Modeling weather impacts on traffic operations: Implementation into Florida’s travel time reliability model

Zhuofei Li
Graduate Research Assistant
University of Florida
365 Weil Hall, PO Box 116580
Gainesville, FL 32611
Phone: (352) 392-9537, Ext.
Fax: (352) 392-3394
E-mail: zhuofei@ufl.edu

Lily Elefteriadou, Ph.D.
University of Florida
365 Weil Hall, PO Box 116580
Gainesville, FL 32611
Phone: (352) 392-9537, Ext. 1452
Fax: (352) 392-3394
E-mail: elefter@ce.ufl.edu

Alexandra Kondyli, Ph.D.
Postdoctoral Associate
365 Weil Hall, PO Box 116580
Gainesville, FL 32611
Phone: (352) 392-9537, Ext. 1548
Fax: (352) 392-3394
E-mail: azk133@ufl.edu

Total number of words: 5,500 words + 2,000 (4 Figures + 4 Tables) = 7,500 words

In Proceedings of the 93rd Annual Meeting of the Transportation Research Board
ABSTRACT

Travel time reliability is a measure that allows agencies to evaluate the performance of a facility beyond the peak hour, and to consider operations over a longer period of time considering non-recurring events, such as incidents, adverse weather, and work zones. The Florida Department of Transportation (FDOT) has made considerable efforts in incorporating travel time reliability as a primary mobility performance measure. This paper details the method developed for addressing the effects of weather on travel time, as well as the implementation of the method in travel time reliability estimation for state-wide reporting in Florida. To account for Florida-specific conditions, weather impacts focus only on rain intensity. The methodology incorporates different rainfall characteristics of regions across Florida and calibrates the rainfall intensity distribution models on a zip code basis for every hour within the period of interest. The probability of clear weather, light rain and heavy rain is determined for each hour and then applied to the respective freeway or arterial section based on its zip code.

INTRODUCTION

Travel time reliability is an important mobility measure of the transportation system performance. Agencies are faced with the challenge of evaluating their facilities and improving travel time reliability over their entire network and over the entire year, rather than during a few analysis periods with good weather. However, existing tools such as the 2010 Highway Capacity Manual (2010HCM) [1] do not consider all these variations of travel time. Weather is one such parameter that plays an important role in travel time reliability, and its effects have not been thoroughly examined.

FDOT has made considerable efforts in incorporating travel time reliability as a primary mobility performance measure for state-wide reporting. Details on the overall methodology and quantitative results are provided in [2].

This paper details the method developed for addressing the effects of weather on travel time, as well as the implementation of the method in travel time reliability estimation for freeways and arterial streets state-wide for Florida. To account for Florida-specific conditions, weather impacts focus only on rain intensity. Snow or hail conditions were not considered in the model development as these do not apply to the region. The proposed methodology is based on the differences in precipitation patterns across Florida. Three different areas were considered for developing regional models of rain frequency, and these are then applied to each zip code using the average rainfall over a period of five years.

The following section discusses literature review on the effect of rain and visibility on freeway and arterial travel time reliability, as well as existing research on how the weather effects have been incorporated within travel time reliability methods. Next, the paper presents the model developed for evaluating weather effects on travel time, and illustrates the model implementation within FDOT’s travel time reliability method. The paper concludes with a summary and recommendations.
LITERATURE REVIEW

The first part of this section discusses the literature related to the effects of rain on travel time, while the second part summarizes findings regarding visibility effects. The third part discusses the incorporation of weather impacts on travel time reliability applications.

Effect of rain

Freeways

Several papers have studied the impacts of rain on freeway operations. In one of the earliest papers, Lamm et al. [3] examined 24 rural two-lane highways sections during both dry and wet conditions. They found no statistical difference in operating speed between those two conditions without the consideration of visibility. They concluded that operating speeds are not affected by wet pavement until visibility is also impacted.

Ibrahim and Hall [4] studied the effect of adverse weather on freeway operations in Canada. The study concluded that light rain and snow resulted in similar reductions in speeds (3%–5%), heavy rain caused 14%–15% reductions and heavy snow caused 30%–40% reductions in speeds. However, the rain intensity ranges used to differentiate between light and heavy rain were not provided. The authors indicate that their measurements are site-specific and that the speed changes may be different at other locations based on varying driver experience and roadway characteristics.

Brilon and Ponzlet [5] investigated 15 sites in Germany to assess the impacts of weather and lighting conditions, and other factors on speed-flow relationships. They concluded that wet roadways cause a reduction of 9.5 km/h (6 mph) on four-lane highways and 12 km/h (7.5 mph) on six-lane highways, while capacities were reduced by 350 vph and 500 vph, respectively. However, the study was conducted in Germany, where usually there are no speed limits and drivers’ behavior may be different from that in the U.S.

A recent study [6] of two freeway links emphasized the importance of rainfall intensity values in estimating capacity and average speeds. This research classified rainfall intensity into none (less than 0.01 inches/hour), light (0.01–0.25 inches/hour), and heavy (more than 0.25 inches/hour). They concluded that light and heavy rain decreased freeway capacity by 4–10% and 25–30%, respectively, and that the presence of rain, regardless of intensity, resulted in a 5.0–6.5% average decrease in operating speeds.

A study by [7] used classifications of rain intensities similar to those used by [6], but also added a “Trace” category. Speed reductions of 1%–2%, 2%–4%, and 4%–7% were found for trace, light, and heavy rain, respectively. However, differences in speeds for light and heavy rain (0.01–0.25 and more than 0.25 inches/hour) were not statistically significant.

The studies of [7] and [5] were used in the 2010HCM (Chapter 10) for providing recommendations regarding freeway capacity reductions due to rain and due to wet or dry pavements. The 2010HCM also recommends speed reduction due to light rain or heavy rain similar to the recommendations offered by
[4]; however, it does not define the rainfall intensity ranges associated with the categories “Heavy Rain” and “Light Rain”.

In summary, most of the literature reports that rainfall causes speed reduction of the order of 6% for light rain and about 14% for heavy rain, although the associated rainfall categories are significantly different. Table 1 summarizes the literature findings on speed and capacity reduction on freeways due to rain.

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Facility type</th>
<th>Rain intensity level</th>
<th>Speed reduction</th>
<th>Capacity reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamm et al. (1990)</td>
<td>Freeway/Arterial</td>
<td>Dry and wet conditions</td>
<td>Operating speeds are not affected by wet pavement until visibility is also impacted.</td>
<td>--</td>
</tr>
<tr>
<td>Ibrahim and Hall (1994)</td>
<td>Freeway</td>
<td>Light</td>
<td>3% - 5%</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy</td>
<td>14% - 15%</td>
<td></td>
</tr>
<tr>
<td>Brilon and Ponzlet (1996)</td>
<td>Freeway</td>
<td>Dry and wet conditions</td>
<td>Wet roadway conditions cause speed reduction: 6 mph on four-lane highways; 7.5 mph on six-lane highways</td>
<td>Wet roadway conditions cause capacity reduction: 350 vph on four-lane highways; 500 vph on six lane-highways</td>
</tr>
<tr>
<td>Smith et al. (2004)</td>
<td>Freeway</td>
<td>None (&lt;0.01 in/h)</td>
<td>No speed reduction</td>
<td>No capacity reduction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light (0.01-0.25 in/h)</td>
<td>5% - 6.5%</td>
<td>4% - 10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy (&gt;0.25 in/h)</td>
<td>5% - 6.5%</td>
<td>25% - 30%</td>
</tr>
<tr>
<td>Agarwal et al. (2005)</td>
<td>Freeway</td>
<td>Trace (0-0.01 in/h)</td>
<td>1% - 2%</td>
<td>1% - 3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light (0.01-0.25 in/h)</td>
<td>2% - 4%</td>
<td>5% - 10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy (&gt;0.25 in/h)</td>
<td>4% - 7%</td>
<td></td>
</tr>
<tr>
<td>2010HCM</td>
<td>Freeway</td>
<td>Light</td>
<td>3% - 5%</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy</td>
<td>14% - 15%</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0-0.1 in/h</td>
<td>--</td>
<td>1.2% - 3.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1-0.25 in/h</td>
<td>--</td>
<td>5.7% - 10.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;0.25 in/h</td>
<td>--</td>
<td>10.7% - 17.7%</td>
</tr>
<tr>
<td>Gillam and Withill (1992)</td>
<td>Arterial</td>
<td>Dry and Wet Conditions</td>
<td>11%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 1. Summary of literature review on speed and capacity reduction on freeways and arterials due to rain
<table>
<thead>
<tr>
<th>Mitretek Systems (2002)</th>
<th>Arterial</th>
<th>Dry and Wet Conditions</th>
<th>more than 11% increase in peak period travel time, 3.5% increase in off-peak period</th>
<th>--</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perrin and Martin (2002)</td>
<td>Arterial</td>
<td>Dry and Wet Conditions</td>
<td>10%</td>
<td>6%</td>
</tr>
<tr>
<td>Chin et al. (2004)</td>
<td>Arterial</td>
<td>Light (&lt; 1 in/h)</td>
<td>10%</td>
<td>6%</td>
</tr>
<tr>
<td>Chung et al. (2005)</td>
<td>Arterial</td>
<td>Dry and Wet Conditions</td>
<td>increase travel time by 4.4-6.3%</td>
<td>--</td>
</tr>
<tr>
<td>Abdalla and Abdel-Aty (2006)</td>
<td>Arterial</td>
<td>Light</td>
<td>increase travel time by 9.12%</td>
<td>--</td>
</tr>
<tr>
<td>Athey Creek Consultants (2009)</td>
<td>Arterial</td>
<td>Rain and Snow Conditions</td>
<td>increase travel time but not exact number given</td>
<td>--</td>
</tr>
</tbody>
</table>

1

Arterials

Gillam and Withill [8] investigated weather impacts on adaptive traffic signal systems in four urban areas of the U.K. They analyzed traffic flow under dry and wet pavement conditions and found that delay and congestion increased by 11%, and that saturation flow rate was reduced by 6% with wet pavement.

Mitretek Systems [9] analyzed the impacts of adverse weather on arterial travel time in Washington, D.C. They found that, on average, precipitation increases peak-period travel time by at least 11%. During off-peak periods, travel time may increase by 13% due to visibility, wind, and precipitation. The authors state that precipitation causes a 3.5% travel time increase, and that this value was likely to be lower than reality due to data limitations. They did not distinguish between light and heavy rain.

Perrin and Martin [10] analyzed the impact of inclement weather on speed and saturation flow rate at two intersections in Utah. They found that rain reduced speed and saturation flow rate by 10% and 6%.

Chin et al. [11] analyzed the impacts of weather on operations at different regions across the U.S. Weather conditions were classified into: light rain, heavy rain, light snow, heavy snow, fog and ice. They assumed that rain or snow intensity of at least one inch/hour to be heavy and other amounts to be light. For urban and rural arterials, the drop in capacity and speed was 6% and 10% respectively under both light and heavy rain conditions.

Chung et al. [12] investigated the effects of rainfall on travel demand and travel time at Tokyo Metropolitan Expressway. Travel demand decreased for rainy days, especially during the weekend. At low density, there is no significant difference in travel time between rainy and dry conditions. At high density, travel time is significantly higher at rainy conditions than at dry conditions by 4.4-6.3%. The authors do not differentiate between light and heavy rain.
Abdalla and Abdel-Aty [13] modeled travel time when drivers are equipped with real-time traffic information/advice on urban networks. They found that light and heavy rain increase travel time by 9.1% and 17%, respectively. However, they did not classify precipitation quantitatively by intensity.

Athey Creek Consultants [14] considered the impact of rain or snow on travel time in calibrating the Minnesota arterial travel time estimation model. The travel time was increased if it was raining or snowing by a set number, but the report does not provide the exact increase used.

In summary, most of the literature reported that rain caused a speed reduction on arterials of 9%-11% and a saturation flow rate reduction of about 6%. However, most of the previous research did not classify precipitation by intensity. Table 1 summarizes the literature findings on speed and capacity reduction on arterials due to rain.

### Effects of visibility

According to [15], low visibility has been mostly implied by the presence of heavy rain or snow conditions that reduces sight distance. Brilon and Ponzlet [5] found that darkness caused an average speed reduction by 5 km/h (3 mph), and that darkness reduced the capacity on two- and three-lane autobahns by 200-375 vph. That represents a 13% to 47% reduction in capacity during darkness. However, this study was conducted in Germany, where there are no speed limits on many freeways and driver behavior and expectancies may differ from U.S.

Liang et al. [16] evaluated 75 km (45 miles) of a rural section in Idaho and found that visibility affected speeds according to a logarithmic relationship. Speed at night was 1.6 km/h (1 mph) less than during daylight. Average speed was reduced by 8 km/h (5 mph) during fog; however, this was based on only two fog events.

Kyte et al. [17] analyzed data from Idaho and found that limited visibility (0.1-0.23 miles) caused an insignificant decrease (<1 mph) in operating speeds. In a subsequent article, Kyte et al. [18] explicitly defined a critical visibility distance of 0.3 km (0.18 mile), below which the speed was reduced by 0.77 km/h (0.48 mph) for every 0.01 km (0.0062 mile) reduction in visibility.

Chin et al. [11] used loop detector data from different regions in the US to analyze the impacts of visibility on operations. They found that the loss of capacity and speed under fog conditions was 6% and 13% for freeways and arterials, respectively.

Agarwal et al. [7] classified visibility data due to fog events into four groups: >1 mile (normal weather conditions), 1–0.51, 0.5–0.25, and <0.25 miles. The results showed statistically significant reductions of 10%-12% in freeway capacities for three groups of visibility ranges when compared with normal weather conditions (visibility >1 mile). However, no statistically significant differences in capacities among the three low visibility groups were found, when compared in pairs. They found speed reductions of 6.6%, 7.1%, and 11.8% respectively for three groups of visibility ranges when compared with visibilities greater than one mile.
Rakha et al. [19] used four different levels of visibility: less than 0.8 km (0.5 miles), 0.8-1.6 km (0.5-1 miles), 1.6-4.8 km (1-3 miles), and greater than 4.8 km (3 miles). They concluded that visibility has a larger impact on traffic stream parameters for snow precipitation when compared to rain. When visibility reduces from 4.8 to 0.0 km (3.0 to 0.0 miles), they observed reductions in traffic parameters in the range of 10%.

In summary, the visibility restrictions that have been studied in the literature relate to darkness, fog, and the presence of rain or snow conditions. No paper was found that discussed reduced visibility due to smoke, which is of particular concern to Florida. The observed speed reductions due to low visibility vary significantly among the papers, and some are reported as a speed reduction while others are reported as a percent in reduction. Table 2 provides a summary of the literature regarding speed and capacity reductions caused by visibility restrictions.

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Facility type</th>
<th>Visibility levels</th>
<th>Speed reduction</th>
<th>Capacity reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brilon and Ponzlet (1996)</td>
<td>Freeway (autobahns)</td>
<td>Darkness</td>
<td>By 5 km/h</td>
<td>13% - 47%</td>
</tr>
<tr>
<td>Liang et al. (1998)</td>
<td>Freeway</td>
<td>Darkness</td>
<td>By 1.6 km/h</td>
<td>--</td>
</tr>
<tr>
<td>Kyte et al. (2000)</td>
<td>Freeway</td>
<td>0.1 – 23 mile</td>
<td>Insignificant decrease (&lt; 1mph)</td>
<td>--</td>
</tr>
<tr>
<td>Kyte et al. (2001)</td>
<td>Freeway</td>
<td>&lt; 0.3 km (0.18 mile)</td>
<td>reduce by 0.77 km/hr for every 0.01 km (0.0062 mile) reduction in visibility</td>
<td>--</td>
</tr>
<tr>
<td>Chin et al. (2004)</td>
<td>Freeway and arterial</td>
<td>Fog</td>
<td>13%</td>
<td>6%</td>
</tr>
<tr>
<td>Agarwal et al. (2005)</td>
<td>Freeway</td>
<td>&gt; 1 mile</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – 0.5 mile</td>
<td>6.63%</td>
<td>10% - 12%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 – 0.25 mile</td>
<td>7.10%</td>
<td>10% - 12%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;0.25 mile</td>
<td>11.78%</td>
<td>10% - 12%</td>
</tr>
<tr>
<td>Rakha et al. (2007)</td>
<td>Freeway</td>
<td>Visibility with rain</td>
<td>Sensitive to rain intensity but not impacted by visibility</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visibility with snow, reduce from 4.8 to 0.0 km</td>
<td>&lt; 10%</td>
<td>&lt; 10%</td>
</tr>
</tbody>
</table>

**Travel time reliability**

Recently, significant research has been completed within SHRP 2 to incorporate travel time reliability as a performance measure into the HCM freeways and urban streets methodology. In contrast to the FDOT application of reliability which examines freeways and arterials system-wide, this work focuses on the analysis of individual segments consistent with the HCM definitions. The SHRP 2-L08 project considered...
non-recurring congestion effects, such as weather, incidents, work zones, and special events [20].

Regarding freeways, the different weather conditions pertain to rain (low, medium and high level similar to the 2010HCM categorization), snow (light, medium and high level), visibility (low, minimum), cold, fog, and normal weather. Historical averages by hour and by month are used to calculate the probability of occurrence of eleven weather conditions at 101 metropolitan areas across the US. These data are used as defaults and the analyst should select the metropolitan area closest to the study facility when estimating the weather probabilities.

The SHRP 2-L08 project also studied travel time reliability at urban streets. The procedure is used to obtain the occurrence of rainfall and snowfall and associated intensity. It also obtains the time that the pavement remains wet or is covered with snow or ice, as these conditions may affect the running speed and the saturation flow rate.

The various weather conditions considered in the SHRP 2-L08 project are assumed to impact the speed and capacity of the facility. Capacity (or saturation flow rate) and speed adjustment factors are obtained as a function of weather conditions and free flow speed (FFS). In the freeways methodology, for FFS of 55 mph to 75 mph the adjustment factor ranges from 1% to 3% for low rain level; from 6% to 10% for medium rain level; and from 11% to 18% for high rain level. The capacity adjustments are based on the 2010HCM values and they range from 3% to 9% based on rainfall intensity. The rainfall intensity categories are classified into light (less than 0.10 inches/hour), medium (0.10–0.25 inches/hour), and heavy (more than 0.25 inches/hour).

The L08 urban streets methodology introduces an equation that calculates the saturation flow and speed adjustment factors as a function of the rainfall and snowfall intensities. This equation does not consider rainfall intensity categories but utilizes actual values of the intensity as a continuous variable. For example, these adjustments are 5% for 0.1 inches/hour intensity and 11% for 0.25 inches/hour intensity.

The SHRP2-L08 methods rely on obtaining the rainfall intensity for specific segments along a section, and are not easily generalizable over a region. The method described in this paper obtains relationships between rainfall intensity and frequency for an entire region, so that the use of average rainfall in a zip code together with a pre-calibrated function for the region can be used to obtain the required inputs for reliability analysis.

**MODEL DEVELOPMENT**

This section describes the steps undertaken for evaluating weather impacts in FDOT’s travel time reliability method. Considering the interrelationship between rain and visibility, and to avoid overlapping effects, rain and visibility should be considered jointly. However, only one report [19] studied visibility under rainy conditions. Elefteriadou et al. [21] evaluated the impacts on travel time reliability on a sample freeway segment using visibility data for a year, and found that the differences in travel time estimation when adding visibility impacts was minimal. Therefore, visibility was not considered further in this method.
Rainfall Intensity Classification

Based on the literature review, this research proposes three rainfall intensity categories: “None or Trace”, “Light Rain”, and “Heavy Rain”. The first category includes rainfall intensity of less than 0.01 inches/hour (labeled as “Trace”), as well as hours with no precipitation. These conditions are grouped together because there seems to be no discernible impact on FFS when there are only traces or rain.

The “Light Rain” group and its impact on speed reduction were determined mainly based on the two studies [6, 7]. These studies concluded that speed reductions are similar for both light and heavy rain. As a result, this research combined the categories of light and heavy rain into a “Light Rain” category with rainfall intensity between 0.01 and 0.5 inches/hour for freeway facilities and between 0.01 and 1 inches/hour for arterials. Smith et al. [6] concluded that the presence of light and heavy rain decreased operating speed by 5.0-6.5% regardless of intensity. Agarwal et al. [7] indicate that this speed reduction was found to be 2-7%. On arterials, rain was found to cause speed reduction by 9%-11%, while one paper states that light rain and heavy rain increase the travel time by 9% and 17%, respectively. Based on those results for the “Light Rain” group, an operating speed reduction of 6% was assumed for freeways and a 10% for arterials.

However, the rain intensities considered in the literature [6, 7] was not as high as can occur in Florida. To consider the Florida climate, a rainfall category of “Heavy Rain” is defined for precipitation rate exceeding 0.5 inches/hour on freeways and over 1.0 inch/hour for arterials. A speed reduction of 12% and 17% for freeways and arterials respectively are assumed for this category.

No capacity reductions are assumed for freeways, since the Florida method assumes that the capacity for oversaturated conditions is 10% lower than that for undersaturated conditions (due to the capacity drop phenomenon), and any additional reduction might overestimate the effects of rainfall. A capacity reduction of 6% is assumed for arterials under “Light Rain” and “Heavy Rain” since this was found to be consistent with the literature. The rainfall categories and their suggested impacts on operating speed reduction are shown in Table 3.

<table>
<thead>
<tr>
<th>Rain category</th>
<th>Rainfall intensity (in/h)</th>
<th>Speed reduction (%)</th>
<th>Capacity reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Freeways</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None or Trace</td>
<td>&lt;0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Light</td>
<td>0.01-0.5</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Heavy</td>
<td>&gt;0.5</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None or Trace</td>
<td>&lt;0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Light</td>
<td>0.01-1.0</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Heavy</td>
<td>&gt;1.0</td>
<td>17</td>
<td>6</td>
</tr>
</tbody>
</table>
Estimating the Probability for Each Rainfall Category

When estimating the weather impact for a freeway or arterial section, the probability of occurrence of each rainfall category is first calculated for the analysis period. Based on these results and the assumptions presented in Table 3, speed and capacity reductions are estimated. This section describes the method in estimating the probability for each rainfall category for a specific location in Florida.

Weather impacts were considered based on three regions within Florida (Tallahassee, Orlando, Ft. Lauderdale), and using five years of rainfall data. The effects of weather are estimated for each freeway/arterial section based on the probability of occurrence for a particular rainfall category for each of the 24 hours of analysis. This probability is obtained using a calibrated relationship between rainfall intensity and frequency. This was necessary because using just the average rainfall intensity for a particular hour in the day would not take into consideration the varying rain intensity that might occur during that hour throughout the year. This relationship allows us to obtain the probabilities of none or trace, light rain and heavy rain for each hour of analysis.

As it was very time consuming to obtain a specific rainfall frequency distribution for each location for state-wide reporting, it was assumed that there are three rainfall distributions, representing three different precipitation areas, within Florida. Then, for a specific road section, the average rainfall of its zip code and the respective regional distribution are used to obtain the probability of occurrence of each level of rainfall for this road section.

Based on Florida’s annual precipitation statistical data from the period 1961-1990 (Figure 1) the cities of 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 those three areas to capture 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 4 present the recommended categorization of counties to the three rainfall distribution regions.
Figure 1. Florida Average Annual Precipitation Map (Source: Spatial Climate Analysis Service, Oregon State University, 2000)

Table 4. Rainfall Distribution Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Representative Location</th>
<th>Counties</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region 2</td>
<td>Orlando</td>
<td>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</td>
<td>central low precipitation area</td>
</tr>
<tr>
<td>Region 3</td>
<td>Miami</td>
<td>St. Lucie, Martin, Palm Beach, Broward, Miami-Dade, Monroe</td>
<td>southeast high precipitation area</td>
</tr>
</tbody>
</table>
Rainfall Intensity vs. Frequency Curves

Three distribution models were developed based on a five-year-period dataset (January, 2006 – December, 2010) for the three representative cities of Tallahassee, Orlando, and Miami. The weather data were collected through the Weather Underground website (http://www.wunderground.com).

Based on preliminary statistical analysis, the frequency of rainfall intensity for every location can be represented by the Gamma distribution. The cumulative Gamma function was obtained for each of the three graphs shown in Figure 2.

a) Rainfall intensity distribution for Tallahassee (zip code 32301)
(Mean = 0.1425 in/hr, Variance = 0.073 in²/hr²)

b) Rainfall intensity distribution for Orlando (zip code 32801)
(Mean = 0.1444 in/hr, Variance = 0.064 in²/hr²)
b) Rainfall intensity distribution for Miami (zip code 33127)  
(Mean = 0.1418 in/hr, Variance = 0.070 in²/hr²)

Figure 2. Rainfall Intensity Distribution of Three Representative Locations

Equations 1, 2 and 3 are the cumulative Gamma distribution functions for the three representative regions shown in Figure 2. The shape \(k\) and scale \(\theta\) parameters of the Gamma distribution function were calculated using regression based on the five-year hourly rainfall data.

Tallahassee: \(k = 0.2782, \ \theta = 0.5123\)

\[
F_N(x;0.2782,0.5123) = \frac{\gamma(0.2782,x/0.5123)}{\Gamma(0.2782)} = \int_0^{x/0.5123} t^{0.2782-1} e^{-t} dt
\]  \hspace{1cm} (1)

Orlando: \(k = 0.3258, \ \theta = 0.4432\)

\[
F_N(x;0.3258,0.4432) = \frac{\gamma(0.3258,x/0.4432)}{\Gamma(0.3258)} = \int_0^{x/0.4432} t^{0.3258-1} e^{-t} dt
\]  \hspace{1cm} (2)

Miami: \(k = 0.2872, \ \theta = 0.4937\)

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

Where: \(\gamma(k, x/\theta)\) is the lower incomplete gamma function and \(\Gamma(k)\) is the gamma function evaluated at \(k\).

All the rainfall frequency distributions for locations inside 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 location. Since rainfall information is provided by zip code, average rainfall is obtained on a zip code basis. 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 is
obtained for the zip code of the road section), we obtain the specific rainfall distribution for each road section. We finally obtain the probability for each of the three rainfall scenarios (trace or none, light rain, or heavy rain) for each freeway/arterial section from these distributions, as shown in Figure 2.

Example Application
An example of the developed method is illustrated in this section. A freeway section of I-95/SR 9 between Broward Blvd and Sunrise Blvd is used in this example. The zip code for this area is 32819 (Orange county).

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 3 shows the respective calculation table. The highlighted columns indicate the required user inputs.

| 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 |
| 12:1 | 0.0630 | 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 | 0.0681 | 0.646 | 0.354 | 0.000 | 0.026 | 1.000 | 0.000 |
| 4-5 | 0.0467 | 3 | 0.2872 | 0.1626 | 0.492 | 0.502 | 0.006 | 0.042 | 0.993 | 0.011 |
| 5-6 | 0.0388 | 3 | 0.2872 | 0.1351 | 0.518 | 0.479 | 0.003 | 0.042 | 0.964 | 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 | 0.0494 | 0.676 | 0.324 | 0.000 | 0.026 | 1.000 | 0.000 |
| 8-9 | 0.0160 | 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 | 0.026 | 0.993 | 0.007 |
| 11-12 | 0.0063 | 1 | 0.2872 | 0.0289 | 0.762 | 0.236 | 0.000 | 0.014 | 1.000 | 0.000 |
| 12-1 | 0.0179 | 2 | 0.2872 | 0.0623 | 0.636 | 0.364 | 0.000 | 0.026 | 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 | 0.396 | 0.000 | 0.026 | 1.000 | 0.000 |
| 3-4 | 0.0720 | 1 | 0.2872 | 0.2510 | 0.437 | 0.542 | 0.021 | 0.026 | 0.973 | 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 | 0.2177 | 9 | 0.2872 | 0.7559 | 0.320 | 0.545 | 0.136 | 0.125 | 0.801 | 0.199 |
| 7-8 | 0.0814 | 7 | 0.2872 | 0.2834 | 0.422 | 0.560 | 0.028 | 0.125 | 0.851 | 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 | 0.0600 | 3 | 0.2872 | 0.1741 | 0.483 | 0.510 | 0.007 | 0.042 | 0.962 | 0.014 |
| 11-12 | 0.1060 | 4 | 0.2872 | 0.3656 | 0.393 | 0.569 | 0.048 | 0.066 | 0.922 | 0.070 |

Figure 3. Calculation Example

Step 2: Determine Shape (k) and Scale (θ) Parameters

The location of the freeway segment is used to determine the shape of the rainfall intensity distribution. The subject freeway segment is in the Miami rainfall distribution region; therefore, the value used for the shape parameter k of the Gamma distribution is 0.2872. The scale parameter θ, is determined using the average rainfall for this location. For example, for 4-5 PM, the scale parameter θ is:
\[ \theta = \frac{\text{mean}}{k} = \frac{0.1415}{0.2872} = 0.4927 \] (4)

The results of this step are presented in the fourth and fifth columns of Figure 3.

**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 more 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 3.

**Step 4: Estimate the Probability for Three Rainfall Scenarios**

Considering the cumulative Gamma distribution function developed in Step 2, the probability of each of the three rainfall scenarios for the hour of 4-5 PM at this location can be identified.

Based on Equation (1), the probability for “Trace” is:

\[ P(Trace) = F_5(0.01;0.2782,0.4927) = \frac{\gamma(0.2782,0.01/0.4927)}{\Gamma(0.2782)} = 0.361 \] (5)

The probability of “light rain” is:

\[ P(Light\ Rain) = F_5(0.5;0.2782,0.4927) - F_5(0.01;0.2782,0.4927) = \frac{\gamma(0.2782,0.5/0.4927)}{\Gamma(0.2782)} - \frac{\gamma(0.2782,0.01/0.4927)}{\Gamma(0.2782)} = 0.560 \] (6)

The probability of “Heavy Rain” is:

\[ P(Heavy\ Rain) = 1 - P(Trace) - P(Light\ Rain) = 0.078 \] (7)

Calculations for the other hours are the same. The results of this step are presented in columns six to eight of Figure 3.

**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 and Heavy Rain” is:

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

The ratio of “Heavy Rain” to “Light and Heavy Rain” for 4-5 PM is:
These results are presented in the last three columns of Figure 3.

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

The last three columns of Figure 3 are used to calculate the travel time under rain-related scenarios.

The free-flow speed of the freeway segment is 65 mph under normal conditions. The free-flow speed reduction for light rain and heavy rain is 6% and 12% respectively. Therefore, the adjusted free-flow speed for light rain is:

\[
F(Light\ Rain) = FFS \times (1 - FFS \text{ reduction for light rain})
\]

\[
= 65 \times (1 - 0.06) = 61.1
\]

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

\[
F(Heavy\ Rain) = FFS \times (1 - FFS \text{ reduction for heavy rain})
\]

\[
= 65 \times (1 - 0.12) = 57.2
\]

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

\[
\text{Equivalent Free - flow Travel Time for Rain} = (\text{Ratio of Light Rain} \times (3600 / FFS \text{ for light rain)})
\]

\[
+ \text{Ratio of Heavy Rain} \times (3600 / FFS \text{ for heavy rain})) \times \text{Length}
\]

\[
= (0.877 \times (3600 / 61.1) + 0.123 \times (3600 / 57.2)) \times 1.022
\]

\[
= 60.37
\]

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.

APPLICATION OF THE METHOD ON TRAVEL TIME RELIABILITY FOR FDOT

FDOT has developed a methodology for estimating travel time reliability for freeways and arterials within the Strategic Intermodal System (SIS). The basic concept behind FDOT’s methodology is illustrated in Figure 4 [22].
For freeways, the facility is segmented at the section level (interchange to interchange) so that travel time can be obtained along each section and aggregated to the facility level. For arterials travel time is estimated for the entire corridor. In Step 1 the methodology considers a series of scenarios that may occur throughout a year. A scenario constitutes a set of conditions that affect travel time of the section. The conditions considered for developing the scenarios are: recurring congestion (due to excess demand), weather, incidents (lane-blocking or non-lane blocking incidents), and work zones. A combination of these conditions results in 24 scenarios.

In Step 2, the travel time for each scenario identified in Step 1 is estimated considering various models. These estimates are based on the models developed by [23, 24], and refined in [21] based on field observations. The travel time models are of the form: \( E(TT_{\text{scenario}}) = f(\text{congestion, weather, incident, work zone}) \).

In Step 3, the probability of occurrence of each scenario is obtained. Conditional probabilities were used for calculating the probability of containing the combination of different conditions, such as the “no rain, no incident, one lane closure work zone and congested” scenario. The probability of each condition (congestion, weather, incident, and work zone) is estimated by hour of day using existing data of the frequency of specific occurrences. For instance, the probability of recurring congestion is based on the probability of demand exceeding capacity (LOS F) for each hour of the day and by direction. This information is provided by FDOT annual reports of delay and level of congestion throughout the State Highway System based on traffic, roadway and control characteristics, and typical traffic distributions.
The probability of a blocking incident by lane/mile per year is determined for four different scenarios: no rain and no work zone; rain and no work zone; no rain and work zone; and rain and work zone. The incident probability by time of day comes from the FDOT Crash Analysis Reporting System (CARS).

The probabilities of no rain, light rain, and heavy rain are calculated based on the model presented here, which estimates the frequency of rain as a function of rain intensity considering a five-year period dataset.

In Step 4 the travel time distribution for each subject section is obtained by plotting the expected travel times and the corresponding frequencies of each scenario obtained through Steps 2 and 3. Various travel time – reliability-related measures can be estimated based on this distribution. The travel time reliability at the network level is calculated by aggregating the respective performance measures by hour for each section analyzed.

CONCLUSIONS AND RECOMMENDATIONS

This paper presented a methodology currently employed within FDOT’s travel time reliability model to evaluate weather-related impacts on travel time. The methodology incorporates different rainfall characteristics of regions across Florida and calibrates the rainfall intensity distribution models on a zip code basis for every hour within the period of interest. The probability of clear weather, light and heavy rain is determined for each hour and applied to the respective freeway or arterial section based on its zip code. Speed reductions are 6% for light rain and 12% for heavy rain at freeway sections and 10% for light rain and 12% heavy rain at arterials. For arterials, 6% capacity reduction is also considered for light and heavy rain.

The proposed method can be easily applied to generalize the weather-related information required in the SHRP 2-L08 analysis. Suitable functions can be developed to replicate the rainfall or snowfall functions and these can be used to extract the probability of occurrence of specific intensities. At the planning level, the proposed method appears to be more readily applied, since it considers three weather categories, compared to the eleven categories introduced in the SHRP 2-L08 project.

The following recommendations are offered for future work:

- The focus of the proposed methodology is on weather-related impacts. It is recommended to further enhance the models and incorporate visibility-related impacts, as well as the relationship between visibility and rainfall. It is also possible to consider a combination of visibility and weather conditions as separate scenarios for incorporation within the existing reliability methodology.
- The assumed percent reduction of the free-flow speed on freeways and arterials due to rain intensity needs to be verified with additional field data.
- The literature does not provide consistent guidance regarding the possibility of capacity reduction on freeways due to weather impacts. This relationship needs to be further evaluated and if indeed there is a significant effect, it should be incorporated within the travel time reliability framework.
Correlations between different weather conditions and incident occurrence should be reflected in the FDOT analysis models. Although the current method considers the effect of both incidence occurrence and rainfall intensity on speed, this is done independently. A more thorough approach should be developed, that also addresses potential additional effects of rain intensity on incidence occurrence.
REFERENCES


