654.pdf). The probability of rain and the average rainfall was obtained from the internet (http://www.wunderground.com) for a station in close proximity to the study site. The probability of a work zone at a freeway section was not available; therefore, assumptions were employed and implemented to complete the calculations. The probability of a work zone was assumed to be 3% for all hours, which may be high for peak hours. It is expected that additional information on work zones will be obtained in the near future, so that these assumptions can be refined.

Step 4: Development of the travel time distribution for the section, and estimation of selected travel time reliability measures based on this distribution

The travel time distribution for a given section can be obtained based on the results of Step 2 and 3 by plotting the travel times and their respective frequencies. Figure 3 provides an example of such a distribution for a given freeway section. A variety of travel time reliability-related measures can then be estimated based on this distribution, including the probability of on-time arrival, the buffer index, etc.



Notes: DEF A(1) is travel time reliabilitiy according to the Florida Reliability Method
DEFA(2) is travel time reliability according to the Buffer Index
DEF B(1) is travel time reliability when on-time performance is “Speed Limit -10 mph”
DEF B(2) is travel time reliability when on-time performance is “1/3 x Speed Limit”

Figure 3 Example of a Travel Time Distribution

For the purposes of this project, on-time arrival is defined as the percent of trips that their travel time over a designated facility is below a certain threshold (or equivalently, at a given travel speed or higher).” The buffer index is defined (Lomax et al., 2004) as the amount of extra time that must be allowed for the traveler to achieve their destination in a high percentage of the trips. A measure of variability is the average travel time plus one or two standard deviations. The Buffer Time Index is estimated as:

Buffer Index (BI) =

[95th percentile confidence travel rate-average travel rate] /[average travel rate] x 100%

In addition to those measures, the expected travel time by hour of day, the expected travel time for selected peak periods, and the expected travel time for the entire year are estimated. The expected travel time for each hour of the day is estimated as:

$$E[TT]_x = \sum_{1}^{n} TT_{scenario\_j} \times scenario\_\%(x)$$

Where:

$E[TT]_x$: expected travel time for hour x

$TT_{scenario\_j}$: travel time for a given scenario j

n: Number of scenarios

$scenario\_\%$ (x): Probability associated with the occurrence of each scenario during hour x

The expected travel time for the entire year can be estimated either as the average of the expected travel times for each of the 24 hours, or as the weighted-by-volume average of those expected travel times.

Estimating Travel Time Reliability for A Freeway Facility

The travel time reliability for a freeway facility is calculated based on the consolidation of travel time results for the freeway segments contained within the defined freeway facility. As such, segment travel times are summed together to obtain facility travel times from which facility travel time reliability measures are calculated in a similar way to segment travel time reliability measures.

III. EXAMPLE APPLICATION: TRAVEL TIME RELIABITY FOR A FREEWAY SECTION

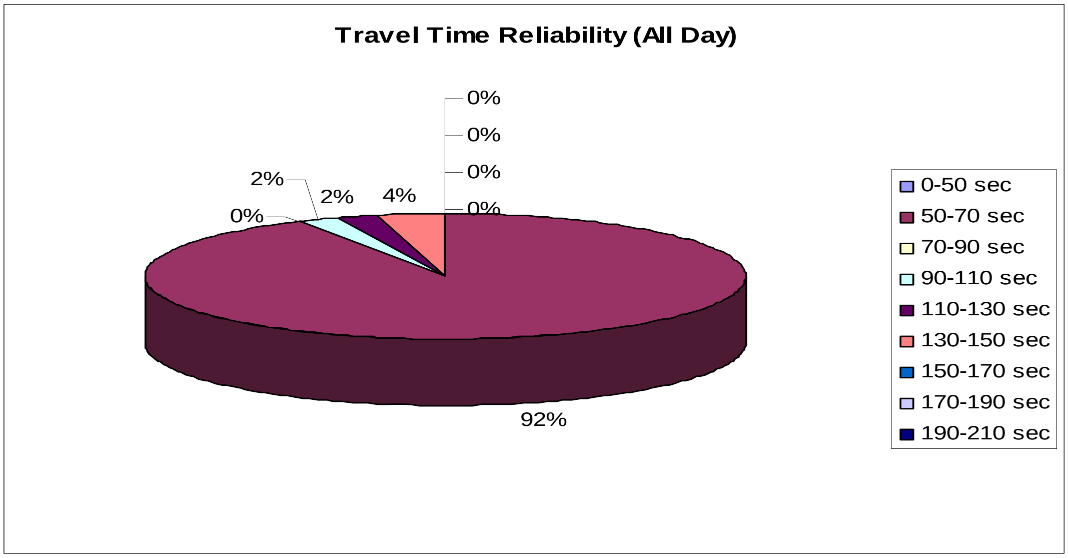
This section summarizes the travel time reliability estimation process for a freeway section in South Florida (I-95 / SR 9 between Broward Blvd. and Sunrise Blvd.) The data on which the calculations are based were obtained from various sources. The geometric information for the site, as well as hourly demands and expected frequency of congestion for each hour, were obtained from the FDOT's Roadway Characteristics Inventory (RCI) database. The incident information was obtained from FDOT's District 4 Sunguide (http://www.smartsunguide.com/Reports/monthly_Broward-120107-123107_010408-102654.pdf), while the weather information was obtained from (http://www.wunderground.com). The methodology was implemented in a spreadsheet application.

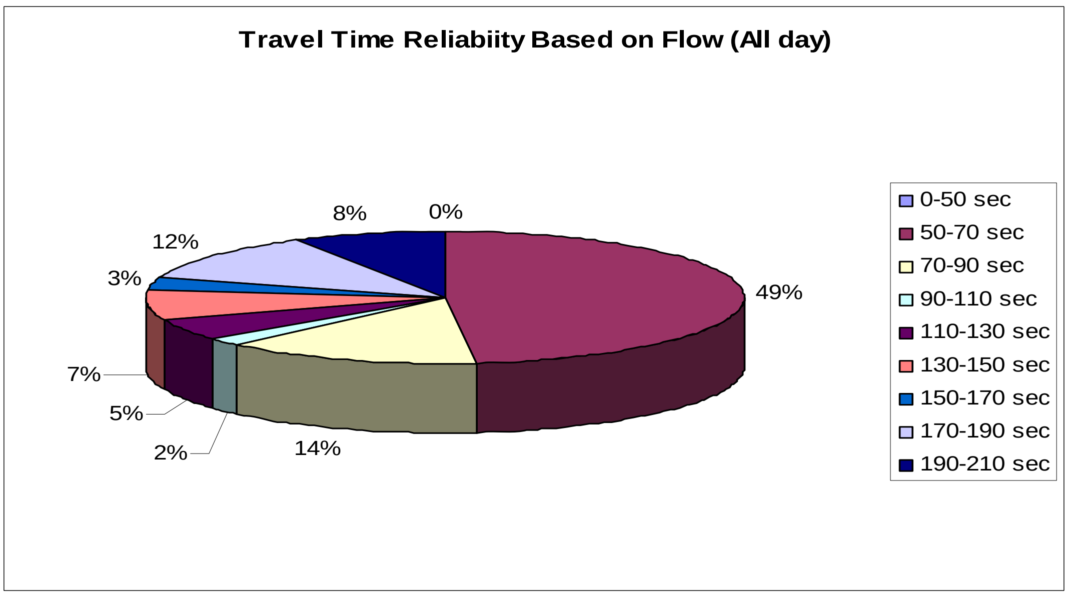
The study section is 1.022 miles long. Each direction (NB and SB) contains a weaving section with an auxiliary lane. The auxiliary lane on the NB approach is slightly longer; the SB ramp approaches the mainline further south, making the weave in this direction slightly shorter. The total number of lanes in each direction is 6, including the auxiliary lane. For the calculations in this spreadsheet, and because the auxiliary lane cannot be assumed to have the capacity of a full lane, it was assumed that the auxiliary lane was equal to half lane. Thus, the total number of lanes per direction was entered as 5.5.

The AADT is divided into the peak direction and the off-peak direction volumes, and it is also distributed throughout the 24-hour period using the K and D factors (according to values previously developed by FDOT).

The probability of an incident by hour was based on data from the year 2007 for the entire Sunguide system in District 4. First the total number of responses to incidents for the year and for each hour are obtained and entered into the spreadsheet. Next, the percent of responses by hour is calculated. This is used to determine the proportion of blocking and non-blocking incidents by hour. The number of responses by hour is used to obtain those percentages, because the Sunguide data do not provide blocking and non-blocking incidents by hour of the day. Then, the total number of lane-miles in the system monitored was obtained from Elefteriadou and Xu (2007), and it was used to estimate the probability of a non-blocking incident and the probability of a blocking incident on a per lane-mile basis. These numbers are average annual frequencies, estimated for each hour in a day. To obtain the frequency of each of the two types of incidents for the study section those numbers are multiplied by the total number of lanes and by the section length.

Next, the travel time distributions considering all 24 hours in the day, as well as the evening peak period are generated. Figure 4 plots the travel time frequencies for all 24 hours in the day by number of hours as well as number of trips, and it provides an estimate of travel time reliability based on on-time arrival, as well as the buffer time index. Figure 5 provides similar information as the previous figure, but only for the hours 4-7 pm, to capture the evening peak hour conditions.





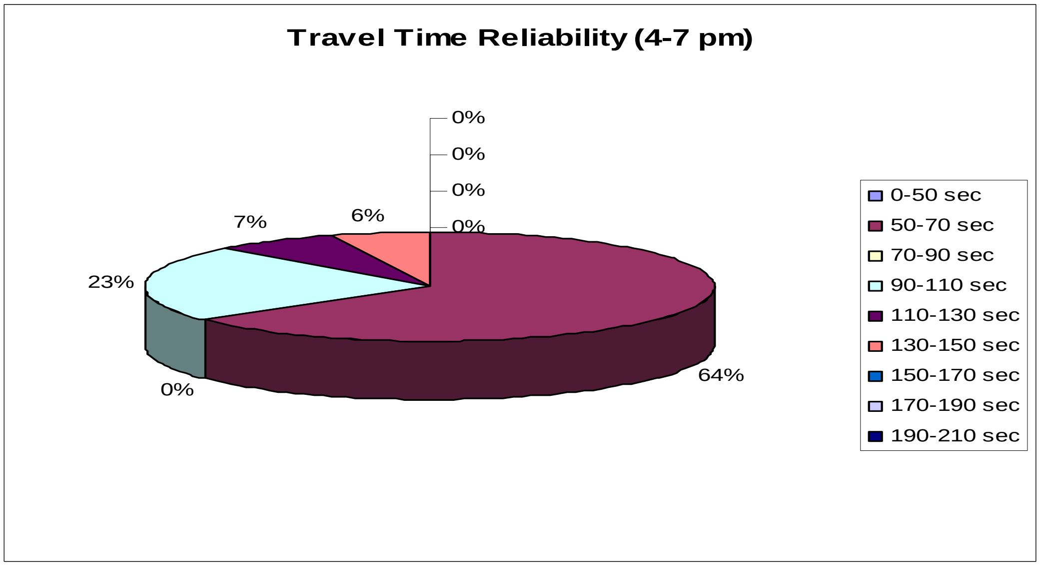
Reliability based on on-time arrival:

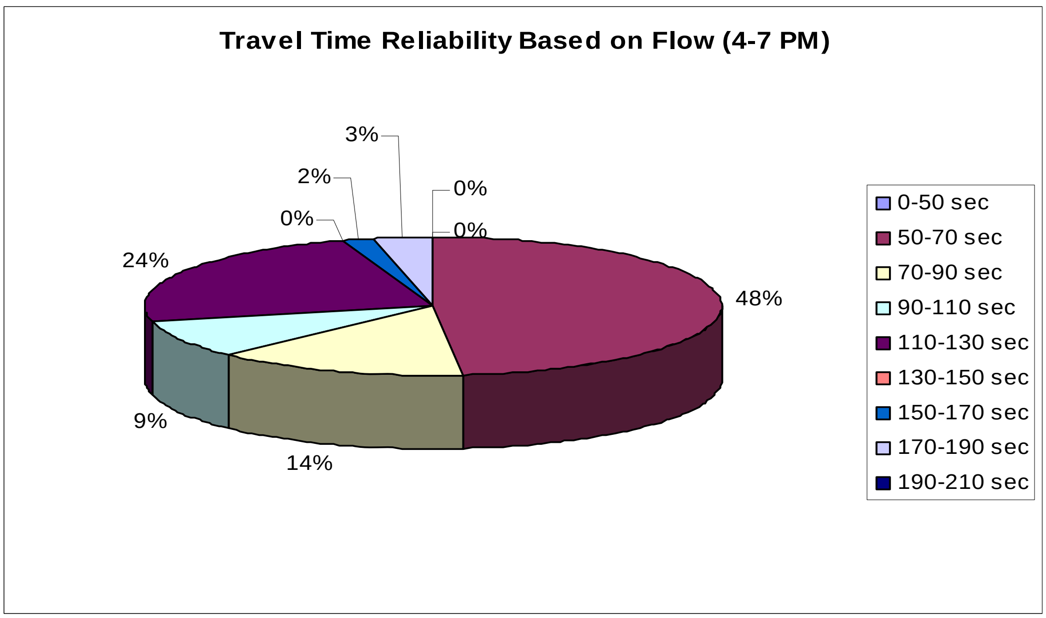
Travel time corresponding to speed limit (65)-10 mph:		66.89 sec	
For speed limit (65)-10 mph:	91.88% of time	(Percent of time travel speed is above 55 mph)	
	29.20% of trips	(Percent of trips travel speed is above 55 mph)	

Reliability based on buffer time index:

95% TT corresponds to	8322 hours and	110 sec or	33.44727 mph
(95%-avg)/avg =	0.778306		

Figure 4 Estimated Travel Time Distribution and Reliability Measures (24-hour period)





Reliability based on on-time arrival:

Travel time corresponding to speed limit (65)-10 mph:			66.89 sec	
For speed limit (65)-10 mph:	52.99%	of time	(Percent of time travel speed is above 55 mph)	
	30.48%	of trips	(Percent of trips travel speed is above 55 mph)	

Reliability based on buffer time index:

95% TT corresponds to	1040.25	hours and	130 sec	28.3015385 mph
(95%-avg)/avg =	0.550			

Figure 5 Estimated Travel Time Distribution and Reliability Measures (4-7 pm evening peak period)

IV. FIELD DATA FROM FLORIDA FOR ESTIMATING TRAVEL TIME RELIABILITY

Field data were obtained from Jacksonville, Florida, and were analyzed to determine whether the models developed under FDOT Contract BD-545, RPWO #48 (Elefteriadou and Cui, 2007) can accurately predict travel times at this location. This section presents the study site and field data, summarizes the data analysis, and provides the results of the comparisons between the estimated and field-measured travel times.

Description of the Study Site and Field Data

The study route is a 25- mile section along I-95 in Jacksonville, FL. A sketch of the area is shown in Figure 6. Data were obtained from multiple sensors across a 25-mile section of I-95, within the city limits of Jacksonville, FL. In the north, the study area begins in the vicinity of the Jacksonville international airport, and in the south it ends at Philips Road. The northbound and the southbound sections were analyzed separately. There are varying speed limits and numbers of lanes along the study area. The speed limits for the northbound and southbound directions are shown in Figures 7 and 8, while the number of lanes through the two routes are shown in Figures 9 and 10.

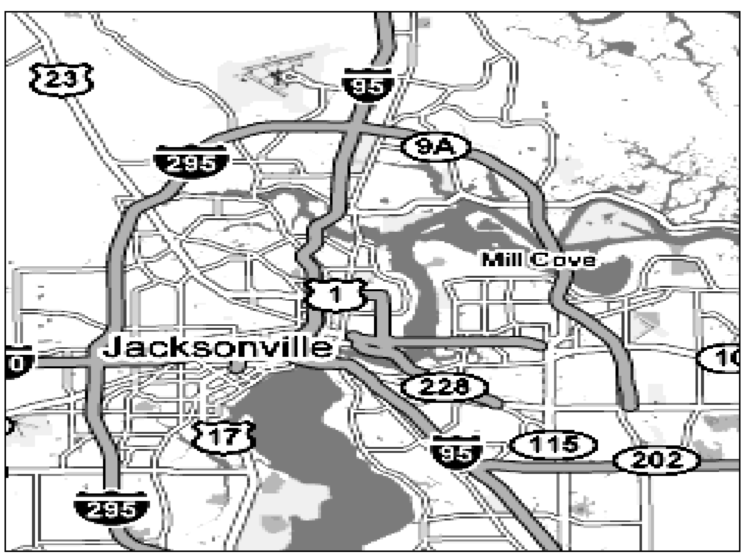


Figure 6 Study Route Along I-95 in Jacksonville, FL
(Source: www.googlemaps.com)

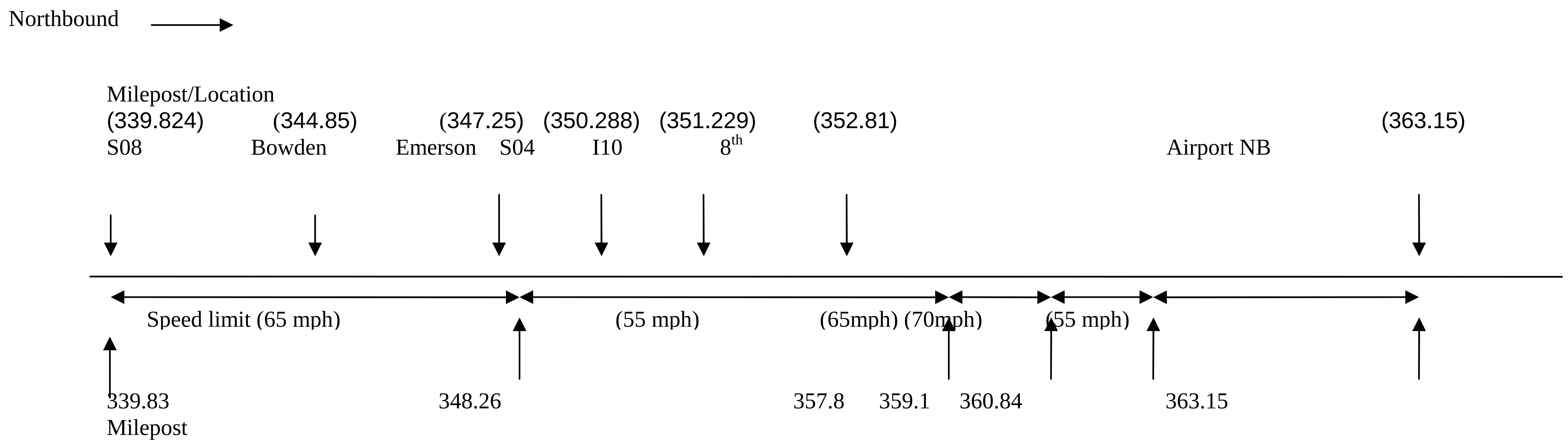


Figure 7 Speed Limits Along I-95 in Jacksonville, FL, Northbound (Source: http://www.dot.state.fl.us/planning/statistics/gis/aboutapps.htm)

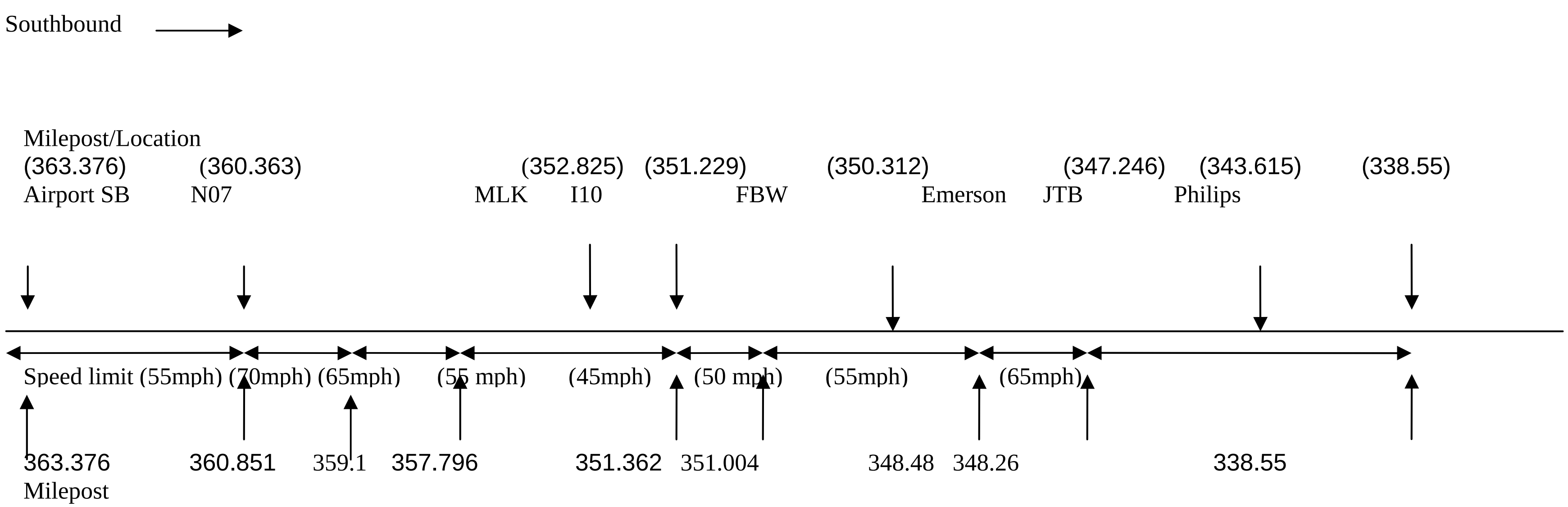


Figure 8 Speed Limits Along I-95 in Jacksonville, FL, Southbound (Source: http://www.dot.state.fl.us/planning/statistics/gis/aboutapps.htm)

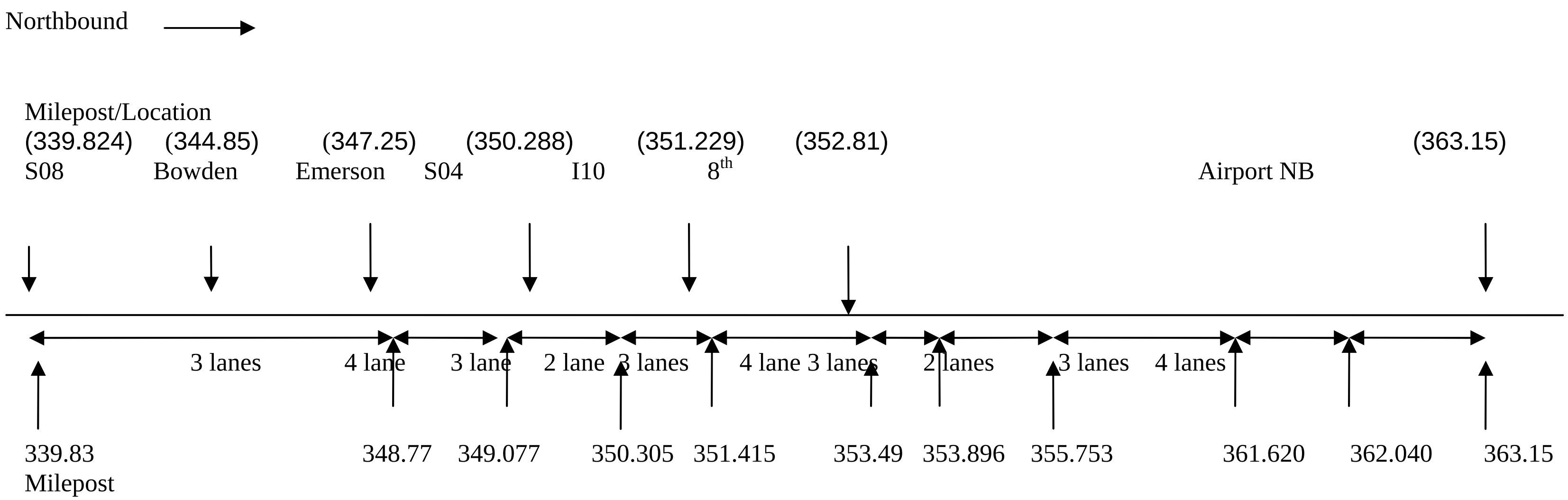


Figure 9 Number of Lanes Along I-95 in Jacksonville, FL, Northbound (Source: http://www.dot.state.fl.us/planning/statistics/gis/aboutapps.htm)

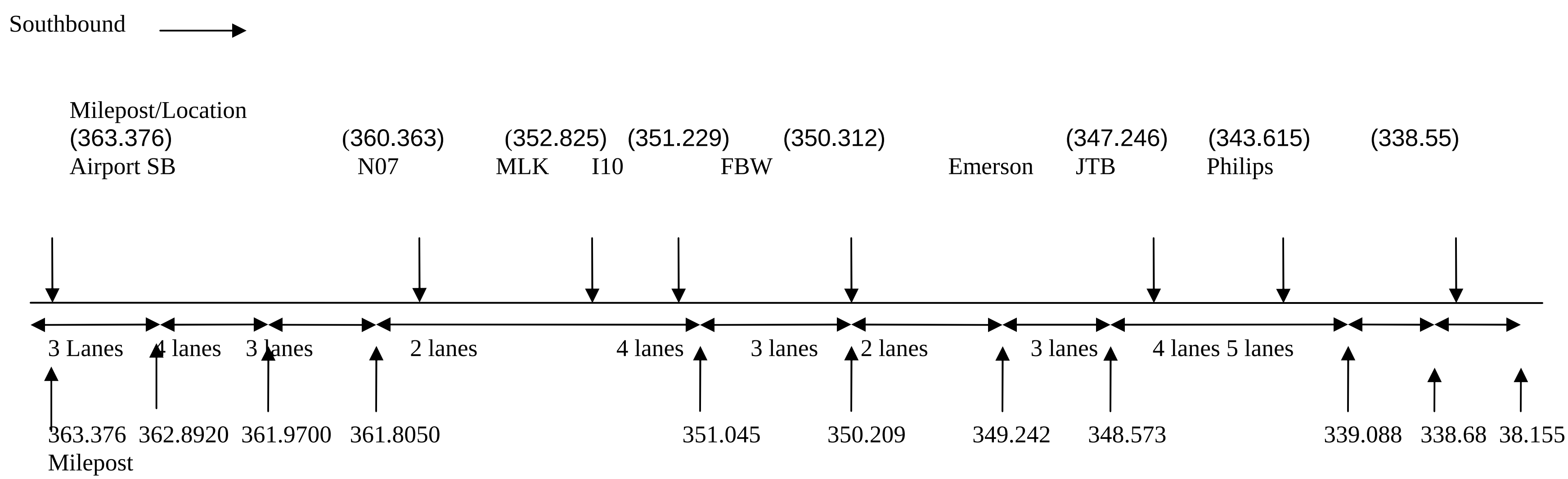


Figure 10 Number of Lanes Along I-95 in Jacksonville, FL, Southbound (Source: http://www.dot.state.fl.us/planning/statistics/gis/aboutapps.htm)

There is a total of 120 sensor locations, 60 along the northbound section and 60 along the southbound section. Data were retrieved from the STEWARD (Statewide Transportation Engineering Warehouse for Archived Regional Data) website (http://cdw880.ce.ufl.edu/steward/index.html), which has collected and stored statewide information from many data sources, and made it available for use by different applications. These data were collected by FDOT District 2 using RTMS and they consist of volume, occupancy, average speed, and percentage of vehicle types classified based on length. Traffic properties records (i.e.e, station data) such as speed, volume, occupancy etc. are provided in the Comma Separated Values (.csv) file format, dating from June 1, 2007 to September 16, 2007, in 5-min intervals.

First, the data were pre-screened to determine data availability throughout the entire time period and across all RTMS. The reasonableness of the speed/flow combination was selected as the criterion to determine whether the specific RTMS sensor was working or not at a specific time. It was concluded that during the 78-day period there were 90 sensors with reasonable speed/flow measurements from 00:00 AM till 14:20 PM. Typical problems included missing data, zero speeds when the flow was at low to medium levels, and low speed/low flow combinations during early morning times. In summary, the total number of sensors with consistent data were 90, while data were obtained from 0:00 am to 2:20 pm from August 20 to September 16, 2007. Therefore, the total number of analysis records is 19,386.

The incident information for the study area is also provided from the STEWARD database. For every incident, the time stamp, incident ID, brief description and location are recorded. Precipitation data were extracted from the website: www.wunderground.com for the observation station in the vicinity of the study area. These data provide precipitation every 10 or 15 minutes. There were no work zones at this corridor for the study period considered, and thus no work-zone related scenarios were considered.

Data Analysis

Once the data were cleaned and the final sensor information to be analyzed was obtained, each pair of sensors was used to define a link so that travel time could be estimated on a link-by-link basis. First, the speed along each link was calculated for each interval as the average of the speeds of the sensors which define the respective link. Second, the travel time over the link was estimated as the distance between those two sensors divided by the link speed. This travel time was expressed in seconds per mile, to assist in comparisons later on. Third, each data point was categorized into on a given scenario (considering congestion, incidents, and weather), and tagged for further analysis. It was assumed that data points with speeds less than 40 mph represented congested conditions. Table 2 summarizes the number of data points by scenario for the entire data base. As shown, the database includes a total of eight scenarios. The vast majority of data points (73.30%) represent non-congested conditions with no incidents or precipitation. The second largest category reprsents congested conditions with no incidents or precipitation (20.64%).

Table 2 Number of Data Points by Scenario

Scenario	Number of Data Points	Percentage of Data Points
Scenario 1: No Congestion, Without Incident, Without Precipitation	14209	73.30%
Scenario 3: Without Congestion, With Incident, Without Precipitation	106	0.55%
Scenario 5: No Congestion, With Incident, With Precipitation	283	1.46%
Scenario 9: With Congestion, Without Incident, Without Precipitation	4001	20.64%
Scenario 10:With Congestion, Without Incident, With Precipitation	734	3.78%
Scenario 13: With Congestion, With Incident, With Precipitation	53	0.27%
Total	19,386	100.00%

Estimated vs. Field Travel Times

The travel time for each time interval was next estimated using the models shown in Table 1. The estimated and field travel times were compared to evaluate the accuracy of each of the models. The percent discrepancy was estimated for each interval and each link as the ratio of the difference between the predicted and the actual travel time divided by the actual travel time. Aggregate comparisons were also conducted by estimating the (weighted) average travel time per mile for each scenario. Table 3 presents the comparison results between the estimated and field travel times. As shown, the differences between model estimates and field observations is relatively low for non-congested conditions (less than 5%), while they are relatively large for congested conditions (as high as 23.7%). This difference for congested conditions can be attributed to several reasons. First, as indicated above, a certain threshold (40 mph) was assumed to categorize congested conditions. This might lead to data points being erroneously categorized as congested conditions when they are not, and vice versa. To address this, a more detailed analysis of congestion identificiation at this particular site might help reduce those errors. Second, as a segment is transitionsing into congested conditions, it is possible that the downstream sensor has low speeds while the upstream sensor has higher speeds because congestion has not reached that location yet. This leads to relatively higher estimates of travel time, which the model does not account for. This might be remedied by considering an additional set of scenarios to account for transitioning, or semi-congested conditions. Third, it was found that two particular sensors show higher differences between model estimates and field obsevations. In this case, the discrepancy may be because these sensors are located upstream of the bottleneck, and these conditions are not adequately modeled. It may also be due to calibration issues for those two detectors.

Table 3 Comparison of Estimated and Field Travel Times

Scenario	Number of Data Points	Model Estimates (Average TT/mile) In Seconds	Field Observations (Average TT/mile) In Seconds	Percent Difference
Scenario 1: No Congestion, Without Incident, Without Precipitation	14209	0.921	0.919	0.24%
Scenario 3: Without Congestion, With Incident, Without Precipitation	106	0.948	0.994	4.63%
Scenario 5: No Congestion, With Incident, With Precipitation	283	0.984	1.014	2.95%
Scenario 9: With Congestion, Without Incident, Without Precipitation	4001	1.394	1.765	21.01%
Scenario 10:With Congestion, Without Incident, With Precipitation	734	1.458	1.912	23.70%
Scenario 13: With Congestion, With Incident, With Precipitation	53	1.977	2.242	11.83%

V. FRAMEWORK FOR TRAVEL TIME ESTIMATION ON ARTERIAL STREETS

The framework for estimating travel time on arterial streets is very similar to that of freeways, and it involves the identification of scenarios for which travel time will be estimated, the development of models to estimate travel time for each of those scenarios, the frequency estimation for each scenario, and finally the development of the travel time distribution, and the calculation of all relevant parameters based on the distribution.

The conditions proposed to be considered for urban streets are as follows:

- Recurring traffic congestion (due to high demand only). For arterials this condition is defined as demand>capacity for the mainline approach at any of the signals along its length.
- Incidents. Only lane-blocking incidents will be considered, since the effect of non-lane blocking incidents will likely be minor, due to the relatively low speeds along urban streets.
- Weather. Rain (expressed in average precipitation by hour) will be considered in the scenarios to estimate travel time.
- Work zones. Only lane-blocking work zones will be considered, since the effect of non-blocking ones will likely be minor, due to the relatively low speeds along urban streets.
-

There are a total of 16 scenarios which could occur as combinations of the above list of conditions. FDOT's Quality of Service Handbook uses the following input variables, which are also likely to affect travel time, and thus be used in arterial travel time estimation: Number of through lanes, Left turn lanes, Roadway class, Posted speed, Median presence, Terrain, AADT, K, D, Signalized Intersection spacing, Cycle length, and g/C.

Table 4 provides the proposed list of scenarios to be considered for arterial travel time estimation, and the variables likely to affect each scenario's travel time.

Table 4 Proposed List of Scenarios for Arterials

	Congestion Level	Weather Level	Incident Level	Work Zone Level	Model to be developed as:
Scenario 1	Non-congested	No rain	No incident	No work zone	Function of: Number of through lanes, Left turn lanes, Roadway class, Posted speed, Median presence, Terrain, AADT, K, D, Signalized Intersection spacing, Cycle length, and g/C
Scenario 2	Non-congested	Rain	No incident	No work zone	Increase in travel time for Scenario 1 proportional to rainfall (in inches)
Scenario 3	Non-congested	No rain	Incident	No work zone	Increase in travel time for Scenario 1 proportional to lanes closed, and incident duration
Scenario 4	Non-congested	No rain	No incident	Work zone	Increase in travel time for Scenario 1 proportional to lanes closed, and work zone duration
Scenario 5	Non-congested	Rain	Incident	No work zone	Increase in travel time for Scenario 3 proportional to rainfall (in inches)
Scenario 6	Non-congested	Rain	No incident	Work zone	Increase in travel time for Scenario 4 proportional to rainfall (in inches)
Scenario 7	Non-congested	No rain	Incident	Work zone	Function of: Number of through lanes, Left turn lanes, Roadway class, Posted speed, Median presence, Terrain, AADT, K, D, Signalized Intersection spacing, Cycle length, g/C,and number of lanes closed (considering both the incident and the work zone)
Scenario 8	Non-congested	Rain	Incident	Work zone	Increase in travel time for Scenario 7 proportional to rainfall (in inches)
Scenario 9	Congested	No Rain	No incident	No work zone	Function of: Number of through lanes, Left turn lanes, Roadway class, Posted speed, Median presence, Terrain, AADT, K, D, Signalized Intersection spacing, Cycle length, and g/C
Scenario 10	Congested	Rain	No incident	No work zone	Increase in travel time for Scenario 9 proportional to rainfall (in inches)
Scenario 11	Congested	No rain	Incident	No work zone	Increase in travel time for Scenario 9 proportional to lanes closed, and incident duration
Scenario 12	Congested	No rain	No incident	Work zone	Increase in travel time for Scenario 9 proportional to lanes closed, and work zone duration
Scenario 13	Congested	Rain	Incident	No work zone	Increase in travel time for Scenario 11 proportional to rainfall (in inches)
Scenario 14	Congested	Rain	No incident	Work zone	Increase in travel time for Scenario 12 proportional to rainfall (in inches)
Scenario 15	Congested	No rain	Incident	Work zone	Function of: Number of through lanes, Left turn lanes, Roadway class, Posted speed, Median presence, Terrain, AADT, K, D, Signalized Intersection spacing, Cycle length, g/C,and number of lanes closed (considering both the incident and the work zone)
Scenario 16	Congested	Rain	Incident	Work zone	Increase in travel time for Scenario 15 proportional to rainfall (in inches)

When field data become available for urban streets, travel time estimation models could be developed for each of the scenarios listed in Table 4. Field data could also be used to obtain the frequency of occurrence for each scenari. Then, a similar process to that developed for freeways could be followed to obtain the travel time distribution, and all relevant travel time reliability-related performance measures.

VI. CONCLUSIONS AND RECOMMENDATIONS

In summary, research under this project implemented the results of two previous FDOT-funded projects to estimate travel time reliability on the Florida SIS, evaluated the previously developed models based on Florida data, and developed a framework for estimating travel time on arterial streets.

The first part of the report describes a methodology and the respective tools for estimating travel time reliability for a freeway section as well as for a freeway network, and it applies those tools and estimate various travel time reliability measures for a freeway section in South Florida. The methods and tools developed can be used as follows:

- Project prioritization based on travel time reliability (either on-time arrival or buffer index) can be performed. Based on agency needs and priorities, travel time reliability can be estimated for given time periods in a year (seasonal or hourly estimates), and projects can be prioritized to improve sections with the lowest reliability.
- Impacts of various types of programs or improvements (such as road rangers, incident removal duration, work zones,) on the expected reliability for each section as well as for the entire system can be estimated. Such improvements can be evaluated considering hours and days of operation, sections affected, etc.
- Travel time reliability can be reported annually to legislators and other decision makers, and can be monitored over time.
- Freight shippers may find the tool useful as an initial planning tool for routing and scheduling trips through major metropolitan areas. It could also serve as a major mobility performance measure for freight.

It should be stressed that the methods and results presented here are the first effort to estimate travel time reliability on a section and freeway network, and it is expected that many refinements will be added to imrpove accuracy and faciliatate the use of the tool for additional applications. Suggested refinements include the following:

- Refinement of travel time estimation models based on a more extensive set of Florida data; as additional data become available in Florida, the travel time estimation models used here can be refined to better represent Florida conditions, and also to consider various types of freeways.

- Refinement of incident data based on section-by-section information; if additional, more detailed data become available to provide incident information on a section-by-section basis, these can be used to estimate more accurately the frequency of incidents by section, and also the resulting travel times during incidents.
- Data regarding work zones; the investigators were not able to locate work zone frequency information for the study area. If these data become available in the future, they can be entered into the existing tools to improve their accuracy.
- Improving spillover effects from one section to another; for example, the effects of a major incident are currently limited in time and space to individual sections and do not extend upstream. A related issue is the consideration of demand values, rather than flows, in estimating travel time. Current models are based on flows measured at detector locations, and they do not consider the queues developing upstream and the additional travel time spent in the upstream queue.
- Refinement of capacity values to account for capacity drop during oversaturated conditions.

The second part of the report summarizes the data analysis conducted using data from Jacksonville, FL, to evaluate the travel time estimation models previously developed. As shown, the differences between model estimates and field observations is relatively low for non-congested conditions (less than 5%), while they are relatively large for congested conditions (as high as 23.7%). This difference for congested conditions can be attributed to several reasons, including model limitations as well as sensor calibration issues. It is recommended that future research address travel time estimation upstream of bottlenecks, to refine the existing models. Furthermore, as additional data become available from the SIS, the models and assumptions used in this project should be refined.

The third part of the report developed a framework for estimating arterial travel time and obtaining the related travel time reliability performance measures. It is recommended that a total of 16 scenarios be used to obtain travel time estimates for arterials. Future work should focus on obtaining field data to calibrate the conceptual models provided in this report. Another possible alternative is the use of simulation to estimate travel times, at least for scenarios involving congested conditions, incidents and work zones; simulation cannot be used to replicate raining conditions.

Generally, it is recommended that the methodology developed and illustrated in this report be implemented to estimate travel time reliability for the SIS, and evaluate the model predictions for existing conditions. Such an evaluation will identify any atypical conditions for which adjustments to the existing models need to be made, and will identify any inconsistencies between predicted and observed travel times. Subsequently, the application can be used to test various project implementations, and estimate travel time reliability in the entire SIS, or in specific SIS sections as a function of various operational and design changes.

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