The Effects of Rain on Traffic Safety and Operations on Florida Freeways

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THE EFFECTS OF RAIN ON TRAFFIC SAFETY AND OPERATIONS ON FLORIDA FREEWAYS

by

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ABSTRACT

Although the association between weather and traffic variables or crash events appear intuitive to motorists, quantifying the effects that weather, especially rain, has on driver response in travel speeds, traffic demands, and susceptibility of accident occurrence is needed to evaluate practical aspects of traffic operations and safety measures. Previous studies have researched driver responses to inclement weather on roadways located primarily in northern and western regions of the United States (U.S.), Canada, and Europe. However, driver familiarity to local weather conditions is a factor that should be considered in determining inclement weather effects on traffic variables and crash occurrence. This research focused on the effects of rain precipitation on freeways located in the Southeast region of the U.S. to determine if results from previous studies are general indicators or location specific in nature. The impacts of rain on hourly mean speeds and traffic volumes were studied for freeway segments in Jacksonville, Florida. Results indicate significant reductions in both traffic parameters with increasing rain intensity. Crash data examined along the same freeway sections found that hourly crash risks and crash rates per 100 million vehicle miles of travel, based on rain exposure hours, increased with increasing rain intensity, and were significant. However, hour-of-day and season of year had little effect on hourly crash occurrence. Rain intensity also significantly increased the proportion of injury accidents in the majority of traffic conditions.

Keywords: rain, traffic, speed, volume, crash, severity

CHAPTER 1 - INTRODUCTION

It is widely recognized that inclement weather can have adverse effects on traffic safety and operations. Analyzing driver behavior, in terms of traffic parameters such as travel speed, spacing, and time headway during weather events is necessary to determine the relationship between precipitation and traffic variables. The effects of environmental exposures, such as weather elements and lighting conditions, on crash occurrence is important for the evaluation of traffic safety measures.

Weather, in general and more specifically rainfall, is a non-traffic component that can influence traffic characteristics by affecting pavement conditions and driver behavior. Although previous research has identified this phenomena and sought to quantify changes in traffic elements and increased risk of crash occurrence during non-ideal driving conditions, such studies have focused on cities where snow precipitation is more frequent, primarily in northern areas of the United States (U.S.), Canada, and Europe. Little focus has been placed on weather effects along freeways located in the Southeast region of the U.S. where rain precipitation is prevalent and snowfall is rare. Previous studies have noted reductions in speeds and traffic volumes with an increase in the number of accidents on roadways during rainy conditions. However, few studies have investigated the effects of rainfall events of varying intensities or subtropical climate zones.

The focus of this research is to examine average hourly speeds and traffic volumes over a duration of four years to determine general tendencies in driver behavior during generally rainy conditions, as well as, during light, moderate, and heavy rains on freeways located in the

Southeast region of the U.S. Crash occurrence and severity based on rain exposure and hour-of-day were also examined. Additionally, seasonal influences on the number of crashes were investigated using rainfall seasons unique to Northeast Florida. Findings were compared with earlier studies to determine if geographical influences and driver familiarity with the local weather patterns present differing results than previously researched regions.

Statement of Problem

Published research has addressed the impact of rain on traffic operation parameters such as speed and capacity on northern regions of the U.S. and Canada. Likewise, crash occurrence and severity due to precipitation have been examined in areas primarily located in the northern and western regions of the U.S., Canada, and Europe. Because precipitation type and frequency can vary by climate zone, more research is needed to gain a better understanding of regional weather effects on traffic safety and operation elements. Studies involving sites located in the lower Southeast region of the U.S. were not found among published literature. This study examines driver response to rain precipitation on Florida freeways to add to the general body of knowledge on the subject, and to determine if weather effects on traffic volumes, travel speeds, and crash occurrence in the Southeast region of the U.S. correlate with previous findings from other U.S. regions and countries.

Significance of Study

Findings from this study will provide quantitative information on travel speeds, traffic flow, and crash occurrence during rainy conditions for various rainfall intensities on high-speed freeways in the lower Southeast region of the U.S., a subtropical climate area. Such information is necessary to better understand, not only the effects of weather on traffic elements by region, but also by type of climate. Moreover, knowledge of the relationship between traffic elements

and rain intensity, by hour-of-day, will contribute to the development of real-time prediction models and safety planning measures.

CHAPTER 2 – REVIEW OF LITERATURE

The types of data required for the study of traffic operation and safety variables are characteristically different, and as a result, have generally been researched independently. This point was evident in the review of the published research on both topics. Therefore, the review of literature on the effects of precipitation on traffic operations (travel speeds and traffic volumes), and traffic safety (crash occurrence), has been presented separately.

Traffic Operations

Several studies have been conducted to quantify the impact of inclement weather on free-flow speeds, time headway and spacing, and capacity resulting from rain and snow precipitation on freeways where snow events are more frequent. Kyte, Khatib, Shannon, & Kitchener (2001) examined the effects of wet or snow covered pavement conditions, wind speeds, and visibility on free-flow speeds along a four-lane rural Interstate section in southeastern Idaho. While their research identified a reduction in speeds of 5.9 mph (9.5 km/h) on wet pavement surfaces during uncongested traffic conditions, the primary focus was more on speed reductions due to poor visibility, more likely resulting from blowing snow. It was unclear what rain intensity was represented from the collected weather data.

Other studies have examined the effects of various rainfall intensities on freeways in Canada and found differing results in speed reductions. One study by Ibrahim and Hall (1994) found speed reductions of 1.2 mph (2 km/h) during light rain events and between 3.1 to 6.2 mph (5 to 10 km/h) reductions during heavy rains under free-flow conditions where travel speeds are

not restricted by heavy traffic volumes. A later study by Unrau and Andrey (2006) found larger reductions. Unrau and Andrey focused on the effects of rain versus dry weather conditions along a six-lane freeway in Canada, specifically on travel speeds and time gaps between vehicles. Only hourly data depicting light rainfall (.01 to 2.4 mm total accumulation) was used in the study due to the small sample size for moderate to heavy rainfall hours. Findings include a decline in travel speeds of 5 mph during daytime uncongested light rain conditions regardless of volume. Time gaps increased, and speed variability decreased. According to the study, travel speeds only slightly deviated from the speed limit during nighttime uncongested light rainfall events. Speed reductions of 3.5 mph (5.7 km/h) were also observed for daytime congested light rain conditions. However, volume or time gaps were not affected during this condition.

Maze, Agarwal, & Burchett (2006) conducted a study at the Center for Transportation Research and Education (CTRE), Iowa State University, to estimate capacity and travel speed reductions during inclement weather on freeways in Minnesota. The study divided rainfall amounts into three categories: Trace (0 to .01 in/h), Light (>.01 to .25 in/h), and Heavy (> .25 in/h) based on earlier CTRE research on freeway capacities and referenced in the *Highway Capacity Manual* (HCM, 2010). The results concluded that heavy rain events can reduce freeway capacity significantly by 14%, with a 6% reduction in travel speeds. Light rainfall events were associated with a 4% decline in speeds, and a 7% decline in capacity. The degree of reduction was directly related to the intensity of precipitation. While Maze et al. (2006) addressed the effects of rainfall on travel speeds, their focus was primarily on estimating capacity reductions, and especially pertaining to snow events since heavy rainfall is uncommon in the Minneapolis-St. Paul area.

Rakha, Farzaneh, Arafeh, & Sterzin (2008) analyzed precipitation and visibility impacts

from moderate to heavy rainfall on traffic stream behavior at three locations in the U. S.: Baltimore Maryland, Minneapolis-Saint Paul, Minnesota, and Seattle, Washington. Their analysis also categorized rain intensities displayed in the HCM (2010) up to .63 in/h. Speed reductions at these sites were consistent with results from Ibrahim and Hall (1994) for light rain conditions, but slightly higher and more consistent with Maze et al. (2006) for heavy rain conditions. The study also concluded that rainfall intensity up to .67 in/h (1.7 cm/h) had little bearing on roadway capacity reductions in general, only the speed at capacity is reduced as rain intensity increases.

Even greater speed reductions were found by Billot, El Faouzi, & De Vuyst (2009) from the study of driver behavior during rainy conditions on a French Interurban motorway. Three rain categories were used in the study: Light (< .08 in/h), Medium (.08 to .11 in/h, and Heavy rain (>.11 in/h) to analyze changes in time headway and spacing during morning and evening peak hours. However, the Heavy rain category was not used due to lack of data. Results concluded that free-flow speeds decreased by 8% to 12.6% under rainy conditions where increases in time headways and vehicle spacing resulted from changes in travel speeds. Overall, these findings were consistent with previous studies which indicate that on average, drivers tend to reduce travel speeds under rainy conditions.

Although the aforementioned studies have addressed the impact of rain on traffic operation parameters such as speed and capacity, the results were most likely influenced by the location of the study sites. Previous research primarily focused on northern regions of the U.S. and Canada. Studies involving sites located in the Southeast region of the U.S. were not found among published literature. The effects of rainfall on driver behavior may be different in other regions of the U.S., particularly in the Southeast. It is difficult to infer that similar effects will be

realized as found from other regions that experience different types and degrees of precipitation. Driver familiarity to local weather conditions must be considered to determine if driver response under rainy conditions varies by location.

Traffic Safety

Numerous studies have been conducted to quantify the impact of inclement weather on crash occurrence resulting from precipitation exposure. Sherretz and Farhar (1978) studied the effects of rain on accident occurrence and related injuries in eight cities outside of St. Louis, Illinois. The study was limited to five consecutive late afternoon hourly time periods for the summer months of June, July, and August when rainfall was frequent. Daily rainfall amounts up to 1.97 inches (50 mm) within the study hours for 12 different rain intensity categories were used in the analyses. Results indicated that rainy conditions significantly increased daily accidents by 68% for rainfall amounts of .3 to 5 mm (.1-.19 inches), and over 150% for rainfall of 5.1-10 mm (.2-.39 inches), with the highest mean accident occurrence, 168%, during heavy rainfall of 25 mm (.98 inches) or greater (Sherretz & Farhar, 1978).

Similar findings between crash occurrence and related injuries were found by Bertness (1980) in a study of roadway accidents in the Chicago, Illinois metropolitan area. On average, accidents during rainy conditions were 2.2 times greater than dry conditions (Bertness, 1980). A later study by Levine, Kim, & Nitz (1995) found a significantly high correlation between rainfall and daily accidents, especially during PM peak volume hours. The study focused on crash occurrences in the metropolitan area of Honolulu, Hawaii, the island of Oahu, using aggregated daily and monthly crash data (Levine et al., 1995).

Other studies have been conducted in Canada and other countries where snow and rain events are widely distributed. Andrey and Yager (1993) focused on road condition exposure and

accident risk during and following rain events for the cities of Calvary and Edmonton, Alberta, Canada, using hourly weather data as a temporal unit of measure. Results concluded that the majority of crashes occurred on wet road conditions, and the overall relative crash risk ratio for accidents occurring during rain events was 1.7, an increase of 70% over dry conditions. Another large scale study was conducted by Andreescu and Frost (1998) on the effects of rain, snow and temperature on accident occurrence in the urban community of Montreal, Quebec, Canada. The study used aggregated daily crash counts for monthly analyses of mixed roadway types with posted speeds of 30-60 mph (50-100 km/h). Significant correlations between roadway crashes and precipitation was found, with coefficients of +0.48 and +0.27 for snow and rain, respectively (Andreescu & Frost, 1998).

Edwards (1999) determined that monthly crash frequency increased during rainy weather in the British Isles, and was spatially correlated with annual rainfall across different regions. Over the ten-year study period, rain related accidents accounted for 12% to 17% of total reported crashes (Edwards, 1999). Another study by Keay and Simmonds (2006) found increases in daily accidents due to rain of 4.6% to 40% over a 15 year study period on freeway sections in Melbourne, Victoria, Australia. Six rain categories were analyzed in 5 mm increments up to 20 mm (.79 inches). However, rain effects varied both seasonally and over durations of years.

Crash severity resulting from weather-related accidents have also been explored through a number of studies. Edwards (1998) found that fatal and serious injury crashes were more frequent during nighttime rainy conditions in England and Wales, a significant difference than for fine weather. Similar findings were noted by Golob and Recker (2003), that wet surface conditions at night tended to increase accident severity. Brodsky and Hakkert (1988) contributed the higher nighttime crash occurrence during rain events to visibility factors influenced by glare,

wet shiny surfaces or poor lighting. Eisenberg (2004) conducted an expansive study that explored state-level crash rates per vehicle miles traveled, based on severity, for the 48 contiguous states in the U.S using five rain categories. Findings revealed mixed results including a decrease in fatal crashes with increased precipitation at a state-month level, but an increase in fatal crashes with increased rain for a state-day time period. However, non-fatal crashes showed an increase in all rain categories (Eisenberg, 2004). Other studies have also found mixed results surrounding the number of injury accidents during rainfall events (Sherretz & Farhar, 1978; Bertness, 1980; Bergel-Hayat, Debbarh, Antoniou, & Yannis, 2013).

Several studies have researched the effects of rain on crash occurrence along U.S. freeways. An early study by Satterthwaite (1975) found that the number of crashes increased by a factor of two during "extremely wet" conditions on California highways. As a result, due to the dry and temperate climate found in much of California, weather had a greater influence on daily roadway accidents than seasonal factors (Satterthwaite, 1975). Jovanis and Chang (1986) studied the relationship between accidents and traffic exposure along the Indiana Toll Road. Although, findings revealed that rainfall increased the mean accident frequency for automobiles, they were not significant. A later study by Jones, Janssen, & Mannering (1991) found that wet roadways increased the number of crashes on congested urban freeways in Seattle, Washington. Yet, rainfall had little effect on accident frequency (Jones et al., 1991). Wet roadway conditions also increased crash risks on limited access roadways in North Carolina, (Khattak, Kantor, & Council, 1998). In a more recent study, Xu, Wang, & Liu (2013) predicted that the risk of crash occurrence on rainy days increases with increasing rain intensity on California freeways.

However, the primary focus the study was to examine the relationship between traffic flow characteristics and crash risk under varying weather conditions.

Previous research has determined a positive association between roadway accidents and rainfall. Thus far, the greater part of research has concentrated on sites located in the northern and western regions of the U.S. and other countries where climates vastly differ from the lower Southeast region. Research on crash occurrence in subtropical to tropical climate types comparable to Florida are few (Levine et al., 1995; Keay & Simmonds, 2006). Moreover, published research involving study sites located in the lower Southeast region of the U.S. are rare (Khattak et al., 1998). Furthermore, the majority of studies have used daily or monthly aggregated crash and weather data to investigate crash frequency or severity. Analyses using hourly data as a temporal unit of measure are limited. Additionally, a number of these studies have used large scale areas of focus containing various types of roadways and traffic conditions. While some research has been conducted on the effects of rain on crash occurrence or severity for high-speed corridors, such as interstate freeways, exposure variables of hourly rainfall, or rain intensity by hour-of-day have not been widely investigated.

CHAPTER 3 - METHODOLOGY

Freeways located in the northeastern portion of Florida were considered for the study due to the subtropical climate conditions found in much of the lower Southeast region of the U.S. The city of focus was determined to be Jacksonville, Florida, the largest city by land area in the continental United States, consisting of approximately 747 square miles and a population of over 820,000 (U.S. Census Bureau, 2014).

Precipitation Data

Historical weather data was retrieved from the Jacksonville Naval Air Station (NAS Jax), one of five weather collection stations in the Jacksonville area. NAS Jax was chosen based on quality of data and high percentage of recorded hours, approximately 99.8 percent. Retrieved data included reported temperature, visibility, cloud cover, wind direction/speed, and precipitation accumulation in inches for each hour of each day. Missing rain data accounted for less than 1% of reported hourly precipitation for the years 2008 to 2012 used in this study.

The summer months of June, July, and August typically experience the greatest hourly rainfall amounts. Although these months coincide with the annual hurricane season in the U.S. (June 1 –November 30), no hurricanes or tropical storms impacted the Jacksonville area for the years used in the study. Figure 3.1 shows historical rainfall amounts reflecting annual precipitation trends and seasonal variations for the years 2008-2012.

In establishing rain categories for the study, rainfall intensity ranges somewhat differed among published literature. Consequently, more extensive research on rainfall classifications

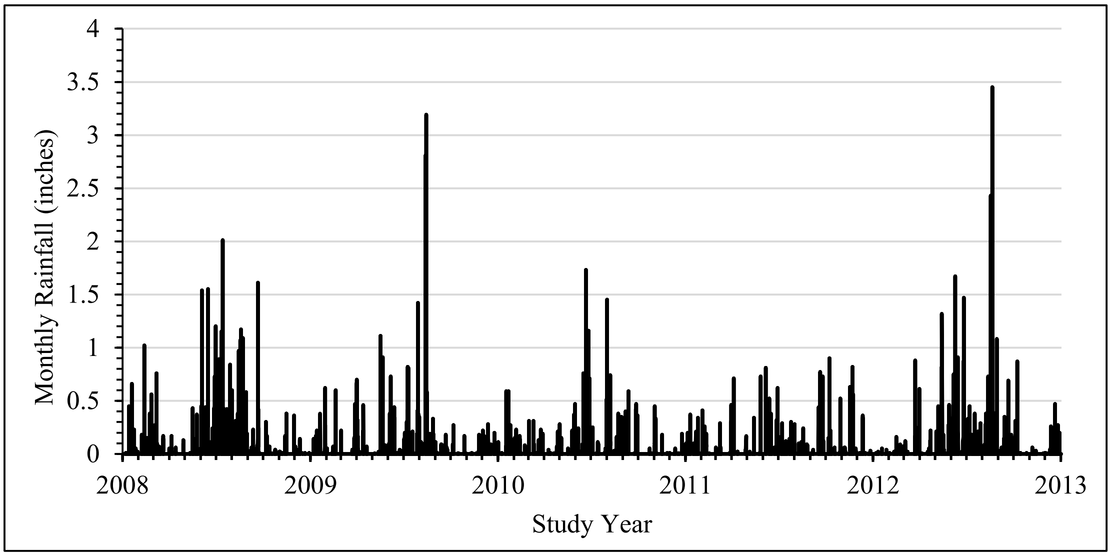

Figure 3.1. Annual rainfall (2008-2012)

was required. It is interesting to note that rainfall intensity classifications vary among weather communities, especially the amount of precipitation that is considered moderate to heavy. For example, the U. S. National Weather Service (NWS) classifies light rain as .11 to .20 in/h (2.6 to 5 mm/h), moderate rainfall as .21 to .50 in/h (5.3 to 12.7 mm/h), and heavy rainfall as greater than .50 in/h (12.7 mm/h) (National Weather Service [NWS], 2013). However, the American Meteorological Society (AMS) classifies light rainfall as trace amounts (< .01 in/h) to .10 in/h (2.5 mm/h), moderate rain as .11 to .30 in/h (2.6 to 7.6 mm/h), and heavy rainfall as amounts greater than .30 in/h (7.6 mm/h) (American Meteorological Society [AMS], 2012). Canada's definitions of the three rain categories are more similar to AMS (*Manual of Surface Weather Observations* [MANOBS], 2013), while United Kingdom's National Weather Service (UK-NWS) referred to as the Met Office, classifies precipitation rates slightly above AMS amounts (Met Office, 2013). Table 3.1 summarizes the various differences in rain intensity definitions among these agencies.

A review of published literature found that rainfall intensity categories used in previous

studies were directly dependent on the location of study. This factor did not appear of consequence in the case of light rain since intensity ranges are fairly consistent among reporting agencies and previous research. Greater discrepancies occur in the moderate and heavy rain classifications. Billot et al. (2009) used an accumulation amount of .08 to .11 in/h and greater than .11 in/h for medium and heavy rainfall, respectively. Other studies such as Maze et al. (2006) and Rakha et al. (2008) that focused on capacity reductions used categories displayed in the *Highway Capacity Manual* (HCM, 2010). The HCM does not specifically classify rain intensity categories, but references a previous study on capacity reductions due to weather and environmental conditions.

Table 3.1

Rain intensity classifications by reporting agency

	Reporting Agency				
Rain Category	AMS	NWS	HCM	Canada	UK-NWS
Light	Trace to .10 in/h	> .11 to .20 in/h	> 0 to .10 in/h	≤ .10 in/h	> 0 to .08 in/h
Moderate	.11 to .30 in/h	0.21 to .50 in/h	> .10 to .25 in/h	> .10 to .30 in/h	> .08 to .39 in/h
Heavy	> .30 in/h	> .50 in/h	> .25 in/h	> .30 in/h	> .39 to 1.96 in/h

Likewise, previous studies that examined crash occurrence and rain categories used varying rainfall intensities (Sherretz & Farhar, 1978; Eisenberg, 2004; Keay & Simmonds, 2006). To better compare results from this study with previous studies of similar focus, such as Ibrahim et al. (1994) and Unrau and Andrey (2006), hourly precipitation data was categorized using the AMS classification system shown in Table 3.1.

Site Selection

Similar to Rakha et al. (2008), study sites were selected based on facility type, proximity

to the weather station, and available traffic and crash data. Additional requirements included the presence of segment lengths outside the influence area of adjoining interchange ramps or large waterway bridges, common in Jacksonville, and away from the downtown district to minimize the influence of city traffic. Segments along two Jacksonville freeways fit the selection criteria: Interstate I-295 (Site 1), a heavily traveled beltway around Jacksonville, and Interstate I-95 (Site 2), a heavily traveled North-South corridor through Jacksonville. Both study sites are six-lane freeway sections with posted speeds of 65 mph.

To study the effects of rain on traffic variables, mid-segment sections along each corridor were selected. Due to the large volume of recorded data, only one direction of traffic was studied at each site. Site 1 (I-295), a Westbound (WB) mid-segment section, located between Blanding and Roosevelt Boulevards, has a WB directional Average Annual Daily Traffic (AADT) volume of approximately 46,500 vehicles over the 4-year study period (2009 to 2012). Site 2 (I-95), a Northbound (NB) mid-segment section, located between Southside Boulevard and Baymeadows Road has a NB directional AADT volume of approximately 50,000 vehicles over the 3-year study period (2010 to 2012). The aerial distance between the weather station and each site is approximately 2.5 miles (4 km) and 6 miles (9.7 km) for I-295 and I-95, respectively. These distances are consistent with previous studies by Rakha et al. (2008) and Billot et al. (2009). Location of the weather station and freeway study segments used in the study of traffic variables are shown in Figure 3.2.

Longer segments were required to study the effects of rain on crash occurrence and severity. A 10.5 mile (17 km) section along Interstate I-295, and a 5 mile (8 km) section on Interstate I-95 were selected for crash analyses over a 4-year study period (2008 to 2011). The aerial distance between the weather station and each freeway study section ranges from 2.5 miles

(4 km) to 8 miles (13 km). Figure 3.3 illustrates the location of the Interstate sections used in the study of traffic safety variables.

Weekday Traffic

As Jacksonville freeways generally experience a high degree of tourist traffic, especially along the I-95 North-South corridor, weekend days (Saturday and Sunday) were removed from each sample set prior to analyses. The observed days for national holidays including New Year's Day, Memorial Day, Independence Day, Labor Day, Thanksgiving Day, and Christmas Day were also removed since schools, public services, and most private sector businesses are closed. If a national holiday occurred on a Saturday, data from the Friday (observed day) before the holiday was removed. Similarly, data from the Monday after a national holiday that occurred on a Sunday was removed. This allowed for a higher probability that the remaining weekday traffic data represented primarily commuter motorists already familiar with the study routes.

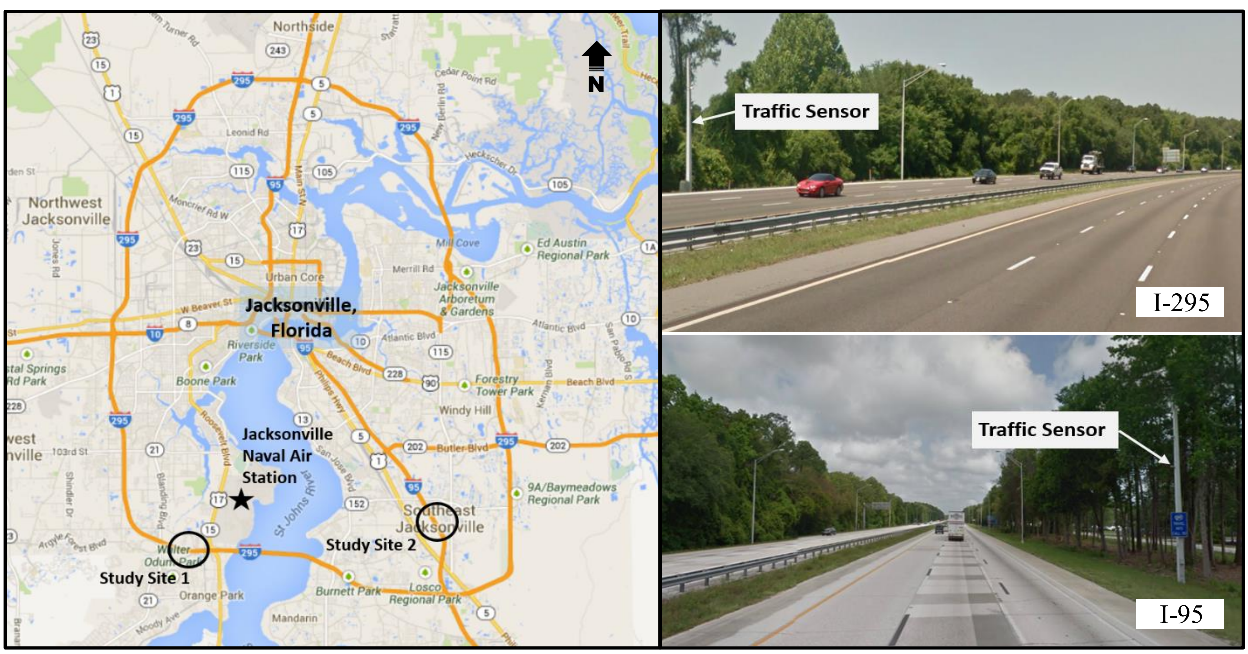

Figure 3.2. Study site location map and photographs.
Source: Google Maps ©2013, Street views March 2011.

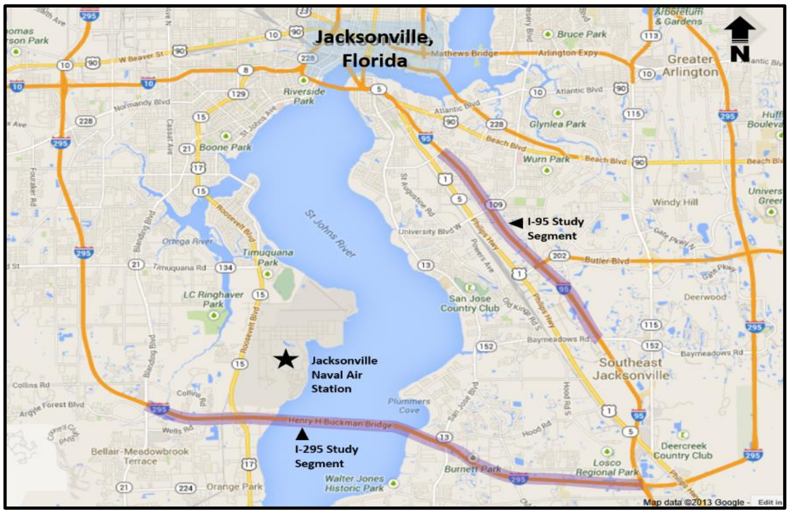

Figure 3.3. Crash study segment location map.
Source: Google Maps ©2013.

Traffic Data

Speed and volume data, recorded by continuous automated traffic sensors, shown in Figure 3.2, at 20 sec intervals, was collected from the Florida Department of Transportation (FDOT) for the study period years 2009 to 2012. Sensor data for year 2009 was not available for the I-95 study segment, thus reducing the study period for this segment to three years (2010-2012). The large number of data hours available for analysis precluded the use of bi-directional traffic flows. Therefore, analyses were limited to directional traffic flow (one direction of travel) at each study location. Directional traffic data used in the study included I-295 Westbound and I-95 Northbound. The data was aggregated into hourly averages to correspond with hourly precipitation data.

Weekday average hourly speed and volume characteristics, using aggregated hourly data, at each sensor site over the respective study periods are represented in Figures 3.4 and 3.5. As shown in Figure 3.4, Westbound morning and evening peak hour volumes along I-295 are nearly the same. However, the I-95 Northbound morning peak volume is nearly double that of the

evening peak (see Figure 3.5). This trend in traffic flow suggests that many commuters often travel both interstates in their commute to and from the downtown area of Jacksonville, thus increasing directional volumes during rush hours along I-95. Average hourly travel speeds along this segment of I-95 generally remain near the posted speed (65 mph) during uncongested conditions, while average speeds on I-295 consistently remain well above the posted speed of 65 mph throughout the day.

Both segments exhibit lower than expected mean speeds during the early morning hours when traffic volumes are exceptionally low. Further analysis of sensor traffic data both upstream and downstream of each selected site indicate that this trend is normal for these freeway segments. Travels speeds along I-295 generally remain higher than posted speeds throughout the day, and drop off to 65 mph after midnight. This trend was also confirmed from the review of nearby sensor traffic data. Additionally, Northbound I-95 typically experiences oversaturated traffic demands during the morning peak hours causing the downward spike as depicted in Figure 3.5.

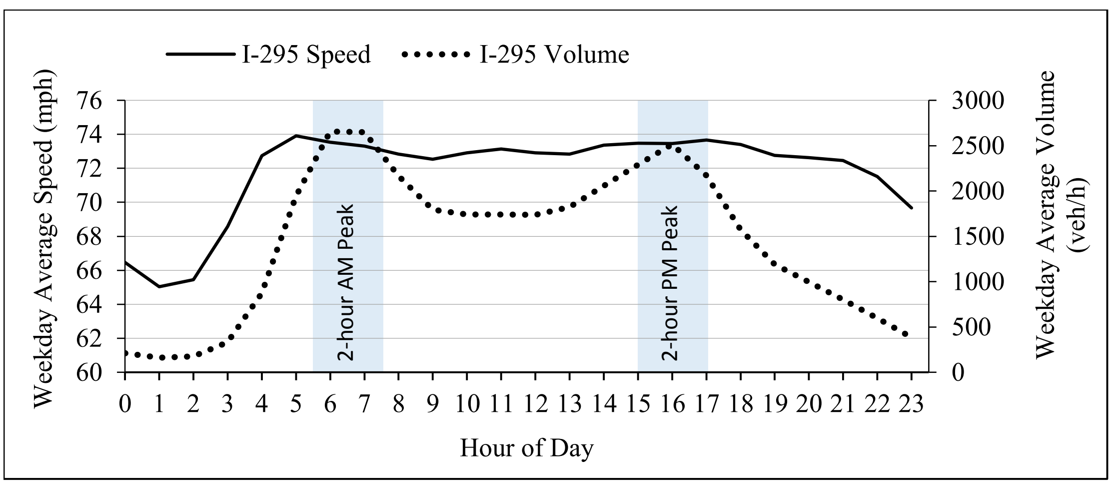

Figure 3.4. I-295 WB directional average traffic characteristics (2009-2012).

After speed and volume traffic data were merged with the corresponding hourly

precipitation data, a total of 10,364 hours compiled the reduced dataset for the I-295 segment. The reduced dataset for the I-95 study segment contained a total of 15,677 hours of combined weather and traffic data.

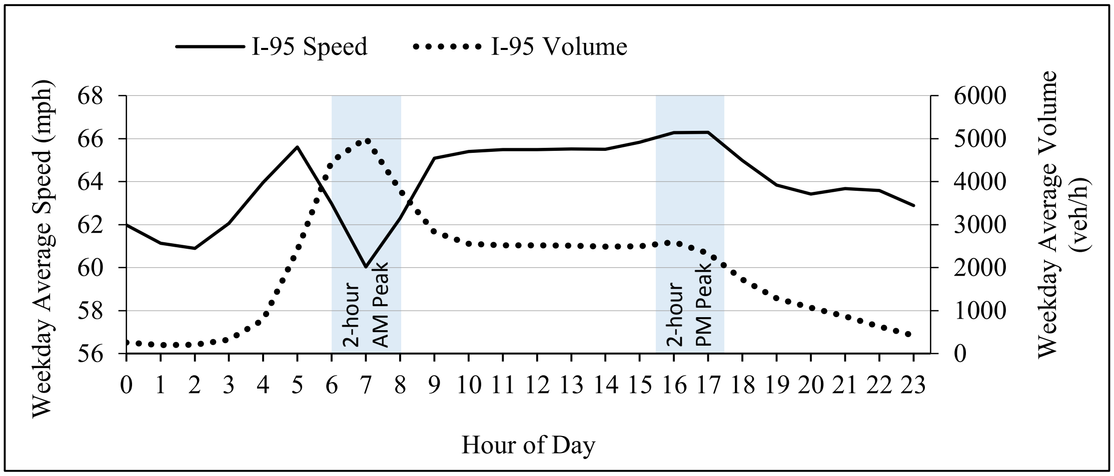

Figure 3.5. I-95 NB directional average traffic characteristics (2010-2012).

Crash Data

Crash data for both study segments was provided by the Florida Department of Transportation (FDOT) for years 2008 to 2011 from the Crash Analysis Reporting System (CARS) database. Reports included documented details of each crash including time and date of occurrence, number of vehicles involved, number of resulting injuries and fatalities, roadway conditions, weather conditions, and Average Annual Daily Traffic (AADT) at each crash location site. Over the four-year period, a total of 691 crashes occurred along the I-95 segment involving 1,378 vehicles with 527 injuries, and 3 fatalities. The number of reported crashes along the I-295 beltway segment were almost double with a total of 1,239 occurrences involving 2,473 vehicles with 952 injuries, and 18 fatalities over the same period. Crashes that occurred within a roadway construction zone, as well as, on an entrance or exit ramp were removed from each sample set. Only main-line crashes that occurred within the limits of each selected freeway

section were included in the study.

The combined dataset containing both Interstate study sections, reduced for weekday traffic with observed holidays removed, yielded an overall total (weather conditions not considered) of 1,405 crash occurrences involving 2,942 vehicles, with 1,051 reported injuries and 13 fatalities over the four-year study period (2008-2011). Figure 3.6 illustrates the crash statistics of the reduced combined dataset.

As indicated in Figure 3.6, approximately 75% of the crashes on each freeway resulted in at least one injured person. Surprisingly, only 1% of the overall crash count resulted in a fatality. The high number of injuries was anticipated since both study segments are high-speed corridors with average hourly speeds at or well above the posted speed limit of 65 mph (105 km/h) (see Figures 3.4 and 3.5). Hourly mean speeds are the greatest along the I-295 section, and subsequently, almost four times more fatalities were recorded over the study period than for the I-95 section.

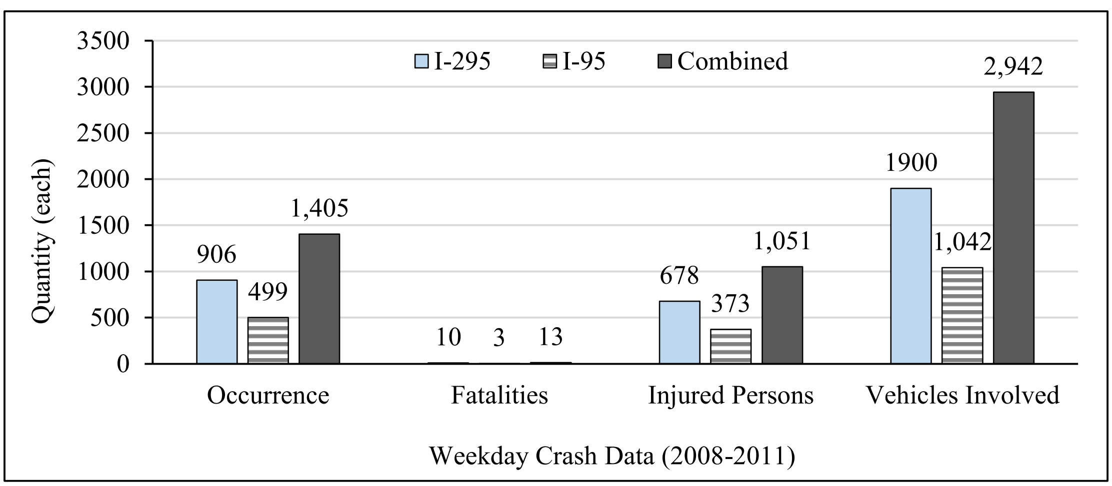

Figure 3.6. Weekday crash data (2008-2011).

Weekday crash severity, shown in Figure 3.7, displays fairly consistent proportions among each freeway section. Injury accidents consisted of almost half of the total collisions.

Likewise, the number of property damage only (PDO) collisions were slightly higher, but also proportionate between the two freeway sections. Additionally, crash frequency by day of week was somewhat evenly distributed, as shown in Figure 3.8. Crashes occurred on each weekday day in the range of 18% to 22%. Similar distributions were also visible in the frequency of Injury and PDO collisions, with the highest frequency occurring on a Wednesday for both severity levels. Fatal crashes were more frequent on Fridays, followed by Mondays, and least frequent on a Wednesday. Overall, the crash statistics of the two freeway study section reflect a discernable amount of homogeneity allowing for a combined dataset with less bias toward either section.

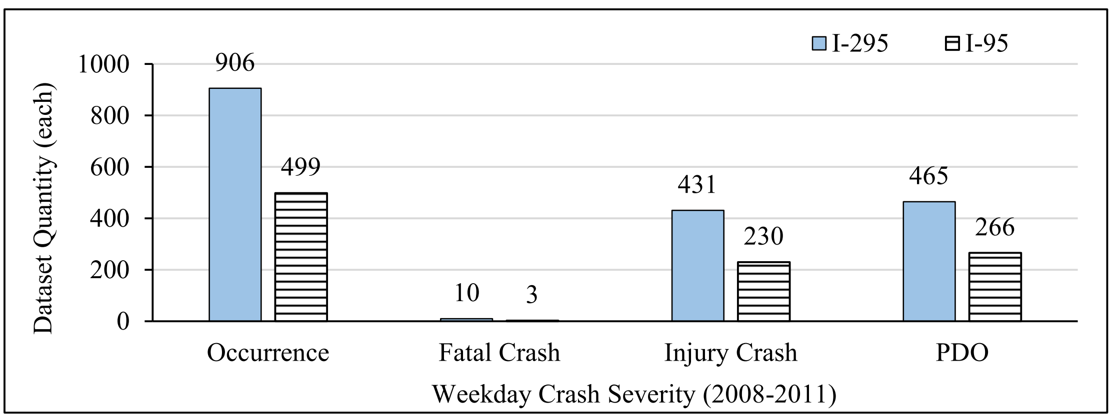

Figure 3.7. Crash severity (2008-2011).

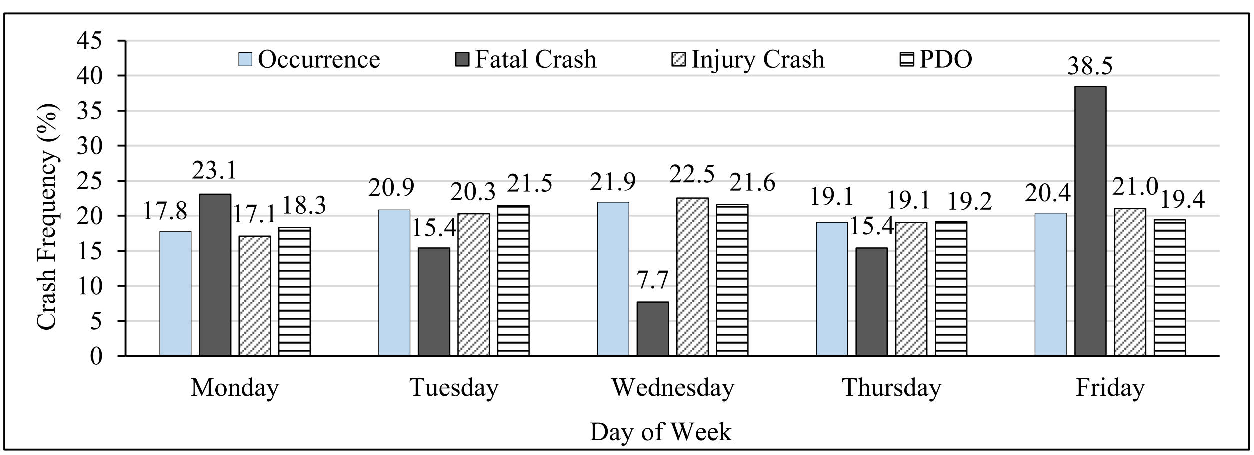

Figure 3.8. Crash frequency by day of week.

Descriptive Analyses

Initial analyses of hourly travel speeds, traffic volumes, and crash occurrence consisted of two rain categories, *Rain* and *No-Rain*. A second analysis was performed with four rain categories, *No-Rain*, *Light Rain*, *Moderate Rain,* and *Heavy Rain*, using rainfall intensity classifications adopted by the AMS (AMS, 2012). Hour-periods were used throughout the study as the time unit of exposure, and one hour-period represents one hour of the day, corresponding with Eastern Standard Time. For traffic variables (speed and volume), average directional hourly values were used for each rain category in the analyses. Crash occurrence and crash rates per 100 Million Vehicle Miles of Travel (MVMT) were analyzed using hourly rain exposure consisting of the number of weather hours (rain or dry) per hour-period for each rain category.

Statistical Analyses

Minitab statistical software (Minitab, Inc., 2013) was used to analyze the datasets for both study sites. To determine if the mean speeds and traffic volumes during rainy conditions statistically differed from dry weather means, with respect to hour-of-day, a paired t-test was performed on the two-category model (rain, no-rain) for both study segments. Likewise, a paired t-test was performed on the two-category model to compare the dry weather and rainy weather hourly means of crash occurrence and crash rates per 100 MVMT, based on rain exposure hours.

A two-way analysis of variance (ANOVA) was performed on the four-category model (no-rain, light, moderate, and heavy rain) for travel speeds and traffic volumes to determine if reductions due to various hourly rainfall amounts with respect to hour-of-day were statistically significant. A two-way ANOVA was also used to analyze the mean percentage of crashes per total percentage of rainfall using a three category (light, moderate, and heavy rain) analysis to determine if crash occurrence was effected by seasonal rains.

For hourly crash occurrence and crash rate four-category models (no-rain, light, moderate, and heavy rain), a linear regression analysis was performed to investigate whether rain intensity and hour-of-day significantly affected crashes and crash rates per 100 MVMT, based on rain exposure, along the two study sites. Additionally, crash severity was also analyzed using a linear regression model for three rain categories (light, moderate, and heavy rain) to determine if rain intensity and traffic condition significantly affected the severity of crashes.

CHAPTER 4 – RESULTS AND DISCUSSION: HOURLY TRAVEL SPEEDS

Descriptive Analysis

An inspection of the directional average traffic characteristics for each interstate section revealed several dissimilarities in average travel speeds between the two sites (see Figures 3.4 and 3.5). Therefore, each interstate study segment was analyzed separately for the effects of rain on mean travel speeds for each hour of the day.

Site 1 (I-295)

Hourly traffic speeds were first examined using two categories, *Rain* and *No-Rain*. Figure 4.1 displays the difference in average travel speeds between rainy and dry conditions at the I-295 study segment. As shown in Figure 4.1, average hourly vehicle speeds during dry conditions are similar to the general speed characteristics over the four year study period shown in Figure 3.4. This was expected due to the overrepresentation of hours with dry conditions among the data. During rainy conditions, travel speeds decreased by an overall average of 1.7 mph (3%) with only minor speed variability.

A second analysis of hourly speeds was conducted based on rain category (no-rain, light, moderate, and heavy rain). As indicated in Figure 4.2, mean hourly speeds tend to decrease and vary considerably by hour-of-day with increasing rainfall amounts. Average speeds under light rain conditions were similar to those of general wet weather shown in Figure 3.4.

Speed reductions of 2.0 mph (2.8%) occurred during uncongested light rain conditions, comparable to findings by Maze et al. (2006), and Rakha et al. (2009), but less than reductions noticed by Unrau and Andrey (2006). Slightly larger decreases in mean hourly speeds were

found during moderate and heavy rain conditions by 2.9 mph (3.9%) and 2.5 mph (3.5%), respectively. These reductions are considerably less than previous studies (Ibrahim & Hall, 1994; Maze et al., 2006; Rakha et al., 2009), specifically in the heavy rain category since few studies included the effects of moderate rain.

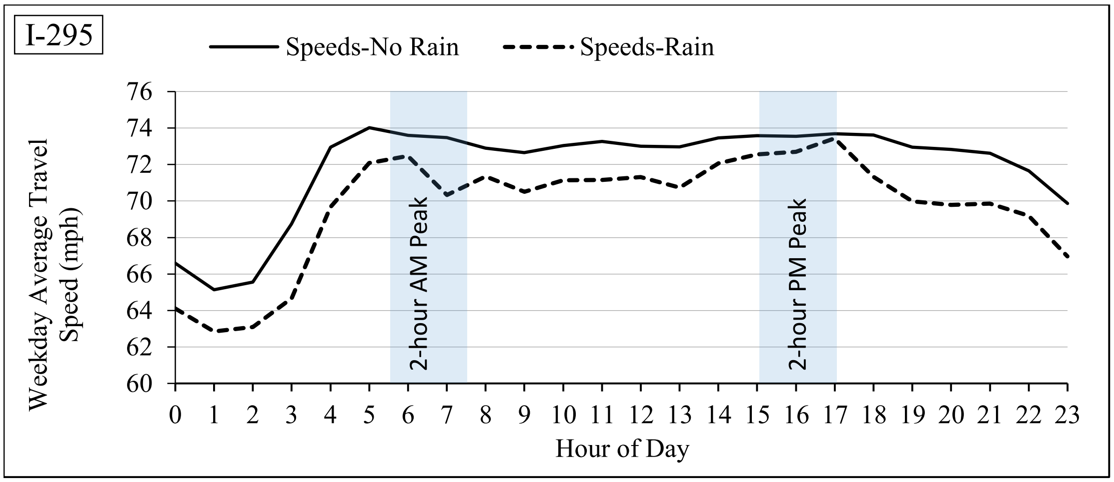

Figure 4.1. Average weekday travel speeds along I-295 (two rain categories).

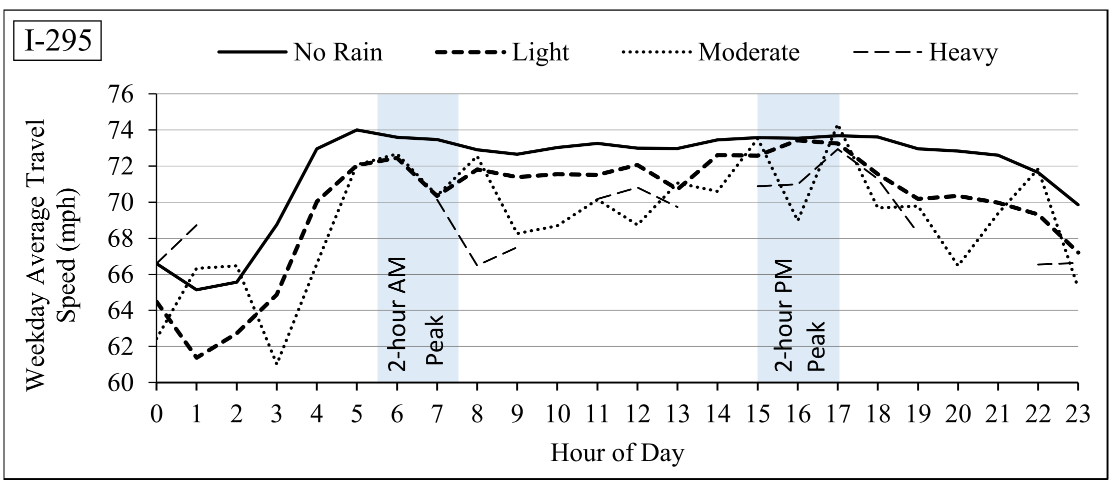

Figure 4.2. Average weekday travel speeds along I-295 (four rain categories).

There was little deviation in average speed reductions during morning peak hours for any amount of rainfall. However, drivers reduced travel speeds in the evening peak hours by an average of 4.5 mph during moderate rains. Visibility factors due to the change in lighting

conditions (daytime to nighttime), that may influence travel speeds during this time of day, especially when Daylight Savings Time is considered, were not examined in this study.

Since heavy rain events compiled only 6.5% of total precipitation hours, some hour-periods did not contain recorded rainfall in this category. This accounts for breaks in the line graph for Heavy Rain shown in Figure 4.2. However, as indicated in Figure 4.2, heavy rain can present considerable reductions in freeway travel speeds. It was therefore decided to include these findings in the present paper.

Site 2 (I-95)

The analysis procedure conducted for the I-295 study segment was repeated for the I-95 segment. A plot of the *Rain- No-Rain* analysis for I-95 average speeds, shown in Figure 4.3, also indicates that hourly speeds are typically lower during rainy conditions. For this freeway segment, travel speeds decreased an overall average of 2.6 mph, 4% lower than dry conditions.

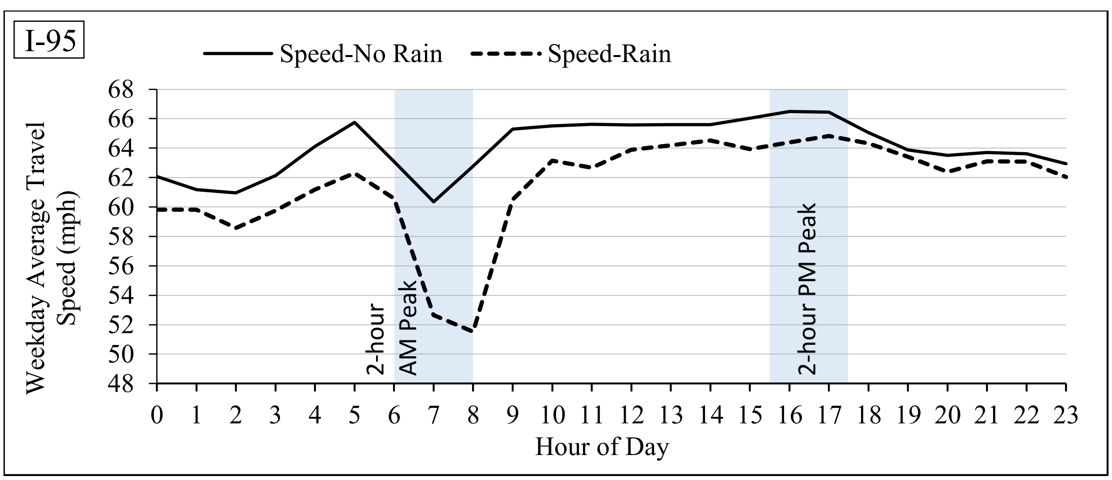

Figure 4.3. Average weekday travel speeds along I-95 (two rain categories).

The greatest drop in mean travel speeds occurred over morning peak hours during rain events by 5.1 mph (8.3%), on average. Alternatively, mean speeds for PM peak volumes reduced by an average of 2.0 mph (3%). Similar to the I-295 two-category analysis, travel

speeds exhibited little variability under wet weather conditions.

Further analysis of the I-95 segment using four categories (no-rain, light, moderate, and heavy rain), are represented in Figure 4.4. Once more, results indicate that mean speeds decrease with increasing rain intensity. This trend was consistent in each rain category for uncongested conditions. Similar to findings by Rakha et al. (2009) for light rain uncongested conditions, average speeds were reduced by 2.1 mph (3.3%), slightly less than those exhibited by general wet weather conditions (see Figure 4.3). This result was anticipated since light rain was more frequent over the study period, constituting over 80% of recorded precipitation. Moderate rain produced an average speed reduction of 3.9 mph (6.1%), and heavy rain lowered speeds slightly more by 4.1 mph (6.4%) for uncongested conditions.

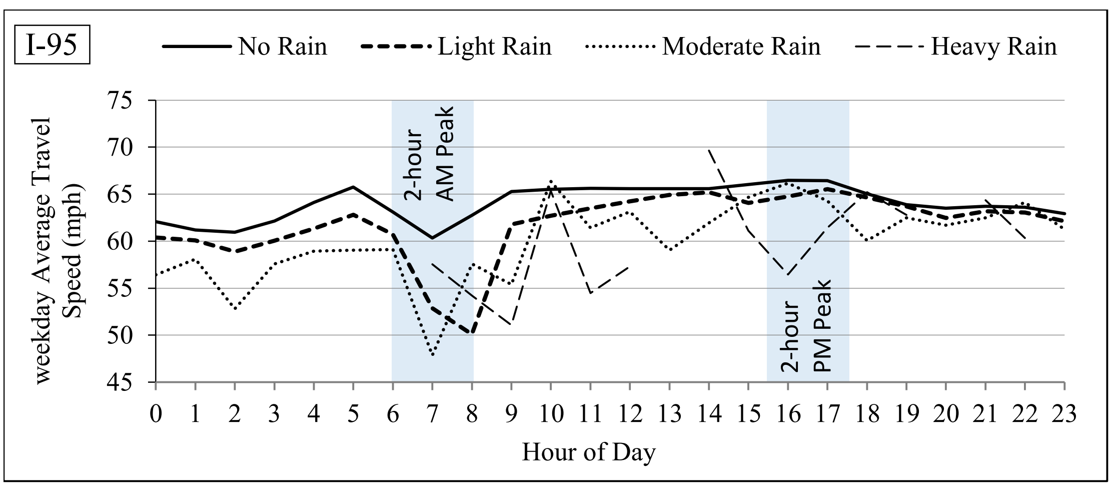

Figure 4.4. Average weekday travel speeds along I-95 (four rain categories).

Results for the heavy rain category were within range of previous studies (Ibrahim & Hall, 1994; Maze et al., 2006; Rakha et al., 2009). The greatest reduction was seen during AM peak hours for light and moderate rainfall with lower mean speeds of 4.9 mph (7.9%) and 8.2 mph (13.3%), respectively. Alternatively, drivers reduced their speeds in heavy rains by an average of 3.4 mph (4.7%) during the typical morning rush hours, most likely the result of

extended peak hours caused by prolonged lower speeds.

Drivers appear to react differently to rainy conditions during evening peak hours with minimal speed reductions for light (1.6 mph) and moderate (1.1 mph) rains, and larger reductions in speeds of 7.5 mph (11.3%) for heavy rain. These results are interesting in that they suggest, apart from heavy rainfall, drivers appear to be more cautious during the morning commute than the return trip home. The change in natural lighting may also be a contributing factor in hourly speed reductions. Increasing speed variability with increasing rain intensity can also be seen with moderate rainfall resulting in the greatest speed variability, consistent with findings for the I-295 segment.

As mentioned in the four-category analyses of hourly travel speeds for the I-295 site (see Figure 4.2), gaps in the effects plot for heavy rain shown in Figure 4.4 indicate hour-periods where no heavy rain events were observed over the three-year study period (2010-2012) for this interstate segment. However, considerable reductions in mean travel speeds during heavy rain events were also present for this study site, thus warranting the inclusion in descriptive analyses. Clearly, more research is needed to fully describe the effects of heavy rain on freeway travel speeds.

Statistical Analysis

Two-Category Model

Minitab statistical software (Minitab, Inc., 2013) was used to analyze the datasets for both study sites. To determine if hourly mean speeds during rainy conditions statistically differ from those during dry weather with respect to hour-of-day, a paired t-test was performed on the two-category model (rain, no-rain) for both study segments. Summarized in Table 4.1, the results indicate that average travel speeds decrease during rainfall events on Florida freeways. A

95% confidence level of the mean reduction in speeds due to rain events was observed to be 1.8 to 2.5 mph for the I-295 study segment, and an average reduction of speeds in the range of 1.5 to 2.2 mph for the I-95 segment, statistically significant reductions (*p*-value < 0.001) for both Interstate segments.

Table 4.1

Summary of paired t-test comparing travel speeds for dry and rainy conditions

Site 1 (I-295) *Speed*				
Sample	N	Mean	StDev	SE Mean
No Rain	24	71.903	2.658	0.543
Rain	24	69.721	3.086	0.630
Difference	24	2.182	0.876	0.179
t-statistic = 12.20	*p*-value = 0.000	α = .05	C.I. (1.812, 2.552)	
Site 2 (I-95) *Speed*				
Sample	N	Mean	StDev	SE Mean
No Rain	21	64.229	1.709	0.373
Rain	21	62.472	1.847	0.403
Difference	21	1.757	0.876	0.191
t-statistic = 9.19	*p*-value = 0.000	α = .05	C.I. (1.359, 2.156)	

N = Number of pairs, one pair per hour-period included in the analysis.

It should be noted that a *p*-value of less than .05 for a 95% confidence level is considered statistically significant. Although, Minitab (2013) software is limited to reporting up to three decimal places for *p*-values, a calculated *p*-value of 0.000 from the Minitab (2013) analyses does not indicate a zero value, but simply reflects a very low value of less than the .05 for the level of significance established prior to performing the statistical analyses (Minitab, Inc., 2013).

The results listed in Table 4.1 indicate that rainfall has a statistically significant effect (*p*-values < .05) on travel speed reductions at both study sites. To satisfy the condition of normality required for paired difference analyses, histograms depicting the distribution of differences were

obtained from Minitab (2013). As shown in Figure 4.5, the distribution of speed differences for the I-295 data appears to be fairly normal in shape. For the I-95 dataset, three hour-periods (seven, eight, and nine) were removed as potential outliers. Although the resulting histogram of the distribution of mean speed differences (see Figure 4.6) did not exhibit a mound shape typical of normal distributions, the data had little skewing and overall, was adequately distributed to satisfy the normality assumption. Since the population of differences are approximately normally distributed, and the paired difference analyses indicate that rainfall has significant effects on travel speeds at both study sites, it can be inferred that travel speeds will be less during rainy conditions on Florida freeways.

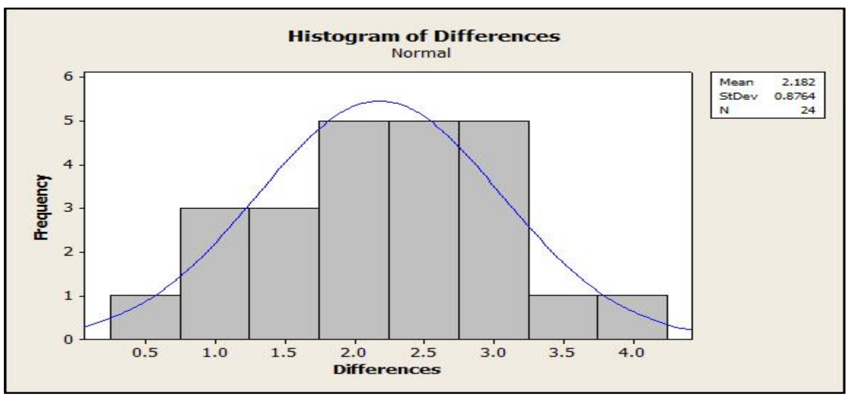

Figure 4.5. I-295 mean hourly speed histogram of differences from paired *t*-test.

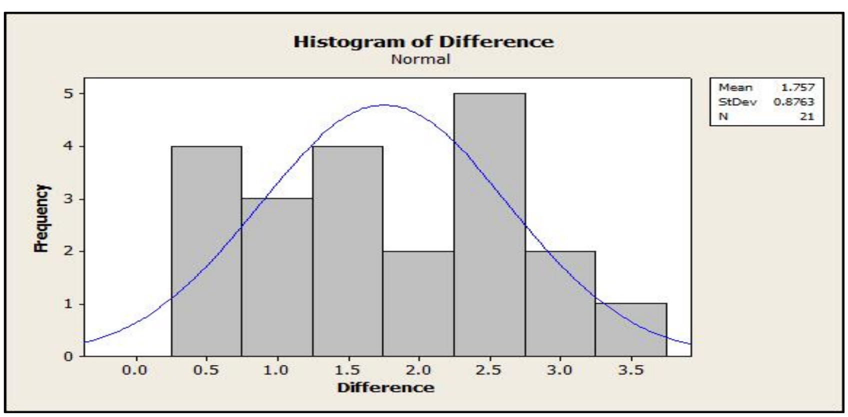

Figure 4.6. I-95 mean hourly speed histogram of differences from paired *t*-test.

Four-Category Model

A two-way analysis of variance (ANOVA) was performed on the four-category model (no-rain, light, moderate, and heavy rain) to analyze the effects of varying hourly rainfall amounts on mean speeds with respect to hour of the day. Because heavy rainfall events compiled only 6.5% of total precipitation hours for these datasets, some hours throughout the day did not contain speed or volume data. A total of 4,601 hours from the I-95 sample set, and 3,470 hours from the I-295 sample set were removed from the ANOVA dataset due to missing data for the heavy rain category. Table 4.2 summarizes the results for the hour-periods analyzed for both study segments.

Table 4.2

Summary of ANOVA comparing travel speeds and weather conditions (four rain categories)

Site 1 (I-295) *Speed versus Hour of Day, Rain Category*					
Source	DF	SS	MS	*F*-statistic	*p*-value
Rain Category	3	72.008	24.0026	15.72	0.000
Hour of Day	13	257.532	19.8102	12.97	0.000
Error	39	59.565	1.5273		
Total	55	389.105			
S = 1.236	R-Sq. = 84.69%	R-Sq.(adj) = 78.41%			
Site 2 (I-95) *Speed versus Hour of Day, Rain Category*					
Source	DF	SS	MS	*F*-statistic	*p*-value
Rain Category	3	73.214	24.4047	7.64	0.001
Hour of Day	10	161.411	16.1411	5.05	0.000
Error	30	95.814	3.1938		
Total	43	330.439			
S = 1.787	R-Sq. = 71.00%	R-Sq.(adj) = 58.44%			

S = Standard deviation

Table 4.2 indicates that reductions in mean travel speeds due to rainy conditions are not only statistically significant (p-value < 0.05 for both segments) based on rainfall intensity, but

also based on the hour-of-day the precipitation occurred indicated by *p*-values less than 0.001 for both the I-295 and I-95 segments. Average speeds reduced along I-295 by 1.8, 2.7, and 2.8 mph from dry conditions during light, moderate, and heavy rain events, respectively. Larger reductions in mean travel speeds were found for the I-95 segment of 1.3, 2.4, and 3.5 mph from dry conditions during light, moderate, and heavy rain events, respectively. These findings are in agreement with descriptive results illustrated in Figures 4.2 and 4.4.

Since the ANOVA indicates statistically significant differences in mean travel speeds between varying rainfall intensities and hours of the day at both study sites, a validation of ANOVA assumptions for each model was performed. Residual plots were obtained from Minitab (2013) to review the normality, equal variance, and independence assumptions to validate the ANOVA results. Shown in Figure 4.7, the factor-level combinations of rain category and hour-of-day appear normally distributed, as indicated by the linear appearance of the data in the *Normal Probability Plot* for the I-295 ANOVA. The *Residual Versus Order* plot shows no discernable pattern, thus satisfying the assumption of independence. Although the *Residual Versus Fits* plot appears to have some patterning, an independent test for equal variances performed on each factor found that the assumption of equal variance needed for the ANOVA was in fact satisfied. Therefore, the ANOVA on the four-category model for Site 1 was considered valid.

The normality, equal variance, and independence of observations were also examined using residual plots obtained from Minitab (2013) to confirm the ANOVA results for the I-95 data. As shown in Figure 4.8, the plots indicate that the residuals follow a normal distribution (Normal Probability Plot), satisfy the constant variance assumption (Residual Versus Fits plot), and satisfy the independence assumption (Residuals Versus Order plot). Additionally, tests for

equal variances were also performed to confirm the constant variance assumption. Thus, the ANOVA results for the I-95 data listed in Table 4.2 are considered to be valid.

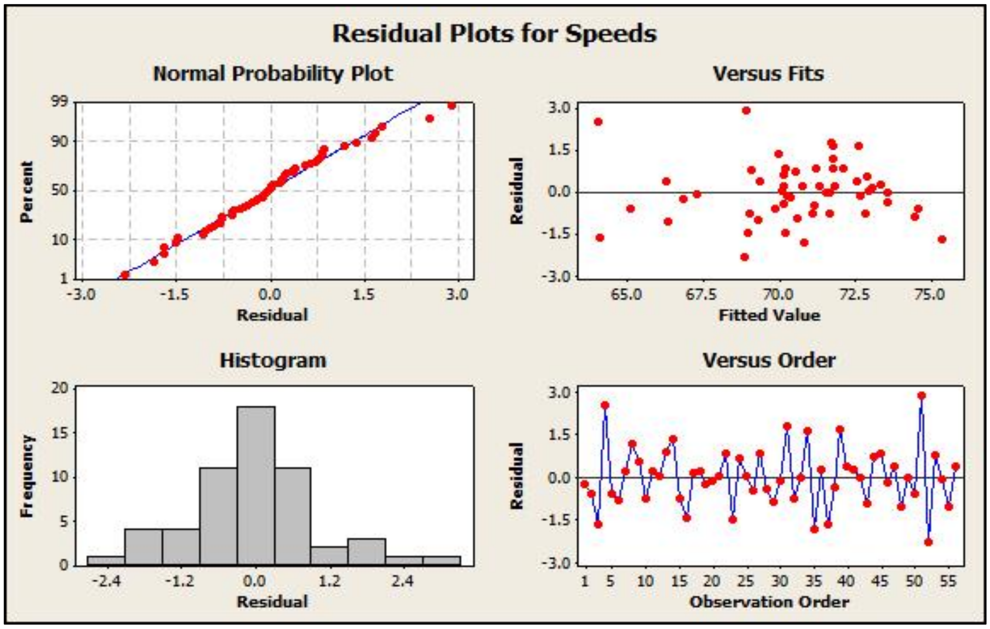

Figure 4.7. I-295 ANOVA residual plots for mean speeds.

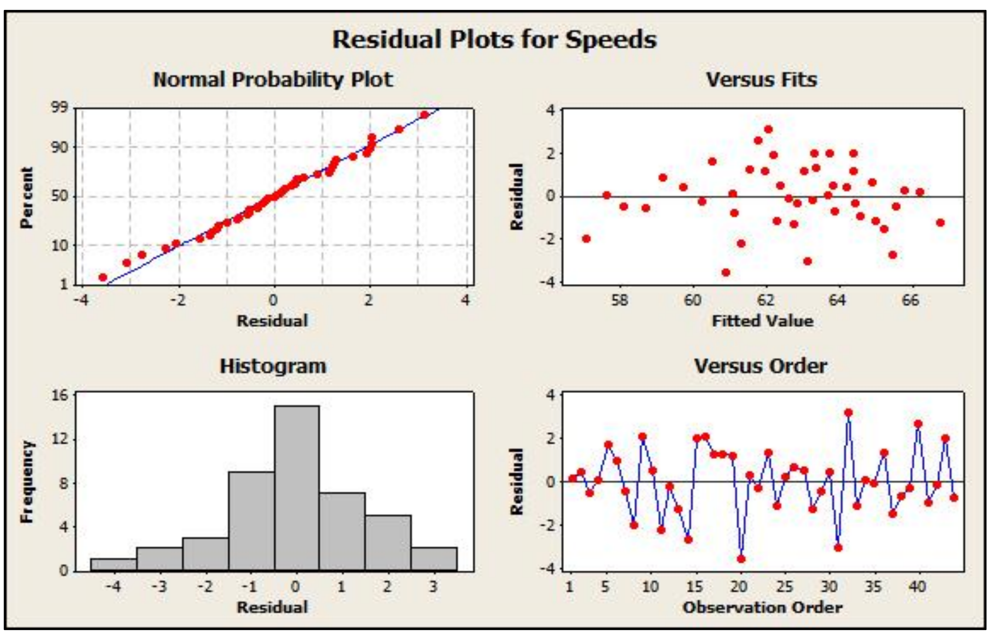

Figure 4.8. I-95 ANOVA residual plots for mean speeds.

95% Confidence Intervals

A graphical view of the 95% confidence intervals for weekday mean speeds for each rain category along the I-95 study segment is shown in Figure 4.9. From Figure 4.9, there is a discernible pattern of decreased upper and lower bounds of the 95% confidence intervals for mean speeds with increased rainfall intensity, and a noticeable linear relationship is present in speed reduction with increased precipitation.

The range of average speed reductions within each rain intensity category is fairly consistent indicating that some drivers reduce travel speeds more than others for any amount of rainfall. However, during dry conditions, drivers typically maintain travel speeds at or near the posted speed limit of 65 mph as illustrated in Figure 4.9. These findings are consistent with the descriptive analysis shown in Figure 4.4.

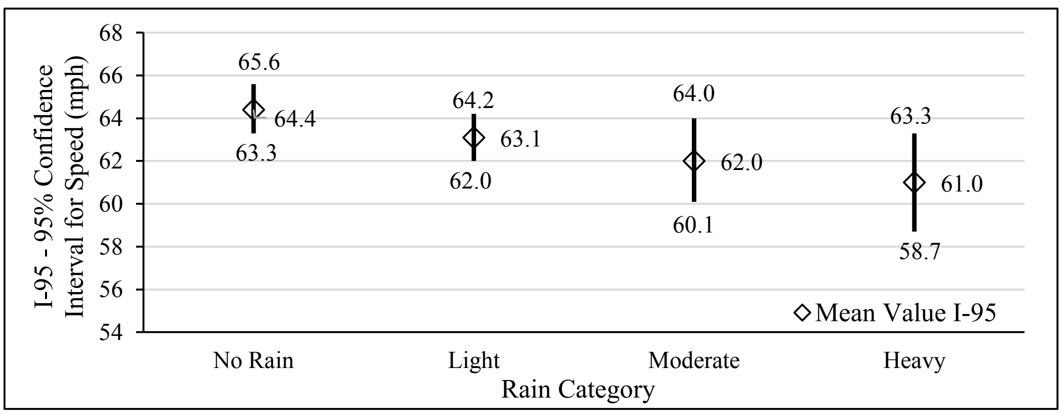

Figure 4.9. I-95 mean speed 95% confidence intervals (four rain categories).

Similar findings also can be seen along the I-295 study segment as shown in Figure 4.10. At a 95% confidence level, mean travel speeds appear to decrease fairly linearly during increased rainfall amounts with little change from moderate to heavy rains. Weekday travel speeds are consistently greater than the 65 mph posted speed for all rainfall categories along this interstate segment. The greatest reduction in speeds occurred during moderate and heavy rainfall events.

These findings are consistent with the descriptive analysis shown in Figure 4.2.

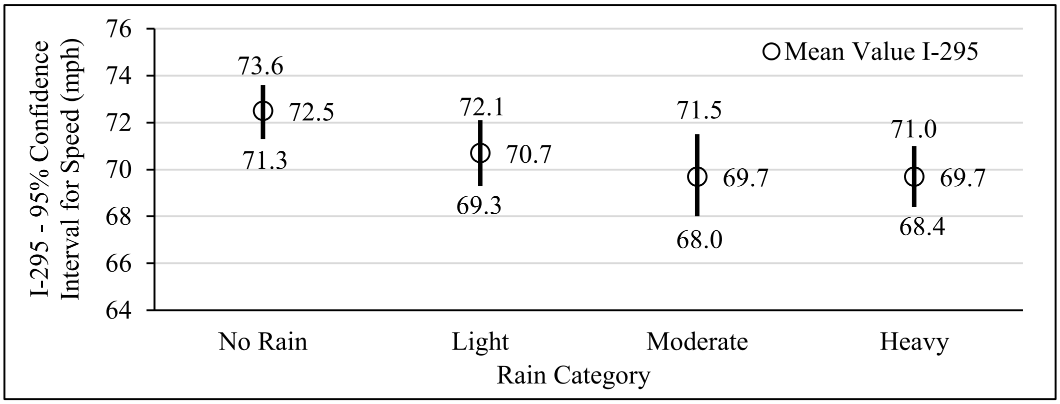

Figure 4.10. I-295 mean speed 95% confidence intervals (four rain categories).

Discussion of Results

Consistent with previous studies, results indicate that drivers tend to reduce travel speeds on freeways during wet weather conditions. However, direct comparisons to speed reductions found in earlier research proved difficult due to the varying rain intensity classifications used among the studies. Since Canada's definition of rainfall intensities is more aligned with rain classifications defined by the AMS, studies on large or heavily populated cities in Canada (Ibrahim & Hall, 1994; Unrau & Andrey, 2006), allowed for direct comparisons of results found in the present study. Speed reductions found in Canadian studies, one by Ibrahim et al. (1994), and another by Unrau and Andrey (2006) vary considerably from speed reductions realized in Jacksonville for light rain, and only slightly correlate with speed reductions during heavy rain events. However, Jacksonville, Florida presents geographically different weather in the form of precipitation than Canadian cities, which may also be a factor in driver response during rain events based on driver familiarity with location specific wet weather conditions.

Reductions in mean speeds in Jacksonville during light rain uncongested conditions compare relatively better with free-flow speed reductions determined by Maze et al. (2006) and

Rakha et al. (2008). However, both previous studies categorized rain intensities using referenced information in the HCM. Moreover, it is unclear if these studies included precipitation up to .25 in/h for light rain, which would constitute moderate rainfall by AMS standards. While speed reductions during heavy rain uncongested conditions found in these two studies are within range of reductions seen in the Jacksonville area, heavy rain precipitation amounts in the present study were analyzed for rainfall amounts greater than .30 in/h, a slight but perhaps significant deviation from the HCM category of greater than .25 in/h.

Additionally, the majority of previous research focused on precipitation effects on free-flow speeds thereby limiting comparisons of speed reductions during congested traffic conditions. Although, Unrau and Andrey (2006) did address mean speeds for daytime congested traffic during light rain events, results found for Jacksonville freeways indicate that mean speed reductions under these conditions were less than those reported by Unrau and Andrey (2006) for light rain, but were two to four times greater during moderate rains.

The effects of moderate rainfall (.11 to .30 in/h) on travel speeds was largely unaddressed by all but one of the referenced studies, Billot et al. (2009), which based on location of the researched roadway and the use of a rainfall rate for medium rain of .08 to .11 in/h, was deemed incompatible for comparison to results found in the present study. The effects of moderate rain on the I-95 segment resulted in considerable reductions in mean speeds during heavily congested morning traffic, far greater than reductions seen for light or heavy rainfall. Alternatively, only minimal speed reductions were observed during evening peak hours in this rain category. Clearly driver response to moderate rainfall requires more research.

The two-category rain analysis (rain, no-rain) was beneficial with respect to general driver response tendencies during rainy weather conditions. Light rain precipitation, based on

the AMS classification system, comprised the majority of precipitation hours used in the present study. Subsequently, light rain appears to be a fair predictor of travel speeds and traffic demands during general wet weather conditions on freeways in this region of the U.S.

Because rainfall accumulation data could only be obtained in hourly values from the chosen weather station, the effects of rainfall on traffic speeds from the two-category (rain, no-rain) analysis in the present study may be more in line with evaluating the effects under wet pavement conditions similar to Kyte et al (2001). Though speed reductions observed in the *Rain, No-Rain* analysis were less than half of those observed by Kyte et al. (2001), the general wet weather conditions may be comparable.

The frequency and intensity of precipitation that drivers are more accustomed to may affect the degree to which they adjust their travel speeds. One example relating to this awareness can be seen in the present study pertaining to the average speeds characteristic on interstate I-295. Speeds along the study segment typically range about 9 mph above the posted speed of 65 mph. While drivers reduced speeds during rainy conditions, traveling speeds still remained well above the posted speed for all rainfall intensities. This may be an indicator of driver familiarity with rainy conditions and confidence with this section of the freeway.

CHAPTER 5 – RESULTS AND DISCUSSION: HOURLY TRAFFIC VOLUMES

Descriptive Analysis

The average directional traffic volume for each study site (see Figures 3.4 and 3.5) varied somewhat between the two study sites. Therefore, similar to the hourly speed analyses, the effects of rain on hourly traffic demand was also analyzed for each study site separately.

Site 1 (I-295)

Weekday hourly volumes comparing dry and rainy conditions for the I-295 segment is shown in Figure 5.1. During wet weather conditions, the number of vehicles on the freeway decreased overall by 9%, on average. Morning and evening peak hour volumes decreased by 3% to 4%, respectively, with rainy conditions. This suggests few trip cancelations or rescheduling during these times of day by motorists due to wet weather as mentioned in previous studies.

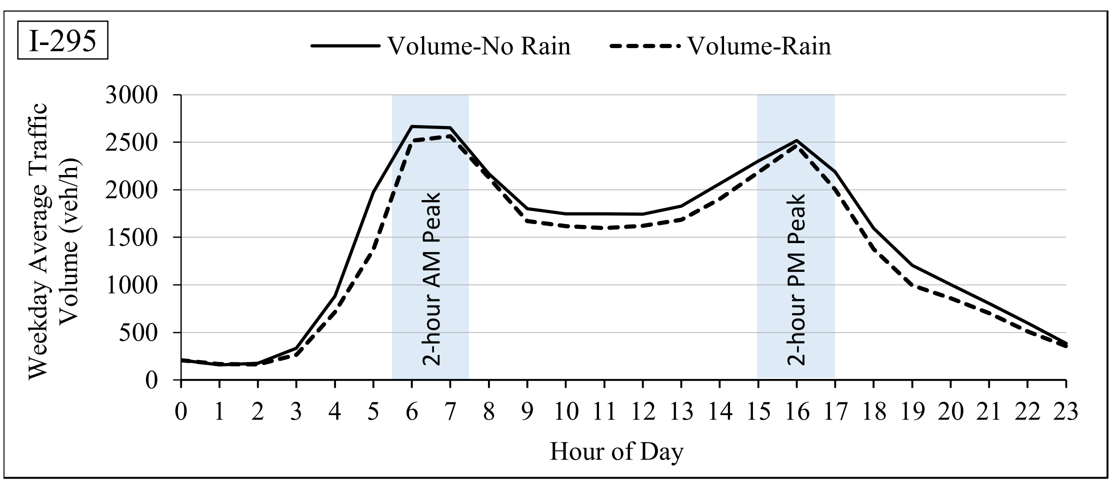

Figure 5.1. Average weekday traffic volumes along I-295 (two rain categories).

Figure 5.2 shows the average hourly traffic volumes over the four-year study period

(2009-2012) for the I-295 segment based on rain intensity category. Average volume reductions for light, moderate, and heavy rain events were found to be 8.2%, 12%, and 14.3%, respectively. These findings signify a direct relationship with travel demand and rainfall amount, and suggest that fewer motorists prefer to travel during moderate to heavy rainfall events. Traffic volumes also fluctuate more during daytime uncongested conditions for moderate and heavy rains suggesting elective trip modifications by drivers.

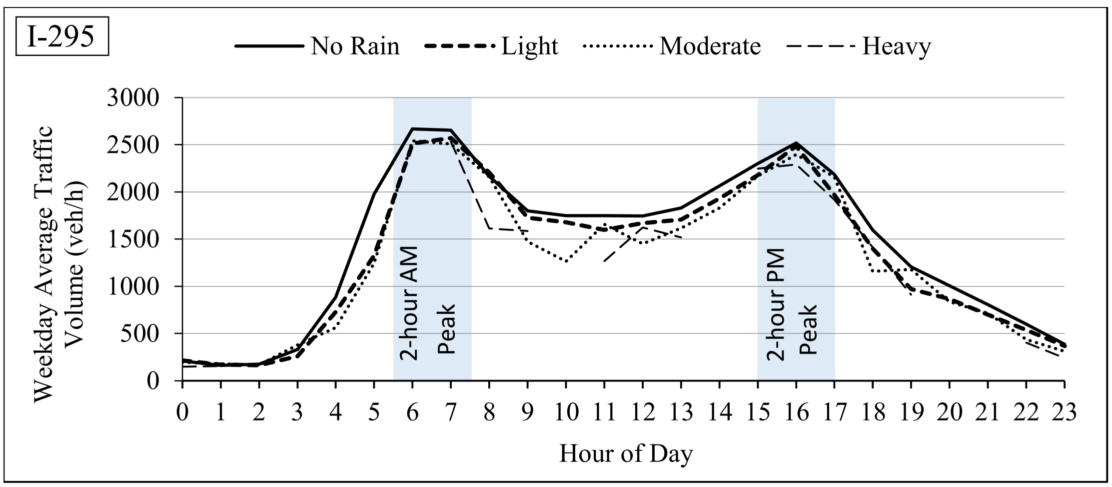

Figure 5.2. Average weekday traffic volumes along I-295 (four rain categories)

Site 2 (I-95)

As shown in Figure 5.3, peak volumes at the I-95 site are nearly double in the morning hours accounting for commuter traffic from I-295 traveling Northbound to the downtown area. In general, rainy conditions reduced average traffic volumes by 6.6% from dry weather conditions on this freeway segment. During rainfall events, morning peak hours occur later than typical rush hours indicating increased delays. This is likely the result of lower speeds during rainy conditions, as shown in Figure 4.3. Volumes during uncongested traffic hours generally remained unaffected by wet weather conditions.

Reductions in average traffic volumes from the four-category analysis for the I-95

segment is depicted in Figure 5.4. Light rain accounted for the least reduction in average hourly volumes (5.6%), with morning and evening peak hours generally unaffected. Moderate rainfall resulted in a 12.6% volume reduction, and heavy rain decreased traffic by 16%, on average. Morning peak hours experienced the largest drop in average volumes during both moderate and heavy rain events.

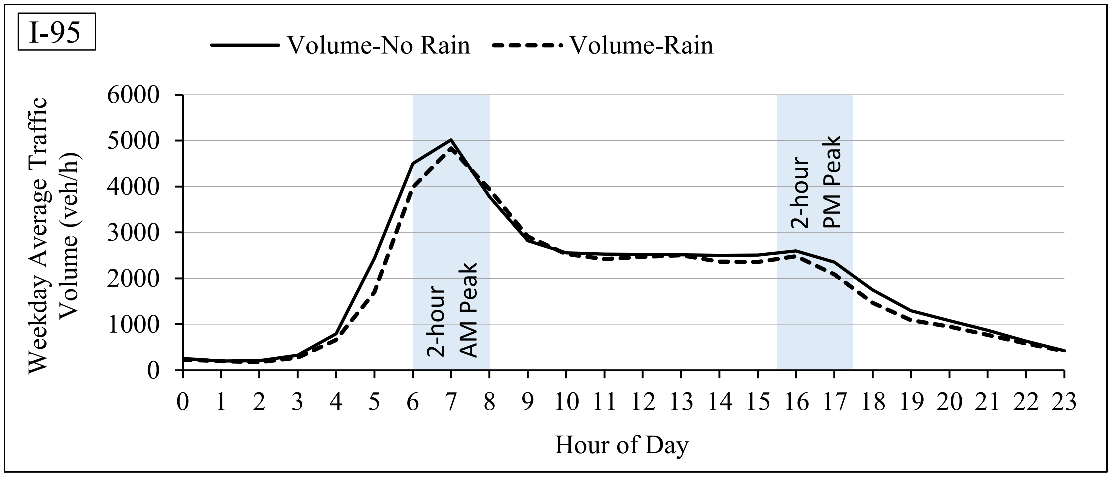

Figure 5.3. Average weekday traffic volumes along I-95 (two rain categories).

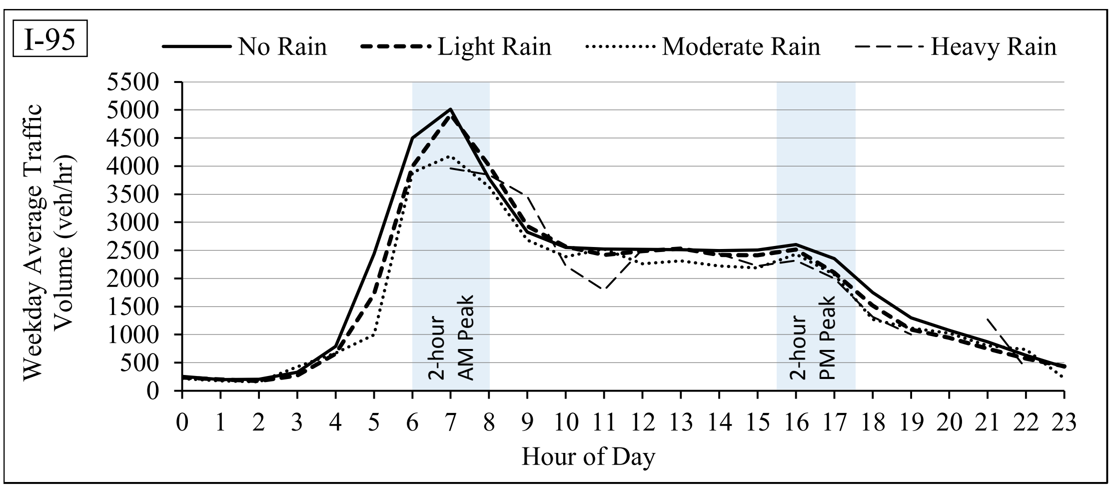

Figure 5.4. Average weekday traffic volumes along I-95 (four rain categories)

Gaps in the line graphs for heavy rain shown in Figures 5.2 and 5.4 indicate hour-periods where no heavy rain events were observed over the three-year study period (2010-2012) for this

freeway segment. The inclusion of the heavy rain category findings provide quantitative value for future research efforts. Nevertheless, more research is needed to fully describe the effects of heavy rain on freeway traffic parameters.

Statistical Analysis

Two-Category Model

Minitab statistical software (Minitab, Inc., 2013) was used to perform a paired t-test on the two-category model (rain, no-rain) for both study segments to determine if hourly mean traffic volumes during rainy conditions statistically differ from then those during dry weather with respect to hour-of-day. Summarized in Table 5.1, the results indicate that the average number of vehicles decrease during rainfall events on Florida freeways.

The paired difference in the means *t*-test indicates that, at a 95% confidence level, average traffic demand reduced by 6.3% to 8.0% vehicles per hour along the I-295 freeway segment. Hour-periods zero, one, two, and five were removed from the analysis as potential outliers, thus reducing the number of pairs to 20 as listed in Table 5.1. Slightly less traffic volume reductions of 2.0% to 7.2% vehicles per hour were observed along I-95 under wet conditions (see Table 5.1). For this segment, hour-periods five and six were removed as possible outliers, reducing the number of analysis pairs to 22 (see Table 5.1). These reductions in hourly volumes are statistically significant as indicated in Table 5.1 by *p*-values of 0.001 and less than 0.001 for I-95 and I-295, respectively.

As indicated in Table 5.1, rainfall has a statistically significant effect (p-values $< .05$) on traffic volume reductions at both study sites. Therefore, it can be inferred that the number of vehicles will be less during rainy conditions on Florida freeways.

Figures 5.5 and 5.6 depict the distributions for the population differences resulting from

the paired difference analyses. As shown in Figure 5.5, the distribution of differences in mean hourly volumes for the I-295 site appears to be fairly normal in shape.

Table 5.1

Summary of paired t-test comparing traffic volumes for dry and rainy conditions

Site 1 (I-295) *Traffic Volumes*				
Sample	N	Mean	StDev	SE Mean
No Rain	20	1612	738	165
Rain	20	1486	734	164
Difference	20	125.6	52.9	11.8
t-statistic = 10.61	*p*-value = 0.000	α = .05	C.I. (100.8, 150.4)	
Site 2 (I-95) *Traffic Volumes*				
Sample	N	Mean	StDev	SE Mean
No Rain	22	1797	1290	275
Rain	22	1714	1290	275
Difference	22	82.3	104.8	22.4
t-statistic = 3.68	*p*-value = 0.001	α = .05	C.I. (35.8, 128.8)	

N = number of pairs, one pair per hour-period included in the analysis.

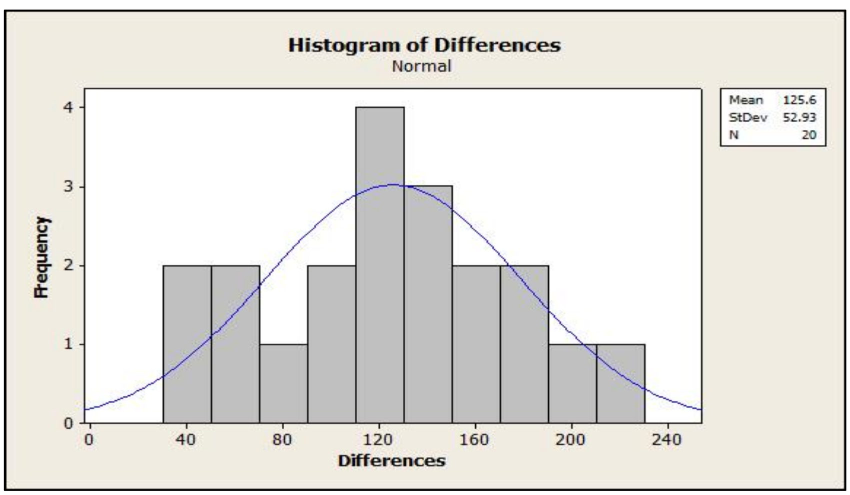

Figure 5.5. I-295 mean hourly volume histogram of differences from paired *t*-test.

Likewise, the I-95 data also exhibits a fairly normal distribution of differences in mean hourly volumes (see Figure 5.6). Because the paired *t*-tests indicate that traffic volumes are

significantly affect by rainfall, and both Figures 5.5 and 5.6 validate the assumptions that the population of differences are approximately normally distributed, it can be inferred that rainy conditions reduces traffic demands on Florida freeways.

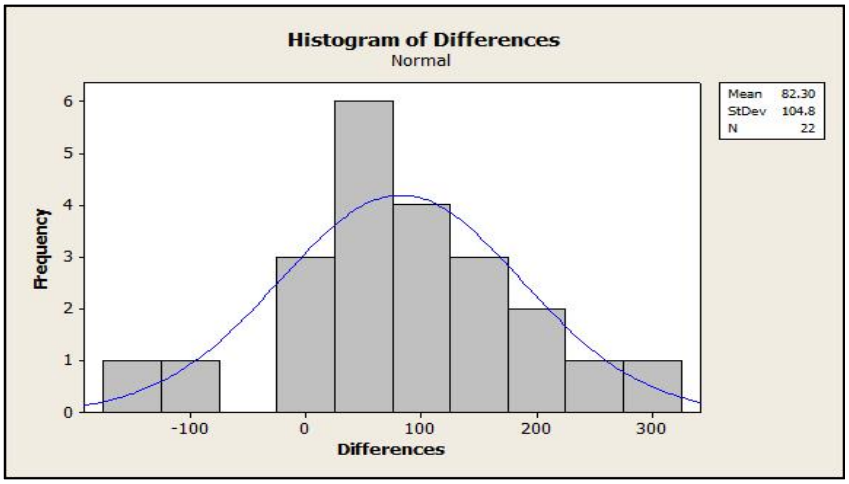

Figure 5.6. I-95 mean hourly volume histogram of differences from paired *t*-test.

Four-Category Model

Using Minitab statistical software (Minitab, Inc., 2013), a two-way analysis of variance (ANOVA) was performed on the four-category model (no-rain, light, moderate, and heavy rain) to analyze the effects of varying hourly rainfall amounts on mean traffic volumes with respect to hour-of-day. Corresponding with the hourly speed analyses, a total of 4,601 hours from the I-95 dataset, and 3,470 hours from the I-295 dataset were removed prior to performing the ANOVA due to missing precipitation data for the heavy rain category. A summary of the ANOVA results for mean traffic volumes is shown in Table 5.2.

Results conclude that reductions in mean traffic volumes due to rainfall intensity are statistically significant as indicated by *p*-values of 0.006 and less than 0.001 for I-95 and I-295, respectively. Average hourly traffic volumes reduced along I-295 during light, moderate, and heavy rainfall by 6.7%, 9.3%, and 12.2%, respectively, from dry conditions. Similar reductions

in mean hourly volumes were observed for the I-95 site with 2.6%, 10.1%, and 9.7% fewer vehicles on the freeway during light, moderate, and heavy rainfall, respectively.

At a .05 level of significance, reductions in traffic volumes with respect to hour-of-day were also significant with *p*-values of less than 0.001 for both segments. These findings are in agreement with descriptive results illustrated in Figures 5.2 and 5.4.

Table 5.2

Summary of ANOVA comparing volumes and weather conditions (four rain categories)

Site 1 (I-295) *Volume versus Hour of Day, Rain Category*					
Source	DF	SS	MS	*F*-statistic	*p*-value
Rain Category	3	311,277	103,759	10.09	0.000
Hour of Day	9	8,249,635	916,626	89.11	0.000
Error	27	277,746	10,287		
Total	39	8,838,658			
S = 101.4	R-Sq. = 96.86%	R-Sq.(adj) = 95.46%			
Site 2 (I-95) *Volume versus Hour of Day, Rain Category*					
Source	DF	SS	MS	*F*-statistic	*p*-value
Rain Category	3	672,510	224,170	4.97	0.006
Hour of Day	11	36,770,049	3,342,732	74.15	0.000
Error	33	38,930,225	45,081		
Total	47	91,514,114			
S = 212.3	R-Sq. = 96.18%	R-Sq.(adj) = 94.56%			

S = Standard deviation

To validate the ANOVA assumptions of normality, equal variance, and independence of observations, residual plots obtained from Minitab (2013) were examined for each analysis. Shown in Figure 5.7, the factor-level combinations of rain category and hour-of-day appear normally distributed, as indicated by the linear appearance of the data in the *Normal Probability Plot* for the I-295 ANOVA. The *Residual Versus Fits* and *Versus Order* plots also show no discernable pattern, thus satisfying the assumptions of equal variance and independence

of the observations, respectively.

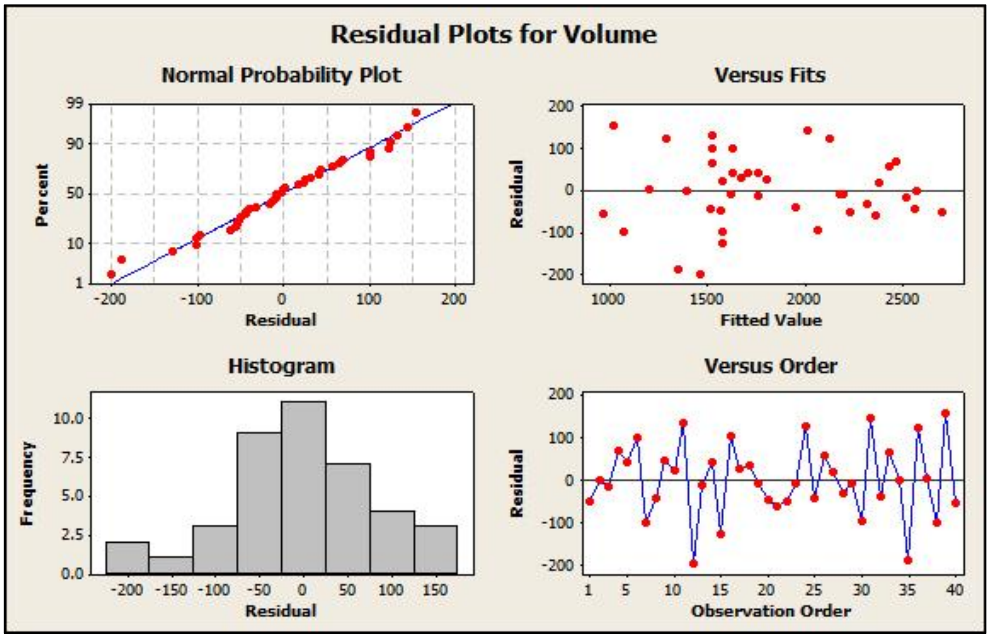

Figure 5.7. I-295 ANOVA residual plots for mean volumes.

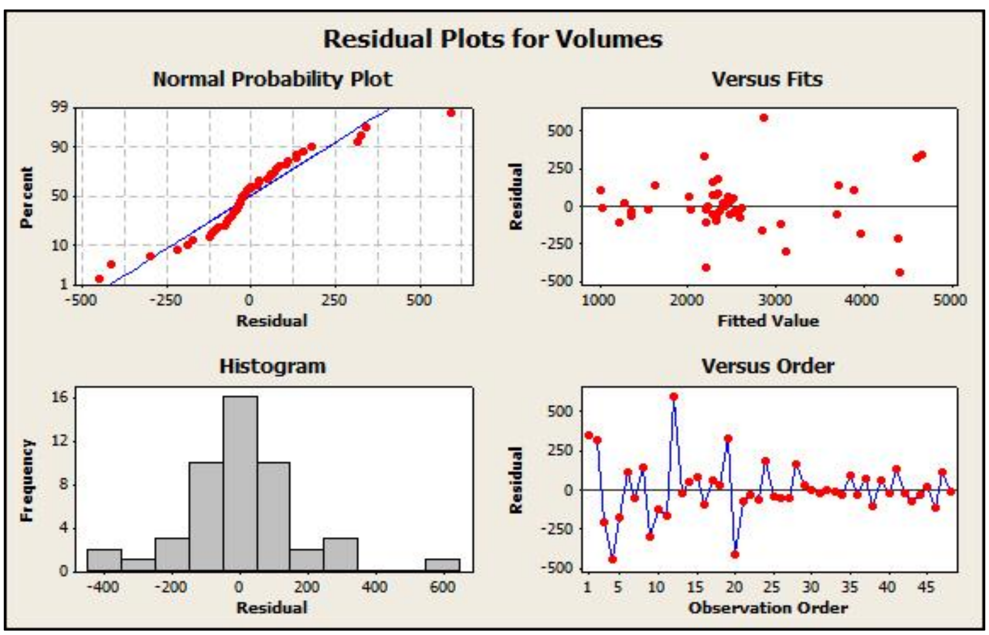

Figure 5.8. I-95 ANOVA residual plots for mean volumes.

Likewise, the normality, equal variance, and independence residual plots obtained from Minitab (2013) also satisfy the ANOVA assumptions for the I-95 data, as shown in Figure 5.8.

Therefore, with the ANOVA assumptions satisfied, the results listed in Table 5.2 for both study segments were considered valid.

95% Confidence Intervals

A graphical view of the 95% confidence intervals for weekday mean traffic volumes along the I-295 study segment, shown in Figure 5.9, reveal a fairly linear trend in decreasing volumes with increasing rain intensity. Although increased rainfall resulted in reductions in traffic demand, mean hourly volumes along I-295 show little variation regardless of rain category, as indicated in Figure 5.9 and consistent with Figure 5.2.

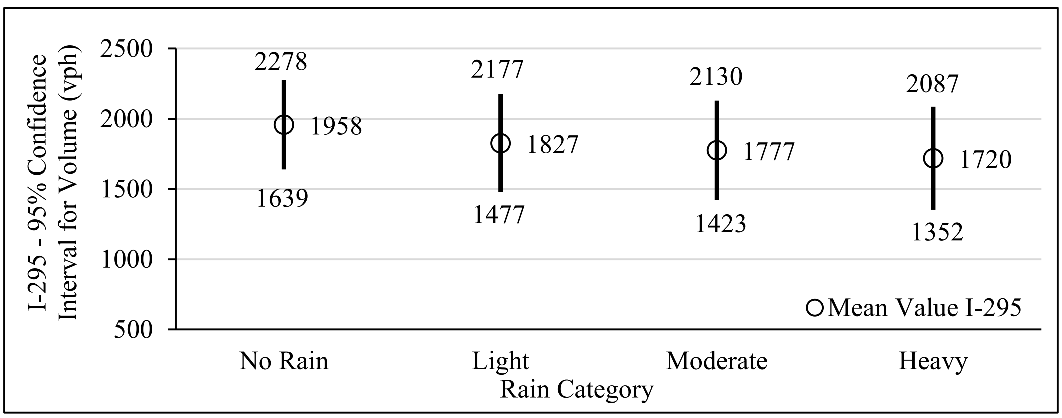

Figure 5.9. I-295 mean volume 95% confidence intervals (four rain categories).

As observed with the I-295 segment, hourly volumes along the I-95 study segment also show little variation in the number of vehicles regardless of rain category, consistent with Figure 5.4. The 95% confidence intervals shown in Figure 5.10 indicate minimal reductions in traffic volumes during wet conditions, with the greatest reduction from dry conditions occurring with moderate rain events. Unlike the I-295 segment, the 95% confidence mean volume for heavy rainfall was slightly above the mean volume for moderate rain events. However, the spread is greater during heavy rain events indicating overall fewer vehicles on the freeway.

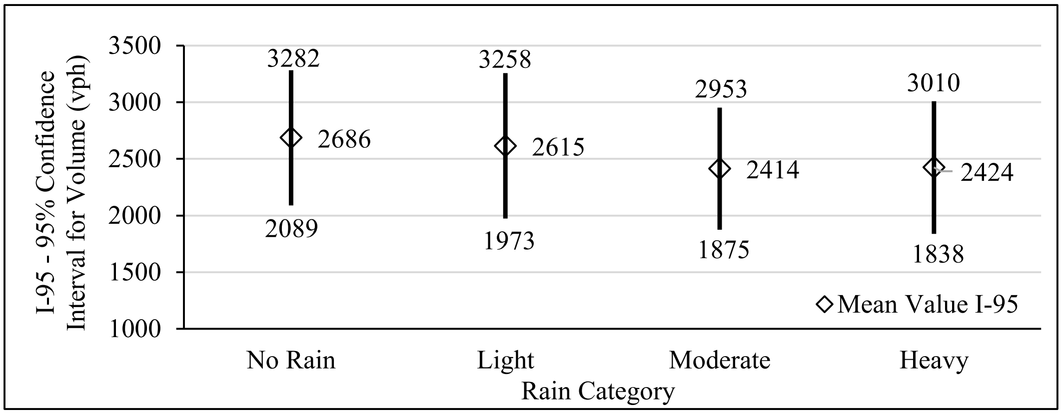

Figure 5.10. I-95 mean volume 95% confidence intervals (four rain categories).

Discussion of Results

Several previous studies examined the effects of precipitation on roadway capacity (Maze et al., 2006; Rakha et al., 2008). The present study examined the effects of wet weather conditions on hourly travel demands, and consequently, are not comparable with previous research. Interestingly, the connectivity of the two study segments greatly affected hourly traffic volumes, of which placed an added factor on freeway volumes during rainfall events. With the exception of peak travelling hours, results show minimal reductions in hourly traffic volumes during rainfall events. Because Jacksonville consists of large land area with many waterway crossings throughout the city limits, drivers adjusting routes to avoid interstate travel during wet weather conditions is not generally practical. This fact should also be considered in ascertaining true effects of rainfall on freeway travel demands. Nonetheless, observations made in the present study of hourly traffic demands gave better insight into traffic patterns and the effects of freeway connectivity in the greater Jacksonville area.

CHAPTER 6 – RESULTS AND DISCUSSION: HOURLY CRASH OCCURRENCE

Descriptive Analysis

The two-category analysis (rain, no-rain), revealed a strong association between precipitation and crash occurrence based on rain exposure. The crash proportion (the number of accident occurrences per number of weather exposure hours) for rainy and dry conditions in each daily hour-period is shown in Figure 6.1. The results indicate that proportionally, more crashes occurred during rain hours. Although drivers were exposed to rain only 5% to 12% of the time during each hour-period, the risk of crash occurrence was up to seven times greater relative to dry conditions, depending on the hour-of-day.

Morning and evening congested hours for both rainy and dry weather contained the most number of crashes, and consequently, produced lower exposure rates relative to dry conditions. The morning and evening hours that generally experienced the highest number of vehicles, or peak traffic volumes, were identified from Figures 3.4 and 3.5 for both freeway sections. As shown in Figure 6.1, a relative rate of 2.3 for the morning peak-hour traffic, 6:00 to 7:00 AM, and a rate of 1.7 for the evening peak-hour traffic, 4:00 to 5:00 PM, indicate an increase in accident risk associated with rain of 130% and 70%, respectively, based on rain exposure. This trend somewhat agrees with findings by Levine et al. (1995).

Interestingly, more crashes occurred during the two hours following both the AM and PM peak traffic hours during rainy and dry conditions. The highest number of dry weather crashes occurred the hour following both AM and PM peak traffic hours, 7:00-8:00 AM and 5:00-6:00 PM, respectively, while the highest number of wet weather crashes occurred during the second

hour following peak traffic, 8:00-9:00 AM and 6:00-7:00 PM.

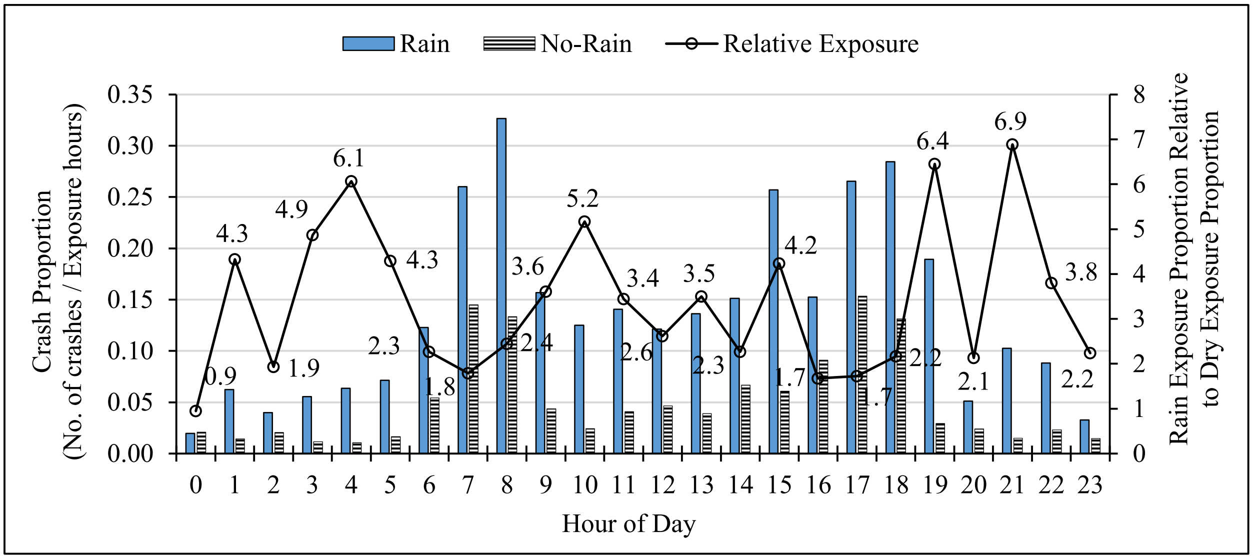

Figure 6.1. Hourly crash proportions per weather exposure (two rain categories).

Wet weather crashes also increased the second hour following peak-hour traffic while dry weather crashes decreased by 7.9% and 14.4% in the morning and evening, respectively. This phenomena may be attributed to a sense of urgency that drivers may develop from rush-hour delays combined with adverse weather, thus driving with less caution to reach their destination. Although crash proportions for rainy and dry conditions during congested traffic hours have similar proportion distributions, the risk of an accident during a rain event, based on total rain exposure per hour-period, is more than double that of dry weather.

Daytime hours with generally uncongested traffic conditions, from 9:00 AM – 4:00 PM (hours nine through 16), also indicate a proportionally higher occurrence of accidents during rain based on hours of exposure. Relative to dry conditions, crash occurrence is considerably greater with rain during these hours of the day. As indicated in Figure 6.1 for hour-period ten (10:00 - 11:00 AM), the risk of accident is over five times greater during a rain event than during dry weather. Likewise, the hour of 3:00-4:00 PM (hour 15), exhibits a substantially higher crash risk

during rainy conditions. Commuters trying to avoid rush-hour traffic or traveling to collect children from school may be contributing factors.

Similar results appear for night driving hours, 8:00 PM -5:00 AM (hours 20 through five), where free-flow speeds are also typical. Higher crash occurrence during rain events at night may be largely due to visibility factors influenced by glare, wet shiny surfaces or poor lighting (Brodsky & Hakkert, 1988), or the reduced reflectivity of pavement markings. Only one hour, midnight to 1:00 AM (hour zero), reflects a slightly higher risk of accident during dry weather, where over 95% of crashes at this time of day occurred during dry hours. Overall, based on weather exposure, the likelihood of a crash is 2.9 times greater during rain events than during dry weather conditions as listed in Table 6.1.

Table 6.1

Hourly crash proportions per weather exposure and traffic condition

Time of Day	Hour Number	Traffic Condition	Total Hours		Total Crashes		Total Crashes per Total Hours		Rain Exposure Relative to Dry Exposure
			Dry	Wet	Dry hour	Wet hour	Dry hour	Wet hour	
5 AM - 9 AM	5, 6, 7, 8	AM Congested	3,852	212	337	40	0.087	0.189	2.2
9 AM - 4 PM	9 thru 15	Day Uncongested	6,604	502	302	82	0.046	0.163	3.6
4 PM - 8 PM	16, 17, 18, 19	PM Congested	3,642	422	368	95	0.101	0.225	2.2
8 PM - 5 AM	20 thru 4	Night Uncongested	8,582	571	147	34	0.017	0.060	3.5
		Overall	22,680	1,707	1,154	251	0.051	0.147	2.9

Table 6.1 lists hourly exposure proportions grouped into daily time blocks representing different traffic conditions. The daily time blocks consist of AM and PM congested hours where higher traffic volumes exist, and daytime and nighttime uncongested traffic conditions. The resulting relative risk pattern of wet to dry weather shown in Figure 6.2, to a lesser degree,

parallels that of Figure 6.1. Morning and evening congested traffic hours naturally exhibit an overall lower rate of relative risk due to the higher number of crash occurrences for both weather categories. Increased risk of a crash for these hours of day may be the product of a combined exposure effect, from traffic volumes and rain. The relative risk of accident occurrence during daytime and nighttime uncongested hours is higher than for congested periods. This result indicates more crashes occur with fewer hours of exposure to rain. However, travel speeds or visibility combined with rainfall may also be contributing factors under these traffic conditions. Figure 6.2 also demonstrates the effect on analysis results when data is further aggregated, where the relative exposure rates for wet to dry conditions are considerably lower than the hour-period rates illustrated in Figure 6.1. Nonetheless, the relative exposure pattern is fairly consistent with Figure 6.2, and provides a more generalized depiction of results.

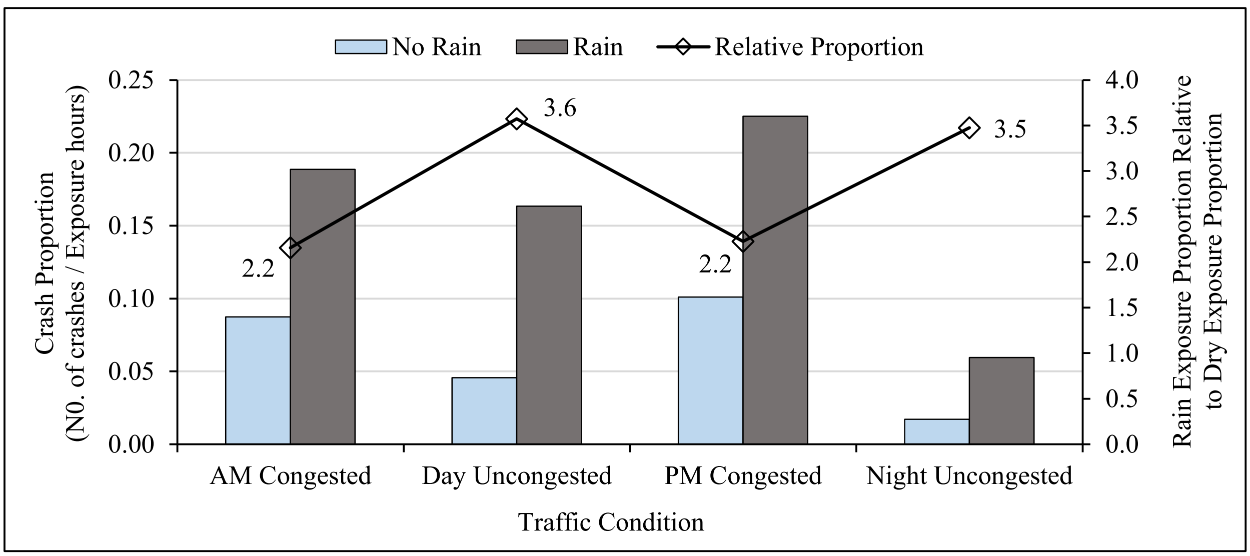

Figure 6.2. Hourly crash proportions per weather exposure and traffic condition.

The analysis of crash data using four rain categories (no-rain, light, moderate, and heavy rain) revealed that, proportionally, heavy rain exposure produced greater risks of accident occurrence, followed by exposure to moderate rainfall, as shown in Figure 6.3. Dry weather

crash frequency was highest during the AM and PM congested traffic hours, 7:00-9:00 AM and 5:00-7:00 PM, respectively. The hour-period of most recorded heavy rain-hours (15 total hours) occurred at 6:00 to 7:00 PM (hour-period 18) and also contained by the highest number of crash occurrences (seven crashes) in that rain category. As a result, the relative risk of an accident at this time of day during heavy rainfall is 3.6 times more likely than during dry weather, illustrated in Figure 6.4. Similar results were recognized for the moderate rainfall category one hour prior, 5:00 to 6:00 PM (hour-period 17), with 17 total moderate rain-hours and 10 recorded crashes yielding a risk rate of 3.8 during moderate rain events relative to dry conditions. In addition, hour-periods 17 and 18, also contain the highest number of crashes during light rain events. Natural lighting conditions change during this time of day, especially during the Fall and Winter months, and when Daylight Savings Time ends in the U.S. However, additional research is needed to explore the effects of lighting on crash occurrence during rain events.

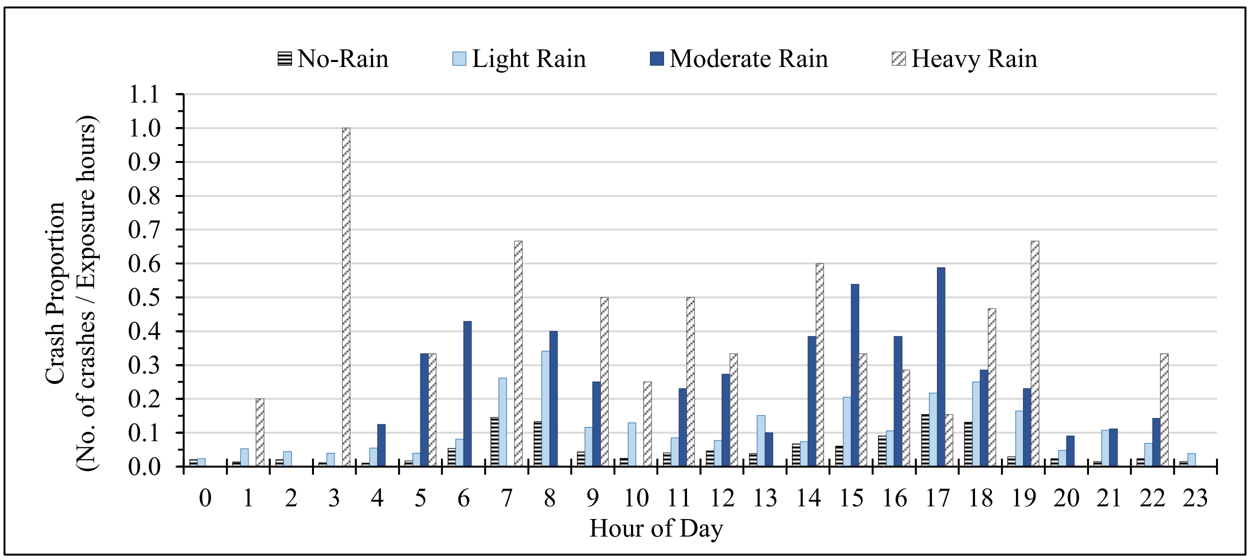

Figure 6.3. Hourly crash proportions per weather exposure (four rain categories).

Outside of PM congested hours, the number of heavy rain exposure hours and reported crashes are considerably fewer for each hour-period, hence the tendency for higher relative risks

during rain events compared to dry weather conditions. An extreme example (see Figure 6.3) is represented for the hour of 3:00 AM where only one hour of heavy rain occurred during the study period, with one reported crash during that hour, thus producing a 100% rate of crash frequency. Consequently, the wet to dry relative proportion rate was 87.6, and for clarity, was not shown in Figure 6.4.

As shown in Figure 6.4, crash risk increase with increasing rain intensity relative to dry conditions, and vary by hour-of-day. These results are similar to findings by Xu et al. (2013). Crashes during rain events were not represented in each rain category for each hour-period. A total of seven hour-periods for the moderate rain category, and nine hour-periods for the heavy rain category did not contain a reported crash, and therefore, graphically reflect a zero value in Figure 6.4. Nonetheless, the exposure proportions for the remaining hours were deemed substantial to include in the analyses.

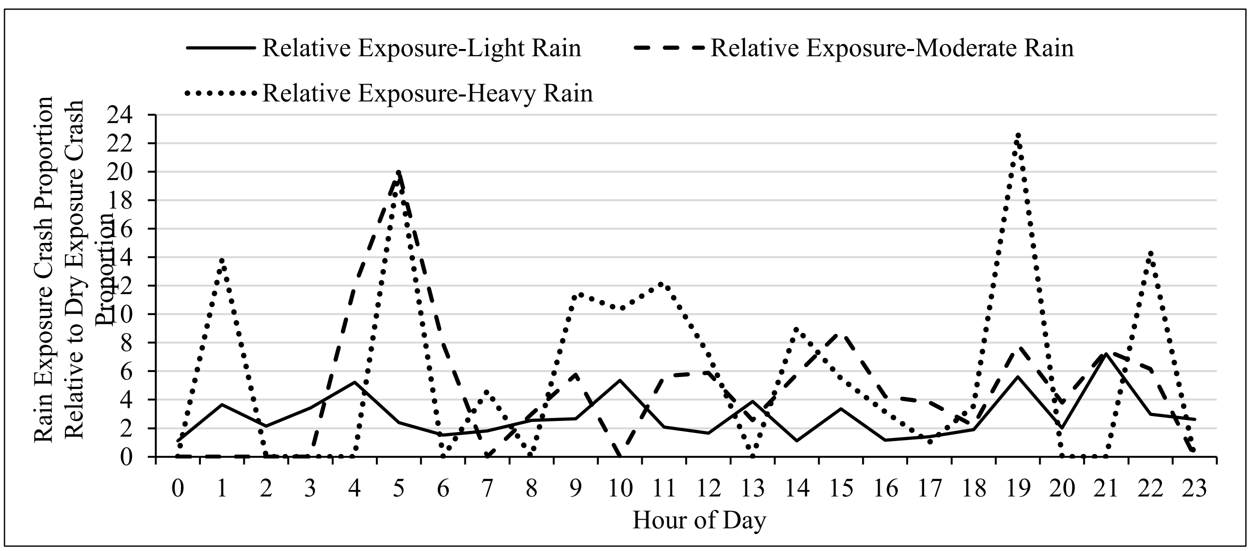

Figure 6.4. Hourly crash proportions relative to dry weather (four rain categories).

Crashes were recorded for all daily hour-periods in the light rain category. Light rain comprised the majority of precipitation hours (82%) of the total rain hours. Correspondingly, the

crash proportion, the number of crashes relative to exposure hours, and the relative rates to dry conditions, was considerably less for light rains than for moderate or heavy rainfall.

Figures 6.3 and 6.4 give perspective on the likelihood of crash occurrence during rain events, especially when rain intensity is considered. Overall, during rain events, crashes are 2.4, 5.0, and 5.9 times more likely to occur during light rain, moderate rain, and heavy rain, respectively, compared to dry weather conditions.

Low numbers of exposure hours or reported accidents should not negate the effects of rain intensity on crash occurrence. A larger dataset containing more exposure hours may yield more reasonable proportions, and subsequently lower relative risk associated with rainfall. Yet, based on the number of exposure hours to rain, the risk of crash occurrence during rainy weather will most likely be greater than during dry weather conditions.

Statistical Analysis

Two-Category Model

To determine if the number of crash occurrences relative to rain exposure hours statistically differ from the number of crashes during dry weather exposure hours, a paired t-test on the two-category model (rain, no-rain) was performed using Minitab statistical software (Minitab, Inc., 2013). Summarized in Table 6.2, the results indicate that, on Florida freeways, the mean number of hourly crashes, based on rain exposure, is nearly 2.7 times greater than the mean number of hourly crashes during dry weather conditions, and the increase is statistically significant (p-value < 0.001).

The histogram of differences shown in Figure 6.5 depicts a fairly normal distribution in the mean differences, thus satisfying the normality of the data assumption for the paired t-test. Therefore, from the results given in Table 6.2 and Figure 6.5, it can be inferred that rainy

conditions increase the number of crash occurrences on Florida freeways, based on rain exposure hours.

Table 6.2

Summary of paired t-test comparing crash proportion for dry and rainy conditions

Crash Occurrence versus Weather Condition				
Weather Condition	N	Mean	StDev	SE Mean
Rain	24	0.1365	0.0872	0.0178
No-Rain	24	0.0513	0.0456	0.0093
Difference	24	0.0853	0.0524	0.0107
t-statistic = 7.96	*p*-value = 0.000	α = .05	C.I. (0.0631, 0.1074)	

N = Number of pairs, one pair per hour-period included in the analysis.

C.I. = Confidence Interval

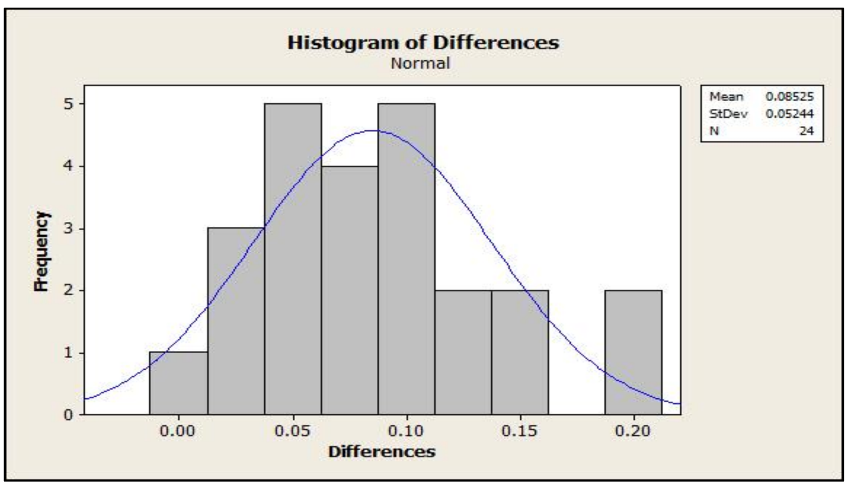

Figure 6.5. Hourly crash proportion histogram of differences from paired *t*-test.

Four-Category Model

To determine if rain intensity or hour-of-day affect crash proportions based on weather exposure hours, a two-way analysis of variance (ANOVA) was initially performed on the four-category model (no-rain, light, moderate, and heavy rain). Only hour-periods containing recorded rainfall data with reported crashes in each category were considered for the analyses. Consequently, 11 hour-periods fit the criteria to be included in the analysis. Although the

ANOVA indicated a significant difference (*p*-value < .05) in the mean crash proportions based on rain exposure, suggesting that the number of crashes increase with increasing rainfall intensity exposure, further inspection found a violation in the constant variance assumption required for a valid analysis.

To improve the subgroup process variation in the data, a two-factor linear regression was performed utilizing a power transformation model (lambda = 0.5) for the expected crash proportion value. Categorical values of zero, one, two, and three were assigned to the no-rain, light rain, moderate rain, and heavy rain categories, respectively. The hour-period number, included in the analysis, served as the categorical value assigned to the hour-of-day factor.

Summarized in Table 6.3, the regression analysis results indicate a positive (Coef. = +0.139) and significant (*p*-value < 0.001) relationship between crash occurrence and increasing rainfall intensity, at a 95% confidence level. Based on the regression equation shown in Table 6.3, the proportion of crashes during rain, the number of crashes per rain exposure hours, is expected to increase by a factor of .139 during light rain conditions using a categorical value of one for light rain. Accordingly, the likelihood of a crash occurring during moderate and heavy rain events increase by a factor of .278 and .417, respectively. However, for a .05 level of significance, the hour-of-day does not significantly affect crash occurrence as indicated by a *p*-value of 0.406 and a very low coefficient of +0.003 from the regression equation listed in Table 6.3. Overall, the model provides a reasonable fit to the calculated crash proportions used in descriptive analyses.

Residual plots developed from the Minitab (2013) regression analysis are shown in Figure 6.6. The linear appearance of the data in the *Normal Probability Plot* indicate a fairly normal distribution for the residuals. However, unlike the initial ANOVA, the *Residual Versus*

Table 6.3

Summary of regression analysis of hourly crash proportions (four rain categories)

Regression Analysis: Crash Proportion versus Rain Category, Hour of Day

Crash Proportion^0.5 = 0.1948 + 0.13887 Rain Category + 0.00295 Hour-of-Day

Term	Coef	SE Coef	*T*-stat	*p*-value
Constant	0.19408	0.05745	3.378	0.002
Rain Category	0.13887	0.0146	9.515	0.000
Hour of Day	0.00295	0.0035	0.839	0.406
S = 0.108239	R-Sq. = 69.00%	R-Sq.(adj) = 67.48%		
R-Sq.(pred) = 64.37%				

Analysis of Variance

Source of Variation	DF	Seq SS	Adj SS	Adj MS	*F*-ratio	*p*-value
Regression	2	1.06896	1.06896	0.5345	45.621	0.000
Rain Category	1	1.0607	1.0607	1.0607	90.537	0.000
Hour of Day	1	0.00825	0.00825	0.0083	0.704	0.406
Error	41	0.4803	0.4803	0.0117		
Total	43	1.5493				

S = Standard deviation

Fits plot reflects a fairly constant variance. The *Residual Versus Order* plot also shows no discernable pattern, thus satisfying the assumption of independence. Consequently, the residual plots confirm the validity of the analysis results.

The four-category analysis results listed in Table 6.3 with the accompanying assumption plots shown in Figure 6.6 indicate that rainfall intensity significantly affects the number of crashes, based on rain exposure hours. Therefore, it can be inferred that the risk of crash occurrence on Florida freeways increases as hourly rain intensity increases. However, the hour-of-day does not effect of the number of hourly crashes.

Discussion of Results

Findings from previous studies indicate that the number of accidents increase during wet weather conditions (Sherretz & Farhar, 1978; Bertness, 1980). The focus of the present study was not the number of crashes during rainy conditions, but the proportion of crashes during rain

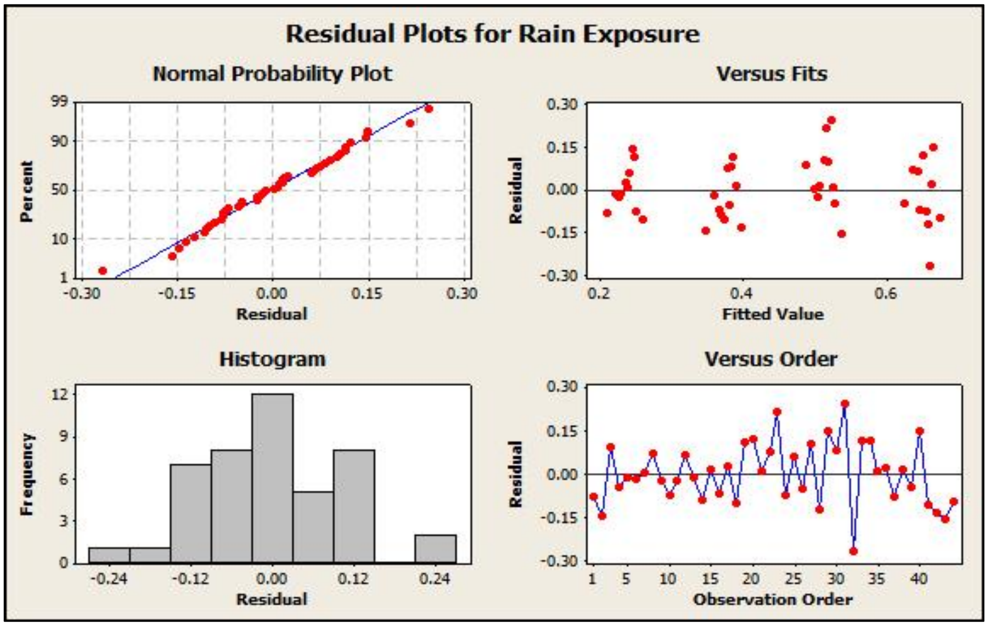

Figure 6.6. Residual plots of crash proportion regression analysis.

exposure compared to dry weather exposure. Results reveal that, although rain hours were fewer than dry hours, the number of crashes were proportionally higher during rain events than during dry weather conditions, and statistically significant. Overall, crashes occurred in only 5.1 % of the total dry weather hours, while crashes during rainy weather occurred in 14.9% of total rain exposure hours, an increase of nearly 10%. The risk of an accident during rainy weather relative to dry weather was higher for each hour of the day, and increased with increasing rain intensity.

However, due to the diversity of research and scope among the studies, direct comparisons were difficult. Much research has focused on large scale analyses covering cities, metropolitan areas, as well as, on a national scale. Although this approach allowed for ample data, the study sites were comprised of dissimilar roadways with varying traffic characteristics, and often with variable weather exposure units. Few studies focused on a specific roadway classification, such as freeways.

The present study examined rain effects on crash occurrence along interstate freeways,

which are high-speed limited access facilities by definition. Of the published literature found that studied similar freeway sections (Keay & Simmonds, 2006; Golob & Recker, 2003; Jovanis & Chang, 1986; Jones et al., 1991; Khattak et al., 1998; Xu et al., 2013), each focused on different elements for crash analyses. Golob and Recker (2003), and Khattak et al. (1998) investigated weather influences on crash type and severity. Jovanis and Chang (1986), examined the relationship between accidents and traffic exposure, in vehicle miles traveled. Jones et al. (1991), focused on statistical techniques of analysis to improve accident management programs. Moreover, these studies used aggregated weather and crash data and time scale units of days to measure exposure variables. The study by Xu et al., (2013) concentrated on crash risk prediction for varying weather and traffic flow conditions using aggregated five-minute intervals just before crashes occurred on California freeways.

The freeway sections studied by Keay and Simmonds (2006) were the most comparable to the characteristics of the freeways used in the present study. The climate in Melbourne, Australia may also be fairly comparable with Jacksonville, Florida. However, Keay and Simmonds (2006) found an increase in daily crash risk during rainy conditions of 0.7 times greater than during clear weather conditions. This increase is considerably lower than the 2.9 relative rate found in the present study.

Although considerably greater, increases in crash occurrence during rain events, in terms of the percentage of increase, are more in the range of findings by Bertness (1980) and Sherretz and Farhar (1978). Interestingly, the average increase in rain-related accidents in these two studies were much higher than other findings at the time (Andrey & Olley, 1990). Quantifying the influence of rainfall at an hourly level of exposure may be a primary factor in the differences between findings in the present study and those from previous research. This suggests that the

temporal unit of measure and the use of heavily aggregated data can greatly affect results, as suggested by Qin et al. (2006) and Eisenberg (2004).

Rainfall data used in the present study was reported in hourly intervals. The actual start and stop time of precipitation cannot be inferred from the data. Additionally, precipitation at any location can exhibit a fair degree of spatial variability. Therefore, it is possible that rain may not have been present at the actual time a vehicle accident occurred. To investigate this possibility, the reported hourly precipitation was compared to the CARS database coded weather condition (clear, rain, or fog) reported by officers on-site of each crash occurrence on four randomly selected crash occurrences for each study year. The examination found that in over 84% of crashes, the stipulated weather condition of "rain" corresponded with the presence of rainfall recorded by the weather station for the hour of the crash. Exceptions were found where the crash report indicated rain, and the weather station recorded no-rain for that date and hour. A closer inspection of these anomalies discovered that the reported time of the crash was within five minutes of the change in hour time, of which rain was reported for the preceding or successive hour of the crash. Therefore, the historical rainfall amounts reported by the weather station was considered a fairly accurate indication of rainfall along both freeway sections used in the study.

CHAPTER 7 – RESULTS AND DISCUSSION: HOURLY CRASH RATES

Reported rain hours comprised only 7.5% of the total hours over the four-year study period, yet almost 18% of crashes occurred during rain events. To examine the rate of crash occurrence based on weather exposure and hour-of-day, crash rates per 100 Million Vehicle Miles of Travel (MVMT) were determined for both the two- and four-category weather conditions for each hour-period. Average Annual Daily Traffic (AADT) volumes provided in the CARS report from the FDOT for each crash occurrence varied, corresponding with the accident location site along each freeway study section. Accordingly, AADT volumes were averaged from the total crash occurrences per hour-period per rain category. However, this measurement of traffic exposure can produce misleading results (Qin, Ivan, Ravishanker, Liu, & Tepas, 2006) since disaggregated AADT volumes into hourly volumes do not consider the actual daily distribution among hour-periods.

Hourly Expansion Factors

Average Hourly Traffic (AHT) volumes, or number of vehicles per hour, is typically determined per industry standards by dividing the AADT by 24, representing 24 hours per day. Because this method does not consider the daily distribution of traffic at a given location, the resulting hourly crash rates can be misleading. The number of vehicles per hour-period based on $1/24^{th}$ of the average daily volume does not accurately represent the average number of vehicles per hour-period that actually exist along a particular roadway segment.

To address the temporal traffic variations among the 24 hour-periods, Hourly Expansion

Factors (HEFs) were developed for each hour-period using mean hourly volumes retrieved from traffic sensors located along each study section (see Figure 3.2), and the overall mean AADT associated with reported total crashes per rain category for the 24 hour-periods. To determine the HEFs, Equation 1 (Garber & Hoel, 2009) and the mean hourly volumes used in analyses on the effects of rain on traffic volumes (see Chapter 5) were used to represent the average daily traffic distribution for the combined study segments.

$$HEF = \frac{total\ volume\ for\ a\ 24\ hour\ period}{volume\ for\ particular\ hour} \qquad \text{(Eq. 1)}$$

Findings from Chapter 5 analyses indicate that rainy conditions and rainfall intensity have a significant effect on hourly traffic volume reductions (see Tables 5.1 and 5.2). Consequently, the mean hourly volumes for each rain category and corresponding hour-period were used to establish the HEFs listed in Table 7.1.

Hourly expansion factors are generally used in Transportation studies to expand hourly traffic counts of less than a 24-hour duration to obtain Average Daily Traffic (ADT) volumes for analysis and reporting purposes using the Equation 2 (Garber & Hoel, 2009):

$$\frac{vehicle\ count}{hour} \times HEF = ADT \qquad \text{(Eq. 2)}$$

For the present study, weather exposure units were expressed in hours. Therefore, it was necessary to convert each hourly ADDT mean into units of vehicles per hour per day (vph/day). The reciprocal of each hourly expansion factor listed in Table 7.1 represents the proportion of the overall mean AADT per rain category relative to the mean hourly volume for each hour-period. For clarity, the product of the reciprocal HEF value and the mean reported AADT value from the CARS report, for each hour-period per rain category is referred to as the Average Annual Hourly Traffic (AAHT). As a measure of hourly traffic exposure, the AAHT was calculated using

Equation 3 for the two- and four-category analyses to determine hourly crash rates per 100 MVMT.

$$Mean\ AADT \times \frac{1}{HEF} = AAHT \qquad \text{(Eq. 3)}$$

Table 7.1

Hourly Expansion Factors (HEFs)

Hourly Expansion Factor (HEF) for I-295 and I-95 Study Sections					
Hour Period	No-Rain	Rain	Light Rain	Moderate Rain	Heavy Rain
0	179.94	167.64	164.93	167.91	231.92
1	230.84	211.81	213.08	195.01	215.08
2	217.24	220.95	223.83	208.72	209.43
3	124.53	139.24	144.04	85.78	179.98
4	48.71	54.06	54.20	56.98	57.17
5	18.09	23.87	24.35	30.73	15.28
6	11.26	11.42	11.47	12.10	12.14
7	10.54	10.24	10.16	10.30	11.48
8	13.64	12.10	12.02	11.40	12.66
9	17.54	16.96	16.74	18.47	15.64
10	18.87	18.61	18.35	23.36	15.77
11	18.99	18.69	18.88	16.81	22.64
12	19.00	18.52	18.29	20.07	16.70
13	18.66	17.65	17.53	17.69	22.78
14	17.79	17.41	17.32	17.09	17.15
15	16.94	16.38	16.47	15.69	15.74
16	15.92	15.14	15.23	14.20	15.57
17	18.04	18.17	28.33	26.64	29.41
18	24.56	26.20	25.92	29.13	24.75
19	32.70	36.17	36.93	29.96	39.62
20	39.07	41.92	42.44	39.31	39.44
21	48.71	52.30	53.55	46.25	46.41
22	66.46	71.60	70.93	68.78	86.71
23	102.19	98.90	96.08	128.66	143.38

Note: Reciprocal HEF multiplied by hourly mean AADT.

Hourly crash rates per 100 MVMT were calculated for each hour-period and weather condition using the general formula shown in Equation 4 (Garber & Hoel, 2009). Equation 4 was then modified for hourly exposure (AAHT) as indicated in Equation 5.

$$RMVM = \frac{No.Crashes \times 100{,}000{,}000}{AADT \times study\ period\ days \times Length\ of\ section} \equiv \frac{No.Crashes}{100\ million\ veh.miles} \quad \text{(Eq. 4)}$$

RMVM = rate per million vehicle miles.

$$RMVM = \frac{No.Crashes \times 100{,}000{,}000}{AAHT \times study\ period\ days \times Length\ of\ section} \equiv \frac{No.Crashes}{100\ million\ veh.miles} \quad \text{(Eq. 5)}$$

For example: the dry weather crash rate per 100 MVMT for hour-period seven (7:00 AM) with 140 dry-hour crashes would be (140 × 100,000,000) divided be the product of 15.5 miles, 965 dry weather exposure hours per four years (965/4), an AAHT of (114,038 × 1/10.54), and a study period of (365 × 4) days to yield a crash rate of .24 crashes per 100 MVMT for the hour of 7:00 to 8:00 AM under dry weather conditions. Computed hourly crash rates for each rain condition are listed in Table 7.2.

If the mean AADT values for each rain category and corresponding hour-period were converted using 24 as the divisor (standard method), with respect to 24 hours per day, the resulting AAHT volumes (vph/day) would grossly distort the computed crash rates. By using HEFs to compute the daily traffic distribution from known AADT values, better estimates of crash rates can be realized. Figure 7.1 graphically demonstrates the degree of distortion in crash rates resulting when AAHT volumes are computed using the standard method, while Figure 7.2 illustrates the results for the two-category analysis using AAHT volumes computed from field measured daily traffic distributions. Both computation methods (standard and 1/HEF) yield the same daily crash rate (2.9) for rainy conditions relative to dry weather. However, comparing the

relative exposure graphs in Figures 7.1 and 7.2, hourly relative crash rates vary considerably between the two methods.

Table 7.2

Hourly crash rates per 100 MVMT from descriptive statistics

Hourly Crash Rate per 100 Million Vehicle Miles of Travel					
Hour of Day	No-rain	Rain	Light Rain	Moderate Rain	Heavy Rain
0	0.57	0.83	0.97	--	--
1	0.54	2.07	1.75	--	6.73
2	0.74	1.72	1.94	--	--
3	0.20	1.29	0.89	--	34.02*
4	0.10	0.54	0.48	0.96	--
5	0.04	0.24	0.14	1.41	0.68
6	0.09	0.22	0.16	0.73	--
7	0.24	0.40	0.41	--	1.12
8	0.28	0.59	0.62	0.65	--
9	0.12	0.40	0.29	0.73	1.09
10	0.07	0.34	0.36	--	0.50
11	0.12	0.40	0.22	0.71	1.63
12	0.13	0.36	0.20	1.07	0.74
13	0.11	0.34	0.37	0.23	--
14	0.19	0.39	0.18	0.98	1.74
15	0.17	0.62	0.49	1.30	0.85
16	0.23	0.41	0.29	0.99	0.64
17	0.44	0.76	0.64	1.46	0.41
18	0.51	1.36	1.20	1.36	2.19
19	0.15	1.04	0.94	1.01	3.58
20	0.14	0.31	0.29	0.56	--
21	0.13	0.78	0.84	0.75	--
22	0.24	0.88	0.67	1.31	4.70
23	0.23	0.47	0.53	--	--
Overall	0.01	0.02	0.02	0.04	0.05

-- Indicates no reported crashes * Indicates insufficient data to validate

Descriptive Analysis

The analyses of crash rates per 100 MVMT for wet and dry weather, as shown in Figure 7.2, indicate that rates during rain events are consistently higher than for dry conditions for every hour-period of the day. Hourly crash rates based on rain exposure are highest for early morning nighttime hours during rain events highlighting the rarity of crash occurrence for this time of day. Morning and evening congested hours also exhibit higher crash rates due to rain exposure, and are somewhat comparable with findings by Levine et al. (1995) for rain effects on daily accident occurrence.

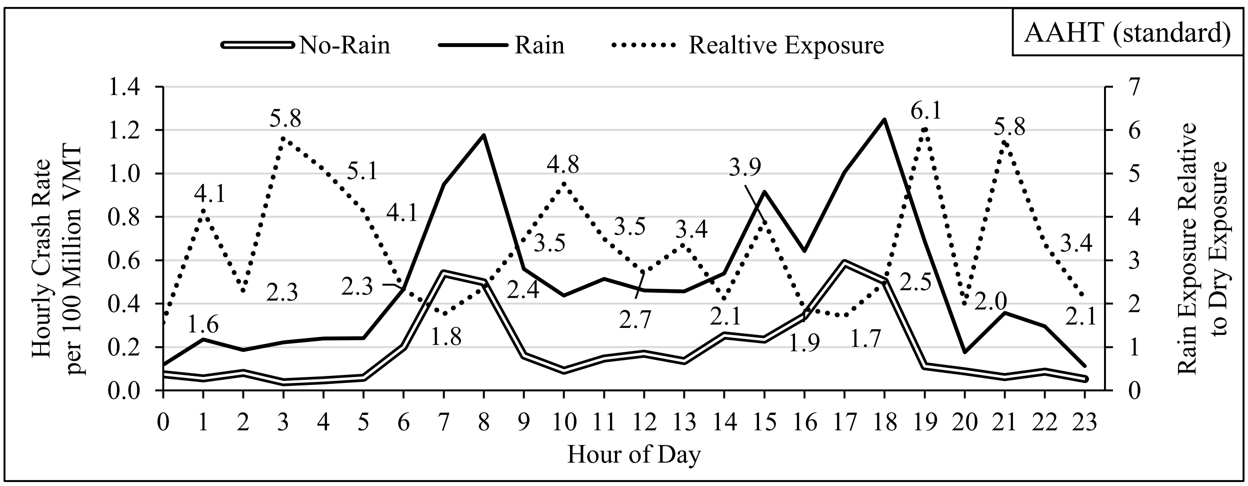

Figure 7.1. Crash rates per 100 MVMT (two rain categories, AADT-standard).

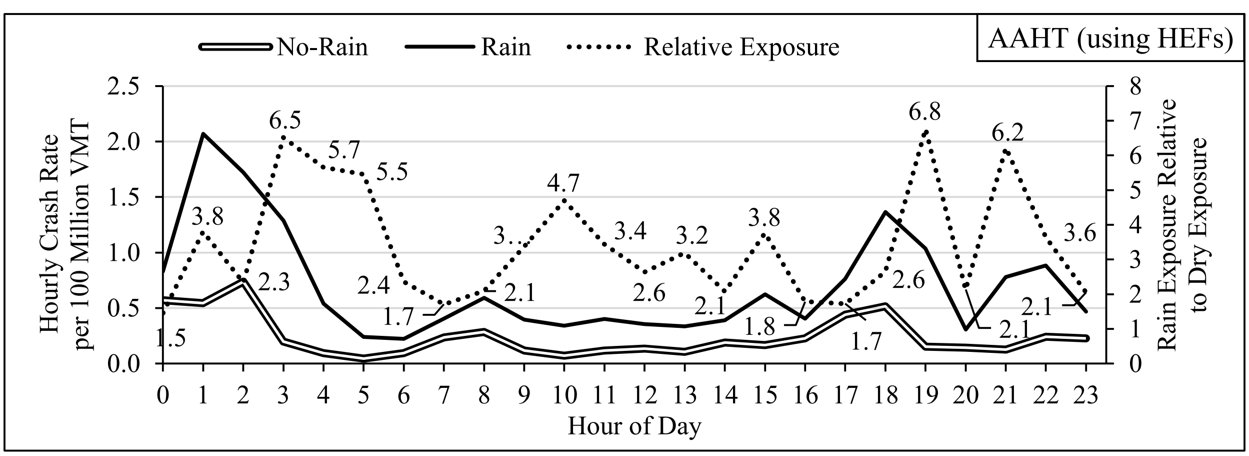

Figure 7.2. Crash rates per 100 MVMT (two rain categories, AADT-using HEFs).

To some extent, the graphical representation of the crash rates per 100 MVMT relative to dry conditions illustrated in Figure 7.2 correlates with the relative hourly crash proportions depicted in Figure 6.1. However, three exposure parameters were utilized in determining the crash rates per 100 MVMT for each hour-period: rainfall exposure in hours, distance exposure in vehicle miles of travel, and hourly traffic volume exposure.

Figure 7.3 graphically portrays the variability in crash rates per 100 MVMT when rain intensity is considered. For clarity, crash rates per 100 MVMT for the heavy rain category are shown for all hour-periods in Figure 7.3(b), and for hour-periods five-19 in Figure 7.3(a), with the nighttime uncongested hours removed.

Zero values in Figure 7.3 reflect hour-periods where no crashes were reported over the four-year study period. From Figure 7.3(a), it is evident that light rain is the dominant influence on hourly crash rates per 100 MVMT during rain events, as light rain is overrepresented for the majority of hour-periods. This is graphically noticeable in comparing the crash rate pattern for light rain, as shown Figure 7.3(a), with the rate pattern exhibited for general wet weather (see Figure 7.2).

Moderate and heavy rainfall produce substantially higher crash rates per 100 MVMT at various hour-periods throughout the day. However, due to fewer observations, these rain categories had little effect on the overall rate of crashes per 100 MVMT per hour-of-day presented in Figure 7.2. Nonetheless, based on rain exposure and adjusted AADT values, the rate of accident occurrence during moderate and heavy rainfall is considerable, as indicated by the crash rates per 100 MVMT shown in Figure 7.3(a).

Evening peak traffic hours had the highest number of exposure hours and crash occurrences for light, moderate, and heavy rainfall. Consequently, moderate and heavy rainfall

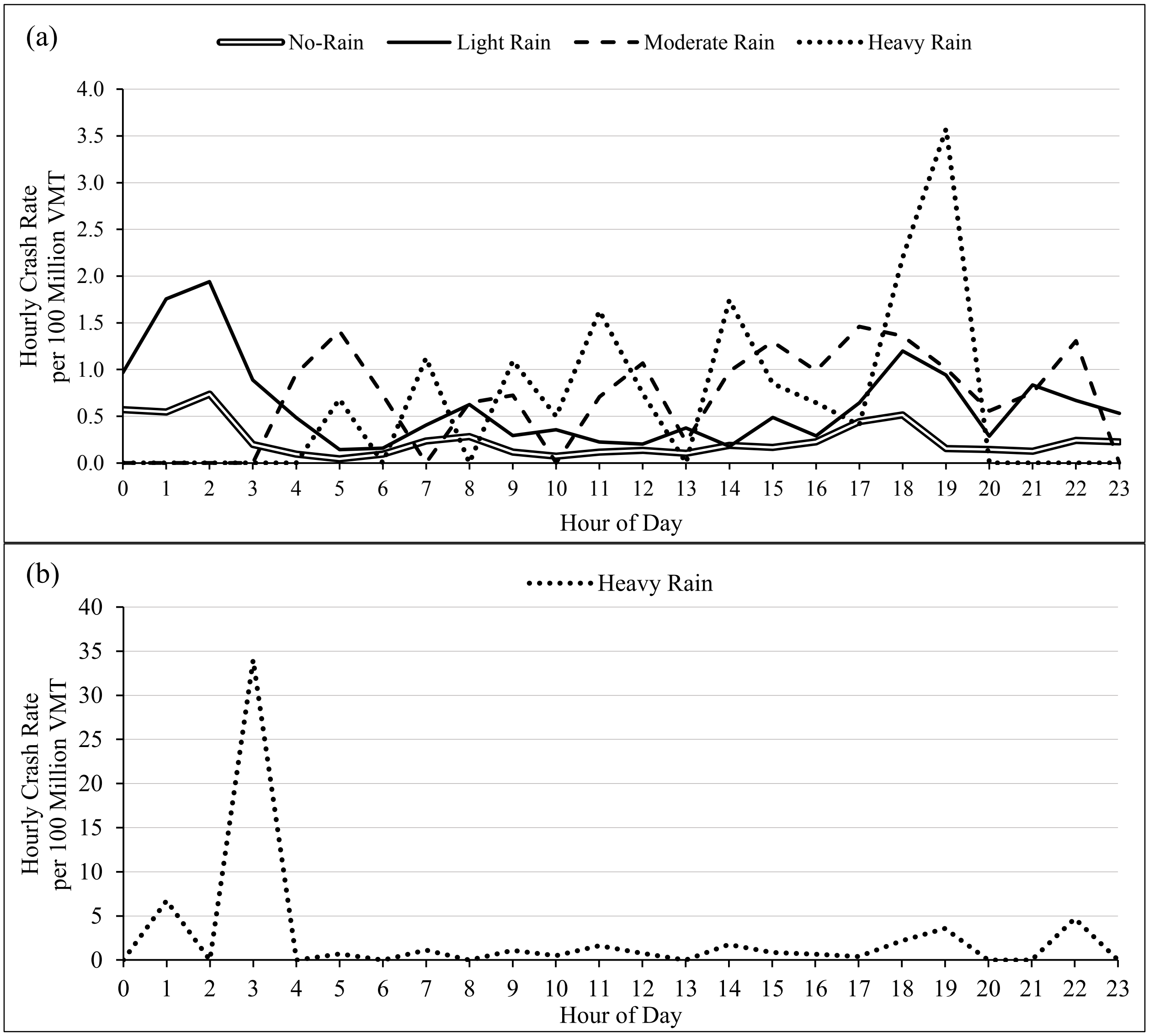

Figure 7.3. Crash rates per 100 MVMT (four rain categories).

actually increased overall crash rates above the dominant light rain rates. This suggests that drivers are more familiar with light rain occurrence on freeways, thus resulting in less crashes per hours of rain exposure. However, moderate and heavy rains present additional challenges for motorists, resulting in more crashes under less exposure, hence higher crash rates. Crashes occurred in approximately 30% of the total heavy rain hours, opposed to 25%, 12%, and 5% in hours of moderate rain, light rain, and dry weather exposure, respectively. Crash rates during the

early morning nighttime hours were greatly affected by rainfall of any amount.

Statistical Analysis

Two-Category Model

To determine if hourly crash rates per 100 MVMT based on weather exposure hours statistically differ between wet and dry conditions, a paired t-test on the two-category model (rain, no-rain) was performed using Minitab statistical software (Minitab, Inc., 2013). Summarized in Table 7.3, findings indicate that at a 95% confidence level, mean crash rates per 100 MVMT increase by up to 2.6 times greater during rain events than during dry weather conditions for any hour of the day. The results are also statistically significant as indicated by a *p*-value less than 0.001 in Table 7.3.

Table 7.3

Summary of paired t-test comparing crash rates/100MVMT for dry and rainy conditions

Crash Rate versus Weather Condition				
Weather Condition	N	Mean	StDev	SE Mean
Rain	19	0.4883	0.2017	0.0463
No-Rain	19	0.1912	0.1301	0.0298
Difference	19	0.2972	0.1502	0.0345
t-statistic = 8.62	*p*-value = 0.000	α = .05	C.I. (0.2247, 0.3696)	

N = Number of pairs, one pair per hour-period used for analysis. C.I. = Confidence Interval

Although somewhat skewed to the right, the histogram of differences shown in Figure 7.4 depicts a fairly normal distribution in the mean differences, thus satisfying the normality assumption for the paired *t*-test. Therefore, from the results given in Table 7.3 and Figure 7.4, it can be inferred that rainy conditions increase crash rates per 100 MVMT on Florida freeways, based on rain exposure hours.

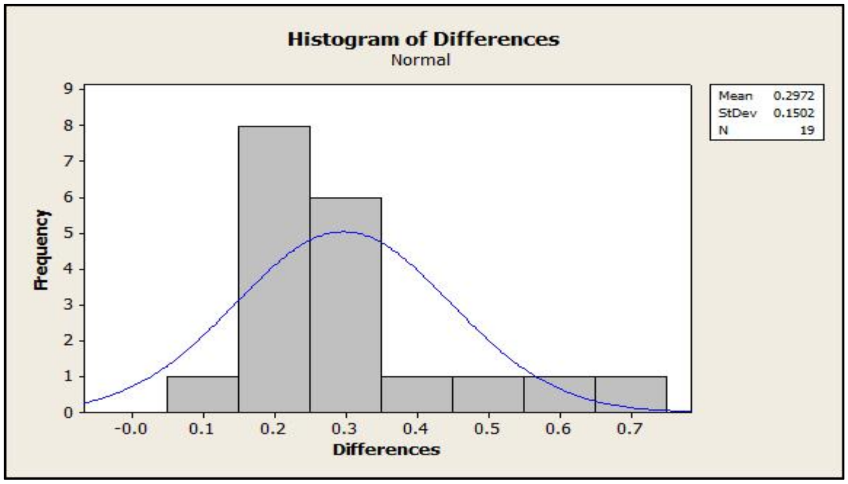

Figure 7.4. Hourly crash rate/100 MVMT histogram of differences from paired *t*-test.

Four-Category Model

Similar to the four-category analysis performed for hourly crash proportions, a two-factor linear regression was performed to determine if rain intensity or hour-of-day significantly affected hourly crash rates per 100 MVMT. Only hour-periods containing both crashes and weather data for each rain category were included in the analysis. A natural log function was applied to the expected crash rate/100 MVMT value, with categorical values of zero, one, two, and three assigned to the no-rain, light rain, moderate rain, and heavy rain categories, respectively. The hour-period number for hour-periods included in the analysis served as the categorical value assigned to the hour-of-day factor.

Summarized in Table 7.4, the regression analysis results indicate a considerably high positive relationship (Coef. = +0.865) between crash rates per 100 MVMT and increasing rainfall intensity. Moreover, for a 95% confidence level, the results were significant as indicated by a *p*-value less than 0.001. From the prediction equation, the crash rates/100 MVMT during light rain events are expected to increase by a factor of .87 above dry weather conditions. For moderate and heavy rain conditions, crash rates per 100 MVMT are expected to increase by a

factor of 1.73 and 2.47, respectively, using a categorical value of two for moderate rain and three for heavy rain.

To a lesser extent, crash rates per 100 MVMT were also affected by the hour-of-day with a positive coefficient of +0.073 from the regression equation listed in Table 7.4. Although the coefficient for the Hour-of-Day factor was considerably smaller than for rain category, the effects on crash rates/100 MVMT were significant (p-value < 0.001). Overall, the model provided a reasonable fit to the calculated crash rates/100 MVMT determined in descriptive analyses (see Table 7.2).

Table 7.4

Summary of regression analysis of crash rates/100 MVMT (four rain categories)

Regression Analysis: Crash Rate versus Rain Category, Hour of Day						
ln (Crash Rate) = -2.88798 + 0.86495 Rain Category + 0.07312 Hour-of-Day						
Term	Coef	SE Coef	*T*-stat	*p*-value		
Constant	-2.88798	0.18263	-15.813	0.000		
Rain Category	0.86495	0.04309	20.069	0.000		
Hour of Day	0.07312	0.01129	6.472	0.000		
S = 0.25476	R-Sq. = 94.64%	R-Sq.(adj) = 94.23%				
R-Sq.(pred) = 93.52%	PRESS = 2.0397					
Analysis of Variance						
Source of Variation	DF	Seq SS	Adj SS	Adj MS	*F*-ratio	*p*-value
Regression	2	29.8003	29.8003	14.9001	229.566	0.000
Rain Category	1	27.0813	26.1421	26.1421	402.772	0.000
Hour of Day	1	2.7190	2.7190	2.7190	41.891	0.000
Error	26	1.6875	1.6875	0.0649		
Total	28	31.4878				

S = Standard deviation

Residual plots developed from the Minitab (2013) regression analysis are shown in Figure 7.5. The linear appearance of the data in the *Normal Probability Plot* indicate a fairly normal distribution for the residuals. Although the *Residual Versus Fits* plot shows slight patterning, the fitted values reflect a somewhat constant variance among the data. The *Residual*

Versus Order plot also shows no discernable pattern, thus satisfying the assumption of independence. Overall the residual plots confirmed the validity of the analysis results.

The four-category regression results listed in Table 7.4 with the accompanying assumption plots shown in Figure 7.5 indicate that rainfall intensity significantly affects the crash rates per 100 million vehicle miles of travel, based on rain exposure hours. Therefore, it can be inferred that hourly crash rates/100 MVMT increase with increasing rainfall intensity exposure on Florida freeways. Additionally, it can be inferred that the hour-of-day significantly affects crash rates/100 MVMT.

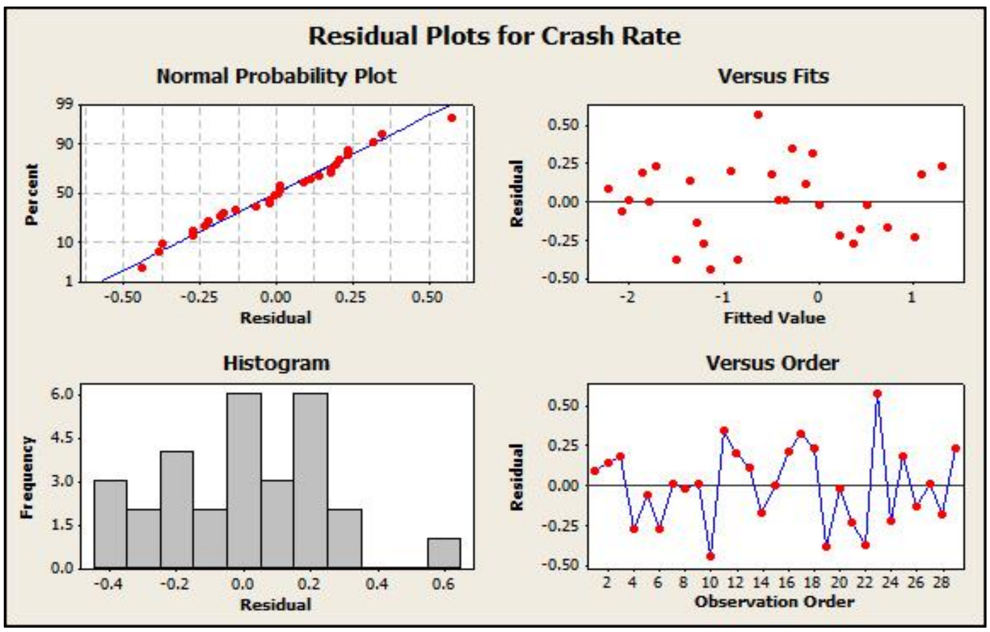

Figure 7.5. Residual plots of crash rates per 100 MVMT regression analysis.

Discussion of Results

Through descriptive and inferential analyses, results indicate that crash rates per 100 MVMT based on hourly weather exposure, increase during general wet weather conditions and with increasing rainfall intensity. Interestingly, the added distance exposure factor required for crash rates/100 MVMT found that hour-of-day has a significant effect on hourly crash

occurrence opposed to results from the crash proportion analyses that did not include distance exposure. Although similar findings were concluded by Qin et al. (2006), the study focused on rural two-lane highways in Michigan and Connecticut and the relationship between crash type and hourly volume exposure.

Since greater traffic volumes present greater opportunities for crash occurrence, using the actual hourly traffic volumes determined from hourly expansion factors developed from field data allowed for more realistic hourly crash rates/100 MVMT along the freeway segments examined in this study. While inferences were made that the results should apply to all freeways with similar characteristics, Qin et al. (2006) argues that the expected number of crashes on roadways with similar characteristics will vary based on the daily traffic volume distribution. Nonetheless, additional research is needed to confirm this trend for high-speed limited access facilities.

From the review of published literature on crash occurrence or crash rates, it was found that previous studies were broadly focused on the topic. The present research focused on the effects of hourly exposure measures of both weather and hour-of day, in conjunction with distance exposure to determine hourly crash rates per 100 million vehicle miles of travel. Comparable studies were not found among published literature; therefore, direct comparison with previous research findings was not possible.

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CHAPTER 8 – RESULTS AND DISCUSSION: SEASONAL CRASHES

To investigate seasonal effects on crash occurrence, weekday crash data over the four year study period (2008-2011) was analyzed using aggregated monthly precipitation amounts for the four-category model (no-rain, light, moderate, and heavy rain). For the purpose of analyses, months were categorized into annual rainfall seasons used by the St. Johns River Water Management District [SJRWMD] (Rao, Jenab, & Clapp, 1989), the agency responsible for the management of water resources in Northeast Florida. The two rainfall seasons typically used by SJRWMD include the Wet or Rainy season (June-October), and the Dry season (November-May). Two alternative rainfall seasons, important with respect to agriculture, are the Warm season (June-September), and the Cold season (December-March) (Rao et al., 1989). The Warm season typically experiences the greatest amount of rainfall each year, while the Cold season receives the least amount of precipitation (Rao et al., 1989). In the present study, for the purpose of crash analyses, the months of April, May, October, and November were combined to represent the dryer precipitation months between the Warm and Cold seasons, and is referred to as the Mid-Dry season.

Descriptive Analysis

Approximately 45 inches of rainfall occurred annually over the four-year study period (2008-2011), within the normal range for the Jacksonville area (Rao et al., 1989). However, to correspond with previous analyses performed in the present study, only weekday precipitation was used, with observed national holidays removed. Although using weekday data reduced the

annual rainfall amounts by 28% for an average of just over 32 inches per study year, the distribution of monthly precipitation remained consistent. In both scenarios, the month of May, included in the Dry season, contained more overall rainfall than the month of September in the Warm season.

Hourly precipitation data for the four-year study period, aggregated into monthly totals, is shown in Figure 8.1. October and December were the driest months, while June through August were the wettest months.

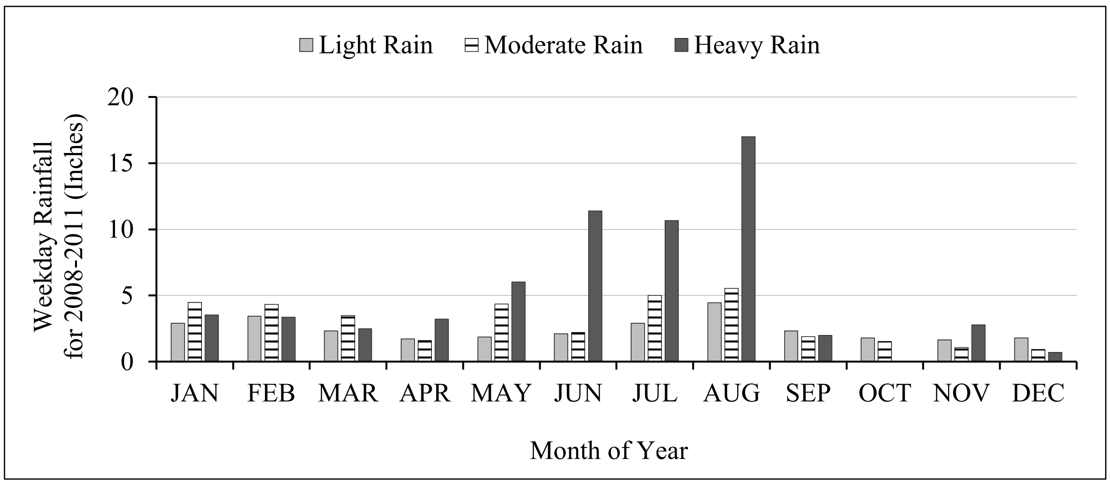

Figure 8.1. Monthly rainfall distribution for weekdays (2008-2011).

The percentage of total weekday light, moderate, and heavy rainfall that occurred during the study period, and separated into rainfall seasons, is depicted in Figure 8.2. While the occurrence of light rain was more prevalent, heavy rainfall (> .3 in/hr) contributed the greatest accumulation total, adding approximately seven inches to yearly weekday totals. As shown in Figure 8.2, heavy rain exceeded the rainfall amounts of both the light and moderate rain categories for each season except the Cold season, where moderate rainfall dominated. Note that the percentage of total rainfall in the light and moderate rain categories was greater in the Dry season than in the Wet season due to the inclusion of the month of May.

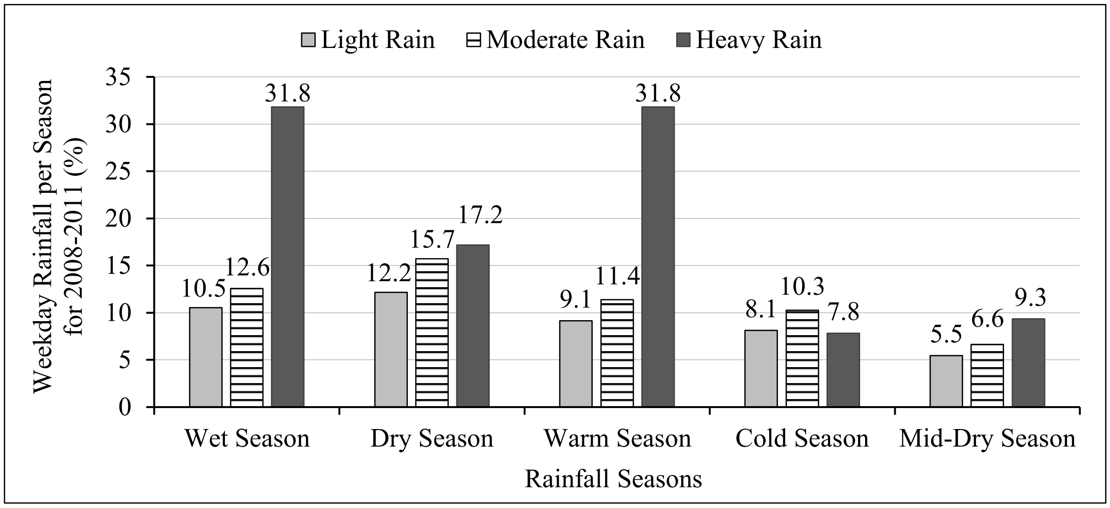

Figure 8.2. Seasonal rainfall distribution for weekdays (2008-2011).

The percentage of weekday crash occurrences for 2008-2011, aggregated for each rainfall season by rain category, is listed in Tables 8.1 and 8.2. The percentage of crashes for the two-season combination (Wet and Dry) listed in Table 8.1, indicate that a greater number of accidents occurred in the Dry season (November-May), with the majority of crashes reported during dry weather conditions. In the Wet season (June-October), crash occurrences during light, moderate, and heavy rain were only slightly elevated above Dry season percentages. This trend is graphically represented in Figure 8.3.

Table 8.1

Percent crashes per rainfall season (two seasons)

Season	Months	No. of Crashes per Season by Rain Category				Total	% of Crashes per Season and by Category			
		No-Rain	Light	Moderate	Heavy		No-Rain	Light	Moderate	Heavy
Wet/ Rainy	June - October	487	85	27	16	615	79.2	13.8	4.4	2.6
Dry	November - May	667	83	25	15	790	84.4	10.5	3.2	1.9
	Total	1154	168	52	31	1405	82.1	12.0	3.7	2.2

When weekday crashes were examined for the three-season combination consisting of the Warm (June-September), Cold (December-March), and Mid-Dry (April, May, October, and November) seasons, a better understanding of seasonal effects on crash occurrence was observed. Indicated in Table 8.2, more crashes occurred in the Warm season for every rain category (37.2% overall), including accidents during dry weather conditions. The percent of crash occurrence during rainy conditions was also higher in the Warm season by 40% and 60% than during the Cold and Mid-Dry season, respectively. This observation agrees with the analyses of hourly crash occurrence (see Chapter 6) that proportionally, the number of crashes increase with increased rain exposure.

Though Florida is a popular tourist destination year-round, the Warm season months generally coincide with peak tourist travel (Florida Guide, 2014) which may influence the number of seasonal crash events. However, distinguishing between tourist travelers and commuter motorists is difficult given the traffic data collection methods currently available.

Table 8.2

Percent crashes per rainfall season (three seasons)

Season	Months	No. of Crashes per Season by Rain Category				Total	% of Crashes per Season by Rain Category			
		No-Rain	Light	Moderate	Heavy		No-Rain	Light	Moderate	Heavy
Warm	June-September	406	74	27	16	523	77.6	14.1	5.2	3.1
Cold	December-March	371	51	14	6	442	83.9	11.5	3.2	1.4
Mid-Dry	April, May, October, November	377	43	11	9	440	85.7	9.8	2.5	2.0
	Total	1154	168	52	31	1405	82.1	12.0	3.7	2.2

Figure 8.3 shows the percentage of weekday crashes recorded during each season, and the relative proportions to the percentage of seasonal rainfall. Roughly 18% of weekday crashes

over the four-year study period occurred during rainy conditions. Although heavy rain contributed the most accumulation of rainfall for all but the Cold season, more crashes occurred during light rainfall (12%) than during moderate and heavy rainfall combined. Accordingly, the percentage of crashes during light rain events relative to the percentage of seasonal rainfall exposure was considerably higher than relative proportions for both moderate and heavy rain for each rainfall season as illustrated in Figure 8.3.

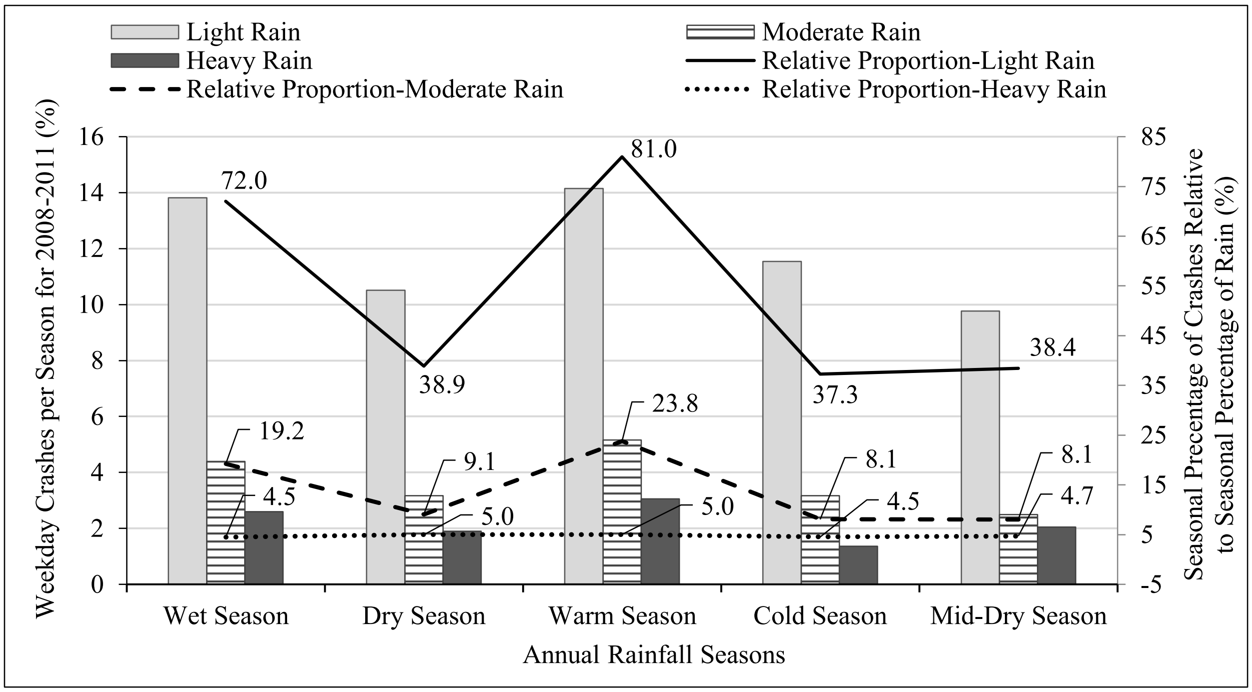

Figure 8.3. Seasonal crashes versus rainfall for weekdays (2008-2011).

The greatest number of light rain accidents occurred in the Wet and Warm season, each considered the *rainy* season within their respective annual season combination. Light rain had the lowest percentage of accumulation in every season, yet the highest percentage of crashes. This observation agrees with descriptive statistics in the analysis of hourly crash occurrence (see Chapter 6). Light rain events were more frequent, and occurred over five times more often than heavy rain, and over three times more often than moderate rain events. Heavy rain contributed

the highest percentage of rainfall, followed by moderate rain, however fewer crashes occurred in both weather conditions.

Interestingly, the Dry season exhibited an almost equal percentage of crashes relative to light rain exposure compared to the Mid-Dry season (see Figure 8.3), which contained the least percentage of light rainfall of any season (see Figure 8.1). However, the amount of light rainfall was approximately equal among the four months included in the Mid-Dry season (April, May, October, and November) as shown in Figure 8.1. This result indicates that a considerably high risk of crash occurrence exists during light rain events in relatively dry months of the year, and is depicted in Figure 8.3 by the relative proportions (% crashes/ % rainfall) for light rain, shown as percentages.

Figure 8.3 also shows that percentage of crashes relative to percentage of rainfall for moderate rain conditions decrease in dryer months while the relative percentage of crashes during heavy rain conditions slightly increase, comparing the Wet to Dry, and Warm to Mid-Dry seasons. This suggests that drivers may become more acclimated to driving in heavy rains during the wettest months of the year, resulting in fewer accidents. However, a larger dataset is needed to confirm this phenomenon.

Although the total number of recorded crashes was greater in the Dry season compared to the Wet season (see Table 8.1), the proportion percent illustrated in Figure 8.3, reveals that proportional to seasonal rainfall, the occurrence of an accident is more likely during the rainiest months of the year. This trend is also recognizable in the Warm season compared to the Cold and Mid-Dry seasons.

Statistical Analysis

A two-factor linear regression was performed to determine if rain intensity or rainfall

season significantly affected hourly crash occurrence. A natural log power transformation function was applied to the expected proportion percent value, with categorical values of one, two, and three assigned to the light rain, moderate rain, and heavy rain categories, respectively. For the semiannual rainfall seasons, categorical values of one and two were assigned to the Wet and Dry seasons, respectively. The regression analysis results for the twice-annual seasonal data is summarized in Table 8.3.

Table 8.3

Summary of regression analysis of seasonal crashes (two seasons)

Regression Analysis: Crash Proportion Percent versus Rain Category, Season						
ln (Proportion Percent) = 5.74657 – 1.20739 Rain Category – 0.42056 Season						
Term	Coef	SE Coef	*T*-stat	*p*-value		
Constant	5.74657	0.476525	12.0593	0.001		
Rain Category	-1.20739	0.145905	-8.2751	0.004		
Season	-0.42056	0.238263	-1.7651	0.176		
S = 0.291811	R-Sq. = 95.98%	R-Sq.(adj) = 93.30%				
R-Sq.(pred) = 81.46%	PRESS = 1.17737					
Analysis of Variance						
Source of Variation	DF	Seq SS	Adj SS	Adj MS	*F*-ratio	*p*-value
Regression	2	6.09642	6.09642	3.04821	35.7966	0.00806
Rain Category	1	5.83112	5.83112	5.83112	68.4777	0.00369
Season	1	0.26530	0.26530	0.26530	3.1156	0.17573
Error	3	0.25546	0.25546	0.08515		
Total	5	6.35189				

S = Standard deviation

As listed in Table 8.3, there is insufficient evidence to conclude that crash occurrence is significantly affected by season (Wet or Dry), indicated by a *p*-value of 0.176. However, a negative coefficient (-0.42) for the relative proportion percent does reflect the trend that, relative to rain exposure, fewer accidents occur in the Dry season, proportionally. Conversely, the effect of rain intensity on crash occurrence was significant at a 95% level of confidence as indicated by a *p*-value of 0.004. The negative coefficient (-1.21) for the Rain Category factor also indicates

that the percent of crashes relative to the percent of rainfall are expected to be fewer in Dry season than in the Wet season. The model was a reasonable fit to the analyzed proportion percentages shown in Figure 8.3.

Residual plots obtained from Minitab (2013) for the two-season combination analysis, shown in Figure 8.4, validate the results listed in Table 8.3 through the *Normal Probability, Residual Versus Fits*, and the *Residual Versus Order* plots. Although the dataset was small, overall, the model assumptions were satisfied.

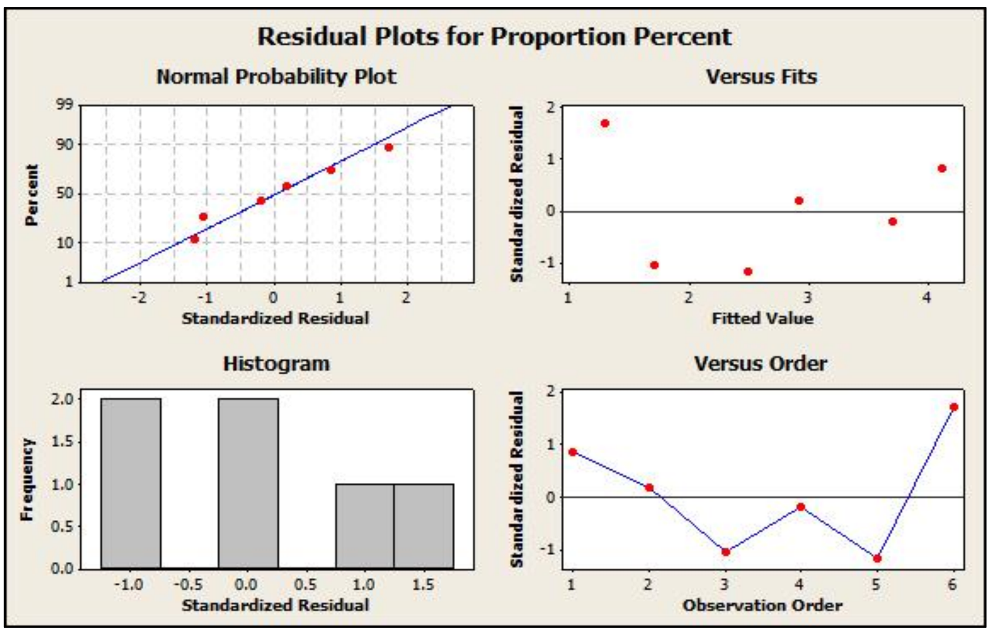

Figure 8.4. Residual plots for seasonal crashes regression analysis (two seasons).

Similar to the two-season statistical analysis, a two-factor linear regression analysis utilizing a power transformation model (lambda = 0.5) was performed on the three-season combination, summarized in Table 8.4. Categorical values of one, two, and three were assigned to the light rain, moderate rain, and heavy rain categories, respectively. Additionally, categorical values of one, two and three were assigned to the Warm, Cold and Mid-Dry seasons, respectively.

Indicated by a *p*-value of 0.064, there is insufficient evidence, at a .05 level of significance, that Season effects crash occurrence, based on the percentage of rainfall exposure. However, crash occurrence based on rain intensity exposure is statistically significant (*p*-value < 0.001). Negative coefficients of -0.157 and -0.035 for the Rain Category and Season factors, respectively, indicate that the relative percentage of crashes to percentage of rainfall decrease from rainy to dryer seasons. These results are consistent with the descriptive statistics shown in Figure 8.3.

Table 8.4

Summary of regression analysis of seasonal crashes (three seasons)

Regression Analysis: Crash Proportion Percent versus Rain Category, Season						
Proportion Percent^ -0.5 = 0.08193 – 0.15668 Rain Category – 0.03548 Season						
Term	Coef	SE Coef	*T*-stat	*p*-value		
Constant	0.08193	0.046188	1.7737	0.126		
Rain Category	-0.15668	0.015689	-9.9862	0.000		
Season	-0.03548	0. 015689	-2.2616	0.064		
S = 0.03843	R-Sq. = 94.59%	R-Sq.(adj) = 92.78%				
R-Sq.(pred) = 88.99%	PRESS = 0.01803					
Analysis of Variance						
Source of Variation	DF	Seq SS	Adj SS	Adj MS	*F*-ratio	*p*-value
Regression	2	0.15484	0.15484	0.07742	52.4198	0.000158
Rain Category	1	0.14729	0.14729	0.14729	99.7251	0.000058
Season	1	0.00755	0.00755	0.00755	5.1146	0.064410
Error	6	0.00886	0.00886	0.00148		
Total	8	0.16371				

S = Standard deviation

From the *Normal Probability, Residual Versus Fits*, and the *Residual Versus Order* residual plots obtained from Minitab (2013) for the three-season combination analysis, shown in Figure 8.5, the results listed in Table 8.4 were validated. Moreover, the prediction model listed in Table 8.4 also compares well to the percentage proportions analyzed in Figure 8.3.

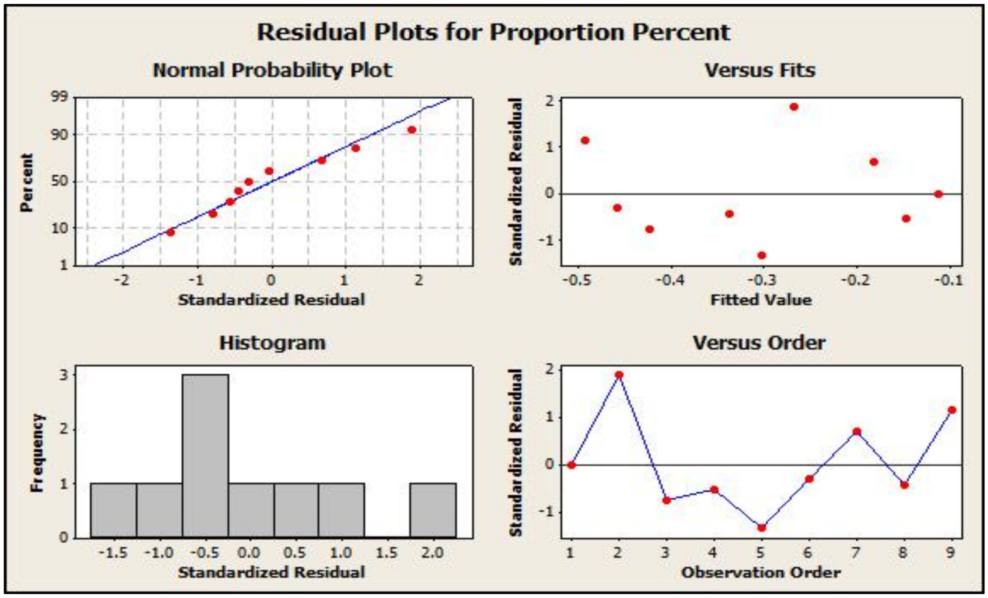

Figure 8.5. Residual plots of seasonal crashes regression analysis (three seasons).

Discussion of Results

The present study focused on weekday rainfall accumulation and crash data with the exclusion of weekend days and observed national holidays. This reduction of data was necessary to compare seasonal results with the preceding hourly exposure findings. Additionally, due to other factors such as unfamiliarity with the study routes and weather patterns, crash occurrences during days of optimal tourist travel (weekends and holidays) may skew the results, as observed by Satterthwaite (1975).

Although rainfall seasons for Northeast Florida are generally grouped into two annual seasons, Wet and Dry, (Rao et al., 1989), the distribution of monthly rainfall within each season may yield misleading results in the relative risk of crash occurrence. The three-season combination appeared to be more representative of the precipitation trends for rainfall during the four-year study period (2008-2011). However, statistical analyses of the two different seasonal groups revealed the same outcome. These findings agree with Satterthwaite (1975) that seasonal factors generally have little effect on crash occurrence.

Relative to seasonal rainfall, the percentage of seasonal crashes, decreased with increasing rain intensity. Contradictory to findings by Satterthwaite (1975), proportionally, the highest risk of an accident occurred during light rain conditions for both seasonal groups. However, there was a slight indication that crash occurrence increased with exposure to heavy rainfall in the dyer months of the year. From the three-season combination analyses, results appear to somewhat correlate with findings by Levine et al. (1995). Relative to exposure, more crashes occurred during rainy months than during dryer months.

Interestingly, preceding analyses based on hourly rain exposure (see Chapter 6) found the opposite result, where heavy rain yielded the greatest risk of crash occurrence, and light rain produced the lowest risk, yet also above dry conditions. Similar to previous studies (Eisenberg, 2004; Qin et al., 2006), these results highlight the variation in the outcome of analyses when the temporal unit of measure for rain exposure is more heavily aggregated into percent total accumulation over seasons.

CHAPTER 9 – RESULTS AND DISCUSSION: CRASH SEVERITY

Descriptive Analysis

An examination of crash severity, based on hourly exposure, found that, overall, accidents resulting in property damage only (PDO) dominated with higher occurrence proportions for 17 of the 24 hour-periods. Fifteen of the 17 hour-periods recorded primarily PDO crashes during dry weather conditions. While rain exposure hours were considerably fewer for each hour-period, the number of injury accidents were fairly consistent with the number of PDO crashes with the proportions of the two severity levels almost equal for the majority of hours. Further investigation based on daily time blocks of varying traffic conditions (see Table 6.1) confirmed this trend, illustrated in Figure 9.1. More or less, about 50% of collisions that occur during rainy conditions result in injuries. Rain exposure increased both injury and PDO crashes substantially for each traffic condition.

As shown in Figure 9.1, relative to dry weather exposure, PDO and injury crashes occurred two to over four times more often during rainy conditions, with daytime and nighttime uncongested hours exhibiting the highest relative increase. Although fatal crashes were evenly distributed among each traffic condition, the relationship between rainfall and crash occurrence could not be examined as only one of the 13 reported fatalities over the four-year study period (2008-2011) occurred during a rain event

Crash severity examined for the four-category model (no-rain, light, moderate, and heavy rain) indicates that the number of injury crashes per the number of heavy rain exposure hours is proportionally higher for all traffic conditions than accidents resulting in injuries during dry

weather, light rain, or moderate rain conditions, as illustrated in Figure 9.2. Interestingly, injury crashes were more predominant than PDO crashes during AM congested and daytime uncongested traffic conditions, while PDO crashes exceeded injury accidents during both the PM congested and nighttime uncongested traffic hours. The highest proportion of crashes that resulted in only property damage occurred during moderate and heavy rain events during evening peak traffic volumes. PDO crashes were also the primary crash type during nighttime hours when traffic volumes are the lowest.

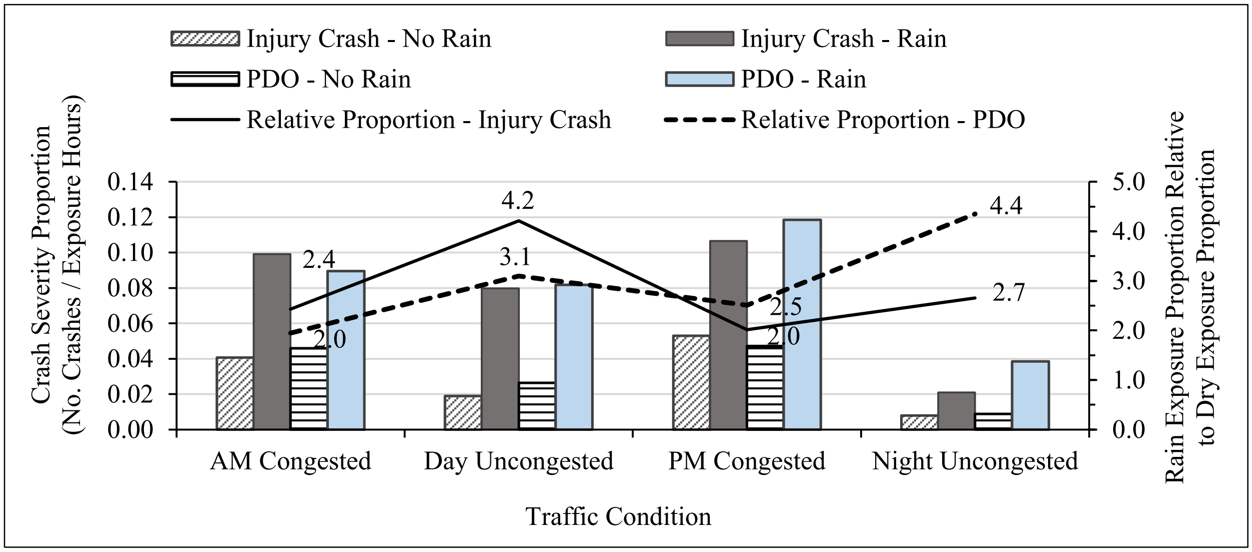

Figure 9.1. Crash severity relative to traffic condition (two rain categories).

Statistical Analysis

To determine if rainfall intensity and hour-of-day significantly affect crash severity (injury or PDO), a linear regression analysis was performed on a three-factor model (Rain Category, Crash Type, and Traffic Condition). Subgroups of Rain Category included light, moderate, and heavy rain, while Crash Type referred to injury and PDO crashes. Crashes resulting in fatalities could not be modeled due to the substantially low occurrence. Subgroups of Traffic Condition include the daily time blocks listed in Table 6.1 and shown in Figures 9.1

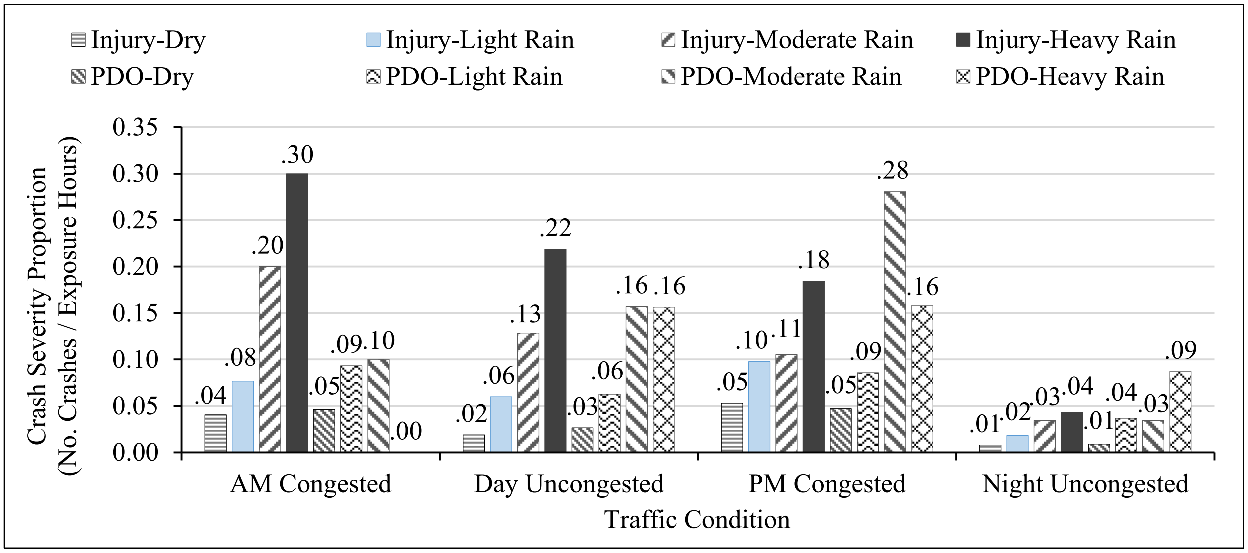

Figure 9.2. Crash severity proportion relative to traffic condition (four rain categories).

and 9.2. Categorical values were assigned to each subgroup features as follows: light rain (1), moderate rain (2), heavy rain (3), injury accident (1), PDO accident (2), AM Congested traffic (1), Day Uncongested traffic (2), PM Congested traffic (3), and Night Uncongested traffic (4). The regression results are summarized in Table 9.1.

As listed in Table 9.1, *p*-values less than 0.001 indicate that both rain intensity and traffic condition have a significant effect on crash severity proportions. However, rain intensity shows a positive coefficient of +0.09, in agreement with Figure 9.2. Although, the Traffic Condition factor shows a negative coefficient (-0.05), this simply indicates that the factor has a significant effect on crash severity as the categorical values increase from AM Congested (0) to Night Uncongested (4). Figure 9.2 graphically illustrates this point with the decrease in crash severity proportions from AM Congested to Night Uncongested traffic conditions.

The equation listed in the Table 9.1 also shows a negative coefficient for the Crash type (injury or PDO) factor (-0.02), yet this factor was not significant (*p*-value = 0.385). These results correspond with descriptive statistics illustrated in Figure 9.2. Moreover, Injury and PDO

accidents share similar frequencies during each traffic condition time block as shown in Figure 9.1. The regression analysis also exhibited a fairly high degree of linearity, indicating a positive linear relationship exists between rain intensity and crash proportions per traffic condition.

Table 9.1

Summary of regression analysis of crash severity (three rain categories)

Regression Analysis: Crash Proportion versus Rain Category, Crash Type, Traffic Condition

Crash Proportion^0.5 = 0.2989 + 0.0863 Rain Category – 0.0162 Crash Type – 0.0487 Traffic Condition

Term	Coef	SE Coef	*T*-stat	*p*-value
Constant	0.29891	0.03546	8.4278	0.000
Rain Category	0.08629	0.00832	10.3703	0.000
Crash Type	- 0.01627	0.01837	-0.8856	0.385
Traffic Condition	-0.04866	0.00810	-6.0058	0.000
S = 0.04754	R-Sq. = 86.13%	R-Sq.(adj) = 84.32%		
R-Sq.(pred) = 81.06%	PRESS = 0.07100			

Analysis of Variance

Source of Variation	DF	Seq SS	Adj SS	Adj MS	*F*-ratio	*p*-value
Regression	3	0.32288	0.32288	0.10762	47.604	0.000000
Rain Category	1	0.23710	0.24314	0.24314	107.543	0.000000
Crash Type	1	0.00423	0.00177	0.001773	0.784	0.384986
Traffic Condition	1	0.08155	0.08155	0.08155	36.069	0.000004
Error	23	0.05200	0.05200	0.00226		
Total	26	0.37489				

S = Standard deviation

Residual plots shown in Figure 9.3 validate these findings through the confirmation of the ANOVA assumptions for normality (Normal Probability Plot), equal variance (Residual Versus Fits plot), and independence (Residual Versus Order plot). From both the descriptive and inferential analyses, it appears that rainfall intensity is a leading factor in injury crashes.

Discussion of Results

Previous studies found positive relationships between injury occurrence and the number of accidents during rainy conditions (Sherretz & Farhar, 1978, Bertness, 1980). The present

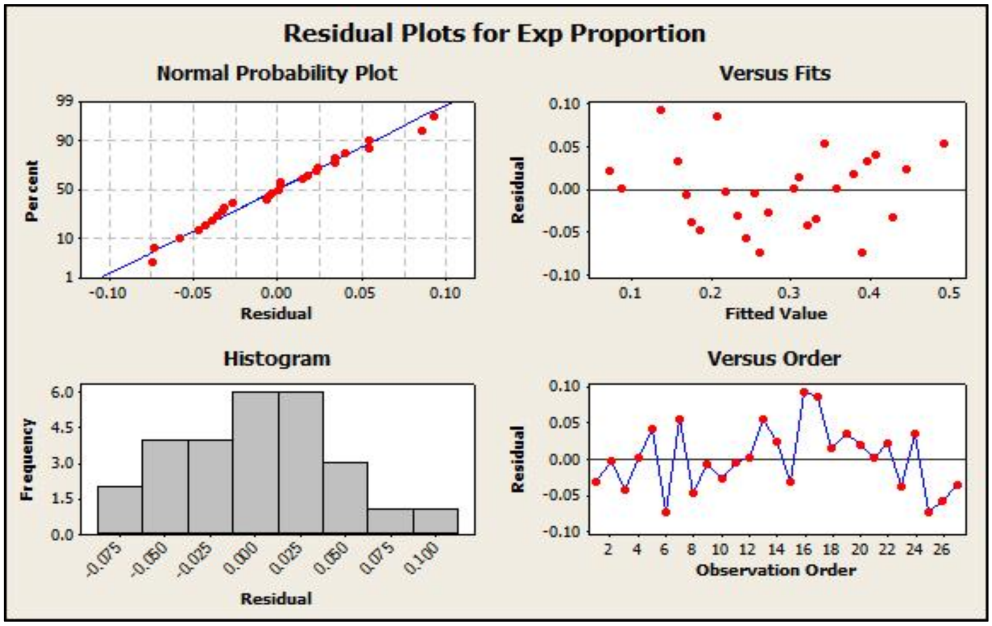

Figure 9.3. Residual plots of crash severity regression analysis.

study investigated the relationship between injury accidents and rain intensity.

Based on rain exposure, results from the present study found that injury accidents were the highest during morning heavy traffic volumes, with the proportion of injury crashes during PM congested hours nearly equal to midday proportions. These results somewhat differ from findings by Golob & Recker (2003) in a study of injury and PDO accidents for rainy versus dry conditions along six-lane freeways in Southern California. Golob & Recker (2003) argues that crash severity is influenced more by volumes than speeds, claiming that low to moderate traffic volumes where travel speeds are fairly constant increase the risk of injury accidents.

While this observation is in agreement with the proportions of injury accidents during daytime uncongested traffic conditions found in the present study, the higher injury crash proportions observed in both the AM and PM congested hours disagree with findings by Golob & Recker (2003). These differences may be explained by the consideration of rain intensity in the present analyses.

CONCLUSIONS

Understanding and quantifying driver response to inclement weather provides valuable insight for transportation planning and management. Although previous studies have addressed the effects of precipitation on various traffic parameters, areas of study have been for the most part limited to northern locations in the U.S. and Canada frequented by snow. Through the review of published literature it is evident that inclement weather effects driver behavior on freeway facilities by reducing travel speeds and increasing time headways.

Two freeway segments along interstates I-295 and I-95 in Jacksonville, Florida were selected to determine if driver responses during rainy weather conditions in the southeast region of the U.S. compare with findings by previous studies for northern regions of the U.S. Traffic and weather data was collected for a four-year study period and analyzed for the effects of rain on average travel speeds and traffic demands. Data was analyzed for general effects of wet weather using two categories (rain, no-rain), and for effects of various rain intensities (no-rain, light, moderate, and heavy rain) categorized using intensity classifications defined by the American Meteorological Society.

Through both descriptive and inferential analysis, results indicate that rain reduces travel speeds and traffic volumes along Florida freeways by comparatively different amounts than reductions observed in northern regions of the U.S. and Canada. A 95% confidence level of the mean reduction in speeds due to rain events was observed to be 1.8 to 2.8 mph for the I-295 study segment, and 1.3 to 3.5 mph for the I-95 segment, statistically significant reductions with *p*-values of 0.001 and less than 0.001 for I-95 and I-295, respectively. Hourly traffic volumes

were also affected by wet weather conditions. Findings indicate that at a 95% confidence level, average traffic demand was reduced by 6.7% to 12.2% vehicles per hour along I-295, and 2.6% to 9.7% vehicles per hour along I-95 under wet conditions. These reductions in hourly volumes are statistically significant as indicated by *p*-values of 0.006 and less than 0.001 for I-95 and I-295, respectively. Graphical analyses of the 95% confidence intervals also indicate fairly linear relationships exist between reductions in travel speeds or hourly volumes and rainfall intensity. While these findings add to overall knowledge of the subject, more research is needed at varying locations throughout the U.S. to better quantify the effects of inclement weather on traffic parameters, and to aide in better transportation management of freeway facilities during rainfall events.

Over the last half-century, a number of studies have been undertaken in an effort to quantify the effects of environmental exposures on accident occurrence and severity. However, little research pertaining to weather effects on crash occurrence in subtropical to tropical climate regions comparable to Florida exist. Moreover, studies conducted on freeways located in the lower southeast region of the U.S. were not found among published literature. The present study examined crash occurrence and severity, based on rain exposure and hour-of-day. A 10.5 mile freeway section along Interstate I-295, and a five mile section along Interstate I-95 in Jacksonville, Florida were selected to determine if crash occurrence and crash rates per 100 Million VMT were affected by rainy weather conditions and hour-of-day.

Results from both descriptive and inferential analyses indicate that during rain events, mean hourly crashes relative to the number of rain exposure hours increase along Florida freeways by as much as 2.7 times greater than during dry weather conditions (p-value < 0.001). Additionally, at a 95% confidence level, rainfall intensity presents statistically significant

increases in hourly crashes (p-value < 0.001) with positive coefficients of +0.14, +0.28 and +0.42 for light, moderate, and heavy rainfall, respectively. However, at a .05 level of significance, there was insufficient evidence (p-value = 0.406) to conclude that hour-of-day has a significant effect on hourly crash occurrence, based on rain exposure.

Crash rates per 100 MVMT increased during all rainfall amounts with positive coefficients of +0.87, +1.73, and +2.47 for light, moderate, and heavy rainfall, respectively, and up to 2.6 times greater during general rainy conditions compared to dry weather. Results were statistically significant at 5% (p-value < 0.001). Unlike hourly crash occurrence, at a .05 level of significance, crash rates per 100 MVMT were significantly affected by hour-of-day (p-value of 0.00).

Crash severity was examined for daily time blocks of varying traffic conditions. Rain exposure increased both injury and PDO crashes substantially for AM and PM congested hours, and daytime and nighttime uncongested traffic hours. From descriptive statistics, relative to dry weather exposure, crashes occurred two to over four times more often during rain, with daytime and nighttime uncongested hours exhibiting the highest relative increase. Crash severity proportions were significantly affected by rain intensity (p-value < 0.001) with the highest proportions of injury crashes occurring during AM congested and daytime uncongested traffic conditions. PDO crashes were predominant during evening peak volume hours and nighttime uncongested traffic hours.

To investigate seasonal effects on crash occurrence, weekday crash data over a four-year study period (2008-2011) was analyzed using aggregated monthly precipitation amounts for the annual Wet and Dry rainfall seasons typical to Northeast Florida. Two alternative rainfall seasons related to agricultural interests, Warm and Cold, were also examined with the addition of

a Mid-Dry season to represent the months between the two growing seasons. Descriptive and inferential statistics revealed that crash occurrence increased for all amounts of rainfall with the highest increase during light rain events. The percentage of crashes relative to the percentage of increased rainfall was statistically significant with *p*-values of 0.004 and less than 0.001 for the two-season and three-season combinations, respectively. However, at a .05 level of significance, there is insufficient evidence to infer that Season affects crash occurrence in either the two-season (p-value = 0.176) or the three-season (p-value = 0.064) annual seasonal combinations.

Although the effects of rainfall on traffic safety and operation elements realized in the present study varied significantly from previous studies, this research was beneficial in adding to the body of knowledge on the subject, with both regional and climatic value. Quantifying the effects of rain and rainfall intensity on freeway travel speeds, traffic volumes, and crash occurrence, especially for regions with different climate conditions, may offer insight in the development of better prediction models. However, more research is needed to fully understand the effects of rain on traffic elements.

LIMITATIONS AND RECOMMENDATIONS

Efforts were made in this study to reduce both temporal averaging and spatial variability of weather exposure, inherent in any study involving weather data, by using the smallest time period (hours) available to conduct the analyses. However, it is recognized that in order to accurately measure weather exposure influences on traffic variables and safety issues such as crash occurrence and crash severity, better weather reporting systems are needed. The implementation of weather collection stations placed along high-speed corridors could greatly improve the quest for enhanced data. Data collected from weather sensors accompanied by traffic sensor data would allow for smaller exposure intervals to be used in analyses. This may lead to a better understanding of the effects of varying weather conditions on crash events and traffic variables along U.S. freeways. Additionally, smaller temporal units of measure may provide a better portrayal of the degree to which traffic variables, such as travel speeds and traffic volumes, affect crash events.

Future research should be conducted to explore to the validity of weather data collected from nearby weather stations often used in studies involving factors of weather exposure. Video data collected in the field during varying weather conditions may offer a good comparison, and may also be used to verify the accuracy of traffic sensor data during all weather conditions. A comparison of weather station rain-gage based data with radar data used in some areas also would be beneficial in identifying the best weather data source.

Results from the present study analyses of rain effects on traffic demand indicate that hourly traffic volumes reduce on Florida freeways with increasing rain intensity. It was also

observed that rainy conditions and varying rainfall amounts tend to widen and somewhat shift morning and evening peak-volume hours, especially as rain intensity increases. Future research is needed to examine of this phenomenon.

Because precipitation at any location can exhibit a fair degree of spatial variability, it is possible that rain may not have been present at the actual time a vehicle accident occurred. Although weather conditions reported on the crash reports and subsequently entered into the CARS database was examined for accordance with the weather station data, future exploration is needed to adequately compare crash report and collected weather data.

From the findings in this study, it was observed that increases in the risk of hourly crash occurrence relative to dry conditions and crash rates per 100 million vehicles miles of travel relative to dry conditions were considerably greater during nighttime hours, as well as, during the hours just prior to AM peak traffic volumes and just after PM peak traffic volumes. Since sunset and sunrise varies throughout the year, the change in lighting conditions, more specifically the change between dusk or dawn and nighttime, may pose a factor in crash events during these times of day. Hours of the day affected by daylight savings time may also skew results when data is combined into daily time blocks. Visibility factors such as lighting conditions were beyond the scope of the present research, and generally have not been widely investigated in previous studies. Future research is needed to examine if lighting conditions have a significant effect on hourly crash occurrence, crash rates, and travel speeds.

Other visibility factors, such as vehicle spray from wet pavement, was not analyzed in the present study. Moreover, visibility data (in miles) retrieved from the weather station, NAS Jax, was unclear as to what height the data referred. If the weather station visibility data was intended for use primarily for aviation purposes, it may be inappropriate for transportation

studies which focus on the height of a driver's eye. Future research should be conducted to investigate visibility recording processes and procedures employed at various weather collection stations, as well as, the effects that visibility factors may have on elements of traffic safety and operations.

A key obstacle in comparing findings from the present study to previous research was the rainfall amounts used to define the rain intensity classifications among published literature. The present study used rain intensity classifications defined by the American Meteorological Society, in part, to enable comparisons with previous studies. Therefore, it is suggested that future transportation research involving precipitation consider this issue when establishing weather data aggregation parameters. Consistency in rainfall ranges when referring to light, moderate, heavy, and very heavy rain classifications in future studies would be beneficial to researchers, thus minimizing variances and allowing for more meaningful comparisons among findings.

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PUBLLICATIONS

Angel, M., Sando T., Chimba D., Kwigizile, V. (2014) "Effects of Rain on Traffic Operations on Florida Freeways" *Transportation Research Record, Journal of The Transportation Research Board.* Expected 2014.

FELLOWSHIPS

AASHTO Transportation Research Fellowship, Spring 2014