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Safety Evaluation of Roadway Lighting Illuminance Levels and its Relationship with Nighttime Crash Injury Severity for West Central Florida Region

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Safety Evaluation of Roadway Lighting Illuminance Levels and its Relationship with Nighttime Crash Injury Severity for West Central Florida Region

by

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DEDICATION

I would like to dedicate this work to my two wonderful children, Fabian E. González-Cortés and Diego A. González-Cortés who have been with me and who have supported me all these years. To my wife Michelle Y. Cortés-Salvá who has always supported me to continue my career and to never give up. I also want to thank my parents, Maria del C. Vélez-Arroyo and Enrique González-González, for all their continued support. Last, but not least, I would like to thank God.

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ABSTRACT

The main role of roadway lighting is to produce quick, accurate and comfortable visibility during nighttime conditions. It is commonly known that good lighting levels enable motorists, pedestrians and bicyclists to obtain necessary visual information in an effective and efficient manner. Many previous studies also proved that roadway lighting minimizes the likelihood of crashes by providing better visibility for roadway users.

Appropriate and adequate roadway lighting illuminance levels for each roadway classification and pedestrian areas are essential to provide safe and comfortable usage. These levels are usually provided by national, or local standards and guidelines. The *Florida Department of Transportation (FDOT) Plan Preparation Manual* recommends a roadway lighting illuminance level average standard of 1.0 horizontal foot candle (fc) for all the roadway segments used in this research. The *FDOT Plan Preparation Manual* also states that this value should be considered standard, but should be increased if necessary to maintain an acceptable uniformity illuminance ratio.

This study aimed to find the relationship between nighttime crash injury severity and roadway lighting illuminance. To accomplish this, the research team analyzed crash data and roadway lighting illuminance measured in roadway segments within the West Central Florida Region. An Ordered Probit Model was developed to understand the relationship between roadway lighting illuminance levels and crash injury severity. Additionally, a Negative Binomial Model was used to determine which roadway lighting illuminance levels can be more beneficial in reducing the counts of crashes resulting in injuries.

A comprehensive literature review was conducted using longitudinal studies with and without roadway lighting. Results showed that on the same roadways there was a significant decrease in the number of nighttime crashes with the presence of roadway lighting. In this research, roadway lighting illuminance was measured every 40 feet using an Advanced Lighting Measurement System (ALMS) on a total of 245 centerline miles of roadway segments within the West Central Florida Region. The data were mapped and then analyzed using the existing mile post.

During the process of crash data analysis, it was observed that rear-end collisions were the most common first harmful event observed in all crashes, regardless of the lighting conditions. Meanwhile, the average injury severity for all crashes, was found to be possible injury regardless of the lighting conditions (day, dark, dusk, and dawn).

Finally, this research presented an Ordered Probit Model, developed to understand the existing relationship between roadway lighting illuminance levels and injury severity within the West Central Florida Region. It was observed that having a roadway lighting

average moving illuminance range between 0.4 to 0.6 foot candles (fc) was more likely to have a positive effect in reducing the probability of injury severity during a nighttime crash. A Negative Binomial Model was conducted to determine if the roadway lighting average moving illuminance level, found on the Ordered Probit Model was beneficial in reducing crash injury severity during nighttime, would also be beneficial in reducing the counts of crashes resulting in injuries. It was observed that a roadway lighting average moving illuminance, range between 0.4 to 0.6 fc, was more likely to reduce the count of crashes resulting in injuries during nighttime conditions, thus increasing roadway safety. It was also observed that other factors such as pavement condition, site location (intersection or no intersection), number of lanes, and traffic volume can affect the severity and counts of nighttime crashes.

The results of this study suggest that simply adding more roadway lighting does not make the roadway safer. The fact is that a reduction in the amount of roadway lighting illuminance can produce savings in energy consumption and help the environment by reducing light pollution. Moreover, these results show that designing roadway lighting systems go beyond the initial design process, it also requires continuous maintenance. Furthermore, regulations for new developments and the introduction of additional lighting sources near roadway facilities (that are not created with the intent of being used for roadway users) need to be created.

CHAPTER 1: SUMMARY

From 2006 to 2008 there were over 32,000 fatal crashes reported in the United States. The percentage of fatal crashes that occurred during dark lighting conditions was roughly 47 percent. Florida reports showed over 2,700 fatal crashes. That represented nearly eight percent of the nationwide fatalities. Over 50 percent of those crashes in Florida occurred during dark lighting conditions. It has been proven that the presence of roadway lighting minimizes the likelihood of crashes by helping drivers obtain sufficient visual information. Furthermore, roadway lighting supplements vehicle headlights. A comprehensive literature review was conducted using longitudinal studies with and without roadway lighting. Results showed that on the same roadways there was a significant decrease in the number of nighttime crashes with the presence of roadway lighting. In addition, it was noticed that continuous roadway lighting illuminance data collection and analysis had not been previously performed due to limitations on traditional roadway lighting illuminance measurement procedures. It was also observed that with the introduction of new roadway lighting illuminance, drivers were more likely to increase their driving speed and reduce their concentration.

1.1 Objectives

The objective of this research was to determine and understand the existing relationship between nighttime crash injury severity and roadway lighting illuminance levels. This research includes an Ordered Probit and a Negative Binomial Model for the analysis of crash data and illuminance levels measured for roadway segments within the West Central Florida Region.

1.2 Data Collection Overview

The criteria used for the selection of the roadway segments for this research was based on an analysis conducted by Florida Department of Transportation (FDOT) District Seven in which they identify 37 segments with higher nighttime crash activity and the need for information related to roadway lighting illuminance levels. These 37 segments correspond to approximately 245 centerline miles of roadway lengths.

An Advanced Lighting Measurement System (ALMS) was used to collect continuous roadway lighting illuminance levels in an efficient, safe, and effective manner. This system was developed at the Center for Urban Transportation Research (CUTR) and funded by FDOT.

Crash data was obtained from FDOT's Crash Analysis Reporting System (CARS). A three-year time frame, from 2005 to 2008, was selected for the analysis. This specific time frame was selected based on the years in which the roadway lighting illuminance measurements were collected (2007-2008). For the scope of this research only nighttime crash data were utilized for the analysis and development of the models.

1.3 Selected Conclusions

Roadway lighting illuminance levels were measured every 40ft using ALMS on a total of 245 centerline miles of roadway segments within the West Central Florida Region. The field measurements were paired with crash data reports for the study area. During the process of crash data analysis, it was found that the primary first harmful event in a crash, regardless of the light condition was a rear-end collision. However, the average injury severity for all crashes, within the scope of this research, was found to be possible injury for all four light conditions (day, dark, dusk, and dawn).

An Ordered Probit Model was developed to investigate how roadway lighting illuminance levels and other roadway factors affect the injury severity on crashes during nighttime conditions. Meanwhile, a Negative Binomial Model was developed to investigate how roadway lighting illuminance levels and other roadway factors affect the probability of the occurrence of crashes resulting in injuries during nighttime conditions. These two models were developed for the analysis of all nighttime crashes and for rear-end nighttime crashes. Based on the models, the following results were obtained:

- It was identified that a roadway lighting illuminance average moving level between 0.4 to 0.6 fc seems beneficial in reducing the likelihood of crashes resulting in injury severity and also the likelihood of being involved in nighttime crashes resulting in injuries.
- With the reduction of roadway lighting illuminance levels, other aspects such as light pollution (glare, lighting trespass, and sky glow) can be alleviated.

- Additional to the mitigation of lighting pollution problems, the reduction of roadway lighting illuminance levels can offer benefits such as economic savings on energy consumption.

- With the evaluation of roadway lighting illuminance levels on approximately 245 center line miles of roads, FDOT saved an excess of $1 million.

1.4 Selected Recommendations

- The results from the Ordered Probit and Negative Binomial Models can be used to select appropriate countermeasures that can help decrease the likelihood of injury severity and at the same time the number of crashes resulting in injuries during nighttime conditions.

- The development of guidelines, standards and regulatory documentation to monitor and evaluate how the introduction of additional lighting (lighting designed for business site facilities, business electronic signs, electronic billboard, etc.) affects the safety of roadway facilities needs to be created.

- More evaluation and maintenance programs for existing roadway facilities and roadway lighting illuminance need to be continuously performed.

CHAPTER 2: INTRODUCTION

Fixed roadway lighting's core role is to achieve a visibility level that enables motorists, pedestrians and bicyclists to see quickly, clearly, and with confidence all of the roadway's important details. Roadway lighting minimizes the likelihood of crashes by helping drivers obtain sufficient visual information.

The most important consideration for the introduction and installation of roadway lighting is that it needs to provide the same usefulness to all roadway streets and highway facilities during nighttime as well as during the daytime. Proper use of roadway lighting as an operational tool provides economic and social benefits to the general public, including reduction in the number of nighttime crashes. Furthermore, roadway lighting supplements vehicle headlights and at the same time can provide other side benefits that include civic beautification, and crime reduction. Additionally, roadway lighting can promote business activities and use of public facilities during nighttime hours.

It has been proven that unlit roadways increase the risk for motorist, pedestrian and bicyclist fatalities due to a decrease in their visual distance. The nighttime fatal crash rate on unlit roadways is about three times that of the daytime rate, based on proportional vehicular distance traveled *(1)*.

2.1 Background

In 2008, there were 34,017 fatal crashes that occurred in the United States of which 5,282 involved pedestrians and pedal-cyclists (non-motorist), representing 15 percent of all fatalities. During dark light conditions 16,051 fatalities were reported, representing 48 percent of the nationwide total. At the same time in 2008, Florida reports showed 2,760 fatal crashes of which 630 were non-motorist users. This number represented 8 percent of the total fatal crashes, and 12 percent of non-motorist users in relation to nationwide fatality statistics *(2)*. The number of fatalities for non-motorists in Florida represents 21 percent of all fatalities. Any research that can be conducted to make a significant reduction in the number of fatalities during dark light conditions deserves attention.

Appropriate and adequate illuminance lighting levels for roadway segments or pedestrian areas are essential for safe and comfortable usage. In some cases, the roadway lighting illuminance levels for those segments are not appropriate for the comfort and safety of the users *(3)*. The *FDOT Plan Preparation Manual (4)* establishes a standard average illumination level of 1.5 foot candle (fc) for interstate, expressway and major arterials, and requires a 4:1 or fewer uniformity ratio average/minimum, and 10:1 or fewer uniformity ratio maximum/minimum. For all other roadways the manual requires 1.0 fc as a standard average on illumination level. Pedestrian ways and bicycle lanes require a 2.5 fc with the same uniformity ratio as interstate, expressway and major arterials.

Table 1 Florida DOT Lighting Criteria

Roadway Classification	Illumination Level Average Initial Horizontal Foot Candle (H.F.C.)	Uniformity Ratios		Veiling Luminance Ratio
		Lavg/Lmin	Lmax/Lmin	Lv(max)/Lavg
Interstate, Expressway, Freeway & Major Arterials	1.5	4:1 or Less	10:1 or Less	0.3:1 or Less
All Other Roadways	1	4:1 or Less	10:1 or Less	0.3:1 or Less
*Pedestrian Ways and Bicycle Lanes	2.5	4:1 or Less	10:1 or Less	

* This assumes a separate facility. Facilities adjacent to a vehicular roadway should use the levels for that roadway. (Source: *Florida Plans Preparation Manual*, Volume 1 – English (Revised - January 1, 2011) Table 7.3.1*(4)*)

2.2 Research Objective

This study aimed to find the relationship between nighttime crash injury severity and roadway lighting illuminance by analyzing crash data and the measured illuminance of roadway segments within the West Central Florida Region. An Ordered Probit Model was developed to understand the relationship between roadway lighting illuminance levels and crash injury severity. Additionally, a Negative Binomial model was used to determine which roadway lighting illuminance level can be more beneficial in reducing the counts of crashes resulting in injuries. These two models were developed for the analysis of all nighttime crashes and for rear-end nighttime crashes.

2.3 Outline

This dissertation contains eight chapters, with a reference and an appendix section. Chapter 1 provides a summary of the research with the inclusion of selected conclusions and recommendations. Chapter 2 provides an overview of the research problem and the research objective. Chapter 3 presents a comprehensive description of previous studies and related topics for the research subject. Chapter 4 summarizes the techniques applied in this project, which includes a detailed description of the proposed methods and basic concepts using an in-data analysis procedure. Chapter 5 talks about the data collection process, and describes the procedures for the data collection and reduction. Chapter 6 presents the model results for the Ordered Probit and Negative Binomial Models. Chapter 7 presents the conclusions and recommendations. Finally, Chapter 8 presents the future research. A list of references follows the final chapter. An appendix follows the references section.

CHAPTER 3: LITERATURE SEARCH AND REVIEW

There is reliable information available that supports the assumption that crash rates are considerably higher at night. Twenty-five percent of vehicle-miles traveled occur at night, and nearly 50 percent of fatalities happen during those hours. The nighttime fatality rate is three times that of the daytime rate *(5)*. If nighttime rates can be moved toward lower numbers, this could save many lives and save society the associate costs for those fatalities.

3.1 Roadway Illuminance Levels and Pedestrian Crashes

A study conducted by the Metropolitan Orlando Bicycle and Pedestrian Program presented an investigation of 617 pedestrian-vehicle crashes from 1993 to 1999. Fifty-three percent of those crashes took place at night with an even distribution between lit and unlit roads. The mid-block location was found to be the location with the highest number of crashes when compared to non-signalized and signalized intersections *(6)*.

Spainhour et al. in 2005, studied three years (1998 – 2000) of Florida crash data to evaluate the causes of fatal traffic crashes and traffic fatalities. A total of 2,080 cases were evaluated. It was found that 71 percent of pedestrian crashes occurred at night; for the cases involving pedestrians not crossing at intersections the percentage increased to over 80 percent. In general, it was found that pedestrian fatalities were almost three times more likely to occur in dark conditions than daylight *(7)*. To address this problem the author mentions as countermeasure the increase of illuminance level for highway lightings in order to improve the visibility in areas with high pedestrian and bicycle activities.

Sullivan and Flannagan conducted a study to estimate the influence of ambient light levels on fatal pedestrian and vehicle crashes on dark roads *(8)*. Three scenarios were selected and eleven years of fatal crashes (1987 to 1997) in the United States were analyzed. The next figure shows the effects of lighting conditions and the number of crashes for each scenario (Source of images: *The Role of Ambient Light Level in Fatal Crashes: Inferences from Daylight Saving Time Transitions (8)*).

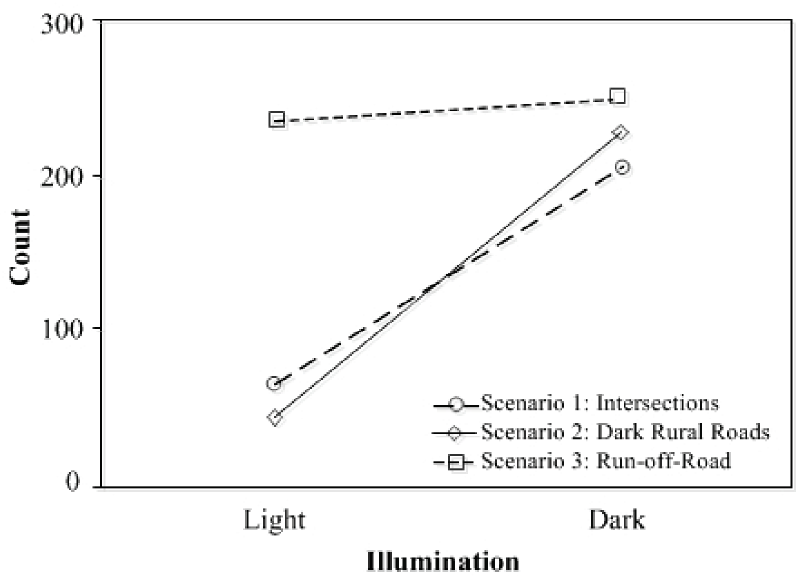

Figure 1 Effect of Ambient Light on Crash Count

It can be seen in scenarios 1 and 2, the strong, significant effect that roadway lighting has on the number of fatal pedestrian crashes. This indicated that pedestrians may be three to almost seven times more vulnerable of being involved in fatal crashes during dark conditions than in daylight.

Siddiqui et al. *(9)* presents a study where a multivariate regression analysis is performed to see how the crossing and light conditions may influence pedestrian injury severity. They found that street lighting reduces the probability of fatal injuries by 42 percent at mid-block locations and by 54 percent at intersections. These results clearly indicate that improvements to the nighttime driving environment could reduce nighttime crash rates.

Other studies *(10)* analyze the impact of street lighting improvement on crime and the fear of crime on urban street and pedestrian footpaths. A before and after study based on a pedestrian survey was the method applied for the analysis. This study found that street lighting improvements reduce crime, and increase pedestrian street use after dark.

In summary, these studies established that fatal crashes are more likely to occur during nighttime hours, and nonfatal crashes are more likely to occur during daytime hours. From previous research the most widely used countermeasure to improve the safety of pedestrian is the improvement (increase) of roadway illuminance lighting levels. Therefore, better lighting decreases the probability of nighttime pedestrian crashes by approximately 48 percent.

3.2 Roadway Illuminance Levels and Vehicle Crashes

In studies conducted in different countries, research shows there is a 20 to 30 percent reduction in nighttime crashes after roadway lighting is installed. In a research study conducted in Southern Finland, where road lighting was cut in half, there was a 13 percent increase in observed crash rates. Meanwhile, a total elimination of roadway lighting resulted in a 25 percent increase in crash rates *(11)*.

Previous studies performed by Hasson and Lutkevich showed the relationship between urban freeway lighting and highway safety evaluation. However, the majority of those studies were conducted in the 1960s and early 1970s. The change in traffic flow, composition and other factors in the past 30 to 40 years on nation's highways can make those previous results outdated *(12)*.

Box, in 1972 *(13)* presented the results of a roadway lighting study completed in 1970 in Syracuse. The purpose of his project was to determine the type, amount, and priority of roadway lighting needed to reduce nighttime vehicle and pedestrian crashes. The economic impact of upgrading the city lights to national standards was analyzed. As part of his study, road streets were classified as major streets (for streets with volumes of more than 5,000 vehicles per day), collector streets (volumes between 2,000 and 5,000 vehicles per day), and local streets (for volumes less than 2,000 vehicles per day). The study covered 105 miles, limited to major and collector streets only.

For this study only partial illumination was collected, and not a total measurement of actual illumination was performed for all the segments. The results showed that those streets with little or with no illumination had substantially higher night-to-day crash ratios, and cost ratios. This means that poor or inadequate lighting illumination contributes to a higher risk of being involved in crashes. The type of road was found to be more of a contributing factor for a crash than the land use. Finally, it was also observed that streets with higher illumination levels were having higher night-to-day crash ratios, and cost ratios than the average group.

In 1976 Box *(14)* presented a study conducted in November of 1974 where 130 lamps were turned off on a segment (2.5 miles) of State Highway 60, Gulf to Bay Boulevard, in Clearwater Florida. The roadway section analyzed included six major (major cross streets) and 22 minor (local or collector cross street) intersections, for one year before and after the study. The average illuminance was measured before, obtaining a 1.8 HFC, and after (0.9 HFC). The recommended level for the segment for that particular time was 1.4 HFC (source American National Standard Practice for Roadway Lighting, Illuminating Engineering Society, 1972). Crash data was tabulated to make an analysis and to compare intersection and mid-block location's injury severity vs. injury type. For the analysis a Poison distribution analysis was used; also a chi-square test was applied.

The research found that day crashes increased by 4 percent and night crashes increased as much as ten times, with an increase of 2.5 percent in traffic volume between the two year study periods. Day injury crashes dropped slightly and night injuries increased substantially. Crash rates changed from 9.5/million vehicles miles (MVM) of travel to 10.3/MVM. Night crash rates change from 7.7/MVM to 10.5/MVM, representing an increase of 36 percent. Before the reduction of light levels, Gulf-to-Bay reported 20 percent of crashes occurring at night. After the reduction was observed, they reported 25 percent, representing a significant increase of 5 percent on crashes.

Walker *(15)* conducted a crash frequency for rural at grade intersections analysis for a three years period immediately before and after lighting installation in 1976. Forty-seven (47) intersections were selected for this analysis. Variables such as raised channelization, a primary route turning at the intersection, and the difference between three-leg and four-leg intersections were examined.

Analysis of variance was used for the overall situation as it pertains to the effects of lighting and time of day. Also, the average rate before and after lighting was used (crash/million entering vehicle (MEV)). Intersections were divided by the number of lights in to three groups: 3 to 5 lights, 6 to 9 lights, and 10 to 15 lights. Average daily traffic was divided in to six groups: lower than 2,500; 2,500 to 2,999; 3,000 to 3,499; 3,500 to 4,399; 4,400 to 5,699; 5,700 and higher.

At the end of the study, the rate of crashes was reduced from 1.89 to 0.91 crash/million entering vehicle, representing a significant reduction of 52 percent. In general, lighting significantly reduced the number of night crashes at average daily traffic levels above 3,500.

Richards *(16)* presented a study in 1973 where continuous roadway lighting on Southbound main lanes of Interstate 35 through Austin, Texas were turned off for a length of 7.2 miles. Crash data were obtained from the Austin Transportation Department and were evaluated for a period of two years before and after the study. Also, an average cost was obtained from the National Safety Council (1972) for each crash.

For the analysis, a crash rate (crash/million vehicle miles) was used and a crash cost was calculated and compared to the energy saving cost. It was observed that a substantial cutback in roadway lighting on urban and suburban freeways may not be satisfactory energy conservation measured. The savings in electricity ($2,500/year) were offset to a large extent by a significant increase in crash frequency and injury severity ($17,000/year).

Lamm *(17)* analyzed a suburban freeway area West of Frankfurt, Federal Republic of Germany from 1972 to 1981. The geometry information and the crash reports filed by the police were obtained. The freeway segment was divided into three subsections; two lit and one unlit for parallel study. The investigation period was also divided into three periods, from 1972 to 1981. The crash rates were used and defined as crashes per 106 vehicle kilometers travelled (VKT).

This study revealed a positive effect of roadway lighting as a counter measurement for reducing nighttime crash rates. Partial lighting for energy conservation purposes was not a good measure due to the increase of crash rates after switching lights off at night between the hours of 10:00 pm to 5:30 am.

Elvik *(18)* analyzed 37 studies containing 142 results evaluating the safety effects of public lighting. The data presented in this report as part of the analysis included the number of nighttime crashes before, or without lighting, the number of nighttime crashes after, or with lighting, the number of daytime crashes before, or without lighting, number of daytime crashes after, or with lighting, and an estimate of the effect of lighting on road safety, among others.

A meta-analysis was used to estimate the safety effect of roadway lighting. For the meta-analysis three investigations were applied; first, the funnel graph method was used for the analysis of bias. Second, a funnel pattern analysis was used for the true mean safety effect. Finally, changes in the odds ratio based on the number of crashes and based on crash rates were observed for comparability of measurements effects.

Changes in crash rates were found to accurately predict changes in the number of crashes associated with the introduction of roadway lighting. All the studies were performed in different decades yielding similar results. Moreover, studies were performed in different countries yielding similar results. The following safety effects of roadway lighting were found: a 65 percent reduction in nighttime fatal crashes, a 30 percent reduction in nighttime injury crashes, and a 15 percent reduction in nighttime property-damage-only crashes.

In 1999 Assum *(19)* presented a study in which he used a hypothesis that drivers will not adjust their behavior; specifically drivers are not expected to increase their speed, reduce their concentration or travel more when road lighting is installed. In other words, drivers would not adapt their use and their behavior due to the presence or addition of roadway lighting. Data on drivers' behavior, including speed and concentration were collected during darkness hours on a section of Route E18 in Southern Norway, before and after roadway lighting was installed in December of 1994. Speed was measured by radar detectors for three weeks before and four weeks after the installation of roadway lighting. Drivers' concentration was measured by two different methods: by interviewing using a questionnaire and by video registration of the lateral displacement of the vehicle's position while driving.

A quasi-experiment, explicitly done before and after the study, with controls, was applied. The speed data from the radars were averaged for each hour during the whole duration of the study. The changes in speed from before to after installation of roadway lighting were evaluated by two analysis of variance models. The first was a two times two (2 x 2) analysis of variance, where the repeated measures factor was measured on the same day, daylight vs darkness, and between groups, pre-lighting vs. post-lighting. The second model was also a 2 x 2 analysis with pre vs. post as the between groups' factor, but in this case the repeated measures factor was control vs. experimental road sections.

The results showed that the highest speed occurred during darkness after the installation of road lighting and the concentration, measured by changes in lateral position, was lowest under the same conditions. This indicated that there is individual compensation for road lighting both in terms of speed and concentration.

Jorgensen *(20)* used Assum's 1999 data and results to try to develop an economic model of drivers' behavior. Assum did not measure what implication the installation of roadway lighting had upon the crash rate.

An economic model of drivers' behavior was utilized by Jorgensen. An assumption of the model was that the driver is a subjective utility maxi-miser with speed and concentration levels as decision variables. When no queue exists, it is easy to accept that the driver controls speed. Secondly, the model assumes that the driver is risk neutral. The last critical assumption of the model was that the costs for the driver were of an increased safety effort due to increased concentration, comes from increased time cost per unit of time. High concentration limits the driver's possibilities to enjoy other activities while driving, such as radio/stereo listening and talking to passengers.

Using an economic model of drivers' behavior, some empirical findings can be observed about the installation of road lighting. These findings included an increase in the drivers' measured average speed, a decrease in the drivers' measured concentration level, and a decrease in drivers' crash rates.

Isebrands *(21)* conducted a study to evaluate the effectiveness of reducing nighttime crashes by the installation of roadway lighting at rural intersections. For this research both a comparative, and before and after statistical analyses was used. The intersection attribute dataset used for the comparative analysis and crash data were provided by the Minnesota DOT Office of Traffic, Security and Highway System Operations. A total of 3,622 rural intersections were selected. Average daily traffic (ADT) was available by approach in the intersection attribute database. For the before and after study evaluation of crash data, information for 34 lit intersections were available. A Poisson Regression Model was used to model the nighttime crash rate. A Linear Regression Model was used to evaluate the reduction in the ratio of night to total crashes.

Unlit intersections had a ratio of night-to-total crashes 27 percent higher than lit intersections. These findings suggest that lighting does have an impact on crashes at rural intersections. The actual night crash rate was 3 percent lower at lit intersections; however, analysis results showed that the mean night crash rate at lit intersections was not statistically significant from lit intersections. The day crash rate, however, was 22 percent higher at lit intersections than unlit intersections and was statistically significant at the 10 percent significance level. The night crash rate was twice as high as the day crash rate at unlit intersections and only 1.43 times higher at lit intersections. Intersections with all legs having posted approach speeds equal to 55 mph had night crash rates that were 43 percent higher than approaches with at least one leg less than 55 mph. Intersections with four approaches had night crash rates 17 percent higher than three approach intersections. This implies that lighting may be more beneficial at intersections with 55 mph posted approach speeds, and at four approach intersections. The before and after analysis showed a 27 percent reduction in night crash frequency, a 32 percent reduction in the ratio of night-to-total crashes and a 35 percent reduction in the night crash rate. The frequency of night crashes and number of night crashes per intersection both decreased by 27 percent after lighting was installed. Crash severity decreased at night by 20 percent in the after period and day crash severity increased by 10 percent. This suggests that the installation of street lighting does reduce the night-to-total crash ratio and nighttime crash rates.

In October of 2001, Monsere *(22)* presented a study which showed 44 interchanges and 5.5 miles of interstate freeway that were modified. Interchanges from full lighting to a partial lighting configuration, interchanges from a partial plus design to a partial lighting configuration, and interstate freeway mainline lineal lighting was reduced. For this study an actual illuminance measurement was not taken before or after any modification was performed. Crash records were obtained from Ohio DOT from 1995 to 2005.

An Empirical-Bayes observational before and after methodology, and a negative binomial regression error structure was used for the analysis. There were five years in the before time period and four years in the after time period. Two reference populations; Group 1: interchanges with full and partial interchange lighting (38 sites) and Group 2: urban freeway sections with and without lighting (42 sites, 53 mi) were used.

The most robust finding of the analysis was a rather significant increase in total and injury nighttime crashes for lineal sections. The analysis found an increase in total nighttime crashes at the group of interchange locations and a decrease in injury night crashes at these same locations. The total day crashes decreased 1.73 percent for these interchanges and the injury day crashes decreased less than injury night crashes. However, the results cannot be considered conclusive because of the variation in findings.

Wanvik *(23)* presented a study to estimate the safety effect of road lighting in nighttime crashes on Dutch roads using data from an interactive database containing 763,000 injury crashes and 3.3 million property damage crashes from 1987 to 2006. The distribution of crashes by daylight conditions on lit and unlit roads was compared in order to evaluate the effects of road lighting on Dutch roads. Two estimators were used to determine the effects. The first was the odds ratio, based on the number of crashes only. This does not refer to any data related to the distribution of traffic between daylight and darkness. The distribution may differ between lit and unlit roads, and this could bias the odds ratio. In order to minimize the potential for bias, the odds ratio was estimated for each hour of the day separately. Only hours that had at least 15 crashes in each of the four groups were included to estimate the odds ratio. This leaves only hours 7, 8, and 18 to 22 for the analysis. All other hours of the day were omitted. The second estimator used to determine the effect was the ratio of odds ratios.

The mean effect of roadway lighting in crashes resulting in injury during the hours of darkness was negative 50 percent (-53%, -47%). A much larger effect than has been found in earlier studies. The effect of roadway lighting in fatal crashes during darkness is slightly larger than the effect on injury crashes. The effect of roadway lighting in crashes during darkness is significantly smaller in urban areas than in rural areas. The estimated effect of roadway lighting on injury crashes during darkness on rural roads is negative 54 percent (-56%, -52%). The safety effect of roadway lighting is significantly smaller during adverse weather and road surface conditions than during fair weather and dry surface conditions. The safety effects of roadway lighting on pedestrian, bicycle and moped crashes are significantly larger than the effects on automobile and motorcycle crashes. The effect of roadway lighting on injury crashes during precipitation with snow is negative 26 percent (-40%, +8%), and the effect on snow or ice covered road surface is negative 22 percent (-31%, -11%). The average increase in risk of injury crashes is 17 percent on lit rural roads and 145 percent on unlit rural roads. The average increase in risk during rainy conditions is 53 percent on lit rural roads and 192 percent on unlit rural roads. The average increase in risk with respect to pedestrian crashes is 141 percent on lit roads and 361 percent on unlit roads (rural).

After completing the literature review, it was learned that the likelihood of nighttime crashes can be decreased with the presence of roadway lighting. Previous longitudinal studies on lit and unlit roadways showed a significant decrease in the number of nighttime crashes with the presence of roadway lighting. Meanwhile, an increase in driving speed and decrease in driver attention was observed with the introduction of new roadway lighting. However, there are a lack of studies conducting actual roadway lighting illuminance measurement research and the analysis of crash injury severity under different roadway lighting illuminance levels.

CHAPTER 4: METHODOLOGY

The following methodology was used to perform the analysis and to determine the relationship between nighttime crash injury severity and roadway lighting illuminance levels.

4.1 Roadway Segments Selection

The criteria used for the selection of the segments for this research was based on an analysis conducted by Florida Department of Transportation (FDOT) District Seven in which they identify 37 segments with higher nighttime crash activity per mile and also, the need for information related to roadway lighting illuminance levels. These 37 segments correspond to approximately 245 centerline miles of roadway lengths. FDOT District Seven has a total of 1,064 centerline miles of roadway length.

A database was required for an in-depth analysis of the possible factors that can affect or influence nighttime crash injury severity. The collection of all geometric characteristics for each of the 37 segments was needed for further analysis, including the following characteristics:

- Number of lanes
- Lanes with
- Median width
- Speed
- Hourly traffic volumes
- Percentage of heavy vehicles
- Bicycle lanes facilities mile post location (O-D)
- Pedestrian facilities mile post location (Sidewalks O-D)
- Intersection milepost location

The roadway geometric characteristic, for each of the 37 segments, was obtained from the FDOT Straight Line Diagrams and from the FDOT Transportation Statistics Office highway data for the State Highway System.

4.2 Roadway Lighting Illuminance Levels

Roadway lighting illuminance levels were the primary, and most important data required for conducting this research. Roadway lighting illuminance levels were measured using an Advanced Lighting Measurement System (ALMS), also called the Mobile Lighting Measurement System (MLMS). This measurement system was developed by the Center for Urban Transportation Research (CUTR) at the University of South Florida (USF) and funded through the FDOT District Seven Grant *(24, 25)*.

Traditional roadway lighting illuminance levels are often measured manually with a handheld light meter, on a limited scale. This process entails an enormous data collection effort and usually requires a crew size of at least four members. The process of collecting measurements, for a mile long of roadway, can take approximately five hours. This traditional collection method also places the light meter operator in the middle of the roadway at night during low visibility conditions, creating a safety concern for both data collection personnel and roadway users. Figure 2 shows an example of the traditional data collection process (Source of images: *Optimum Illumination for Nighttime Flagger Operation, Oregon DOT (26)*).

Figure 2 Example of Traditional Roadway Lighting Illuminance Measurements

With the objective of addressing these issues, ALMS was developed by CUTR (see Figure 3). This system measures the roadway lighting illuminance levels from a moving vehicle using a combination of a laptop computer, a light meter, and a distance measurement instrument (DMI). Each roadway lighting illuminance measurement is recorded using a light meter and then matched the measurement to the corresponding location using a distance measurement instrument (DMI). Therefore, rather than having the data collector standing in the roadway at night, they just operate the vehicle with the system as another vehicle on the roadway at night. The surveyor is then able to analyze the roadway lighting intensities offline back in the safety of his/her office. With the use of an ALMS any evaluation of roadway lighting illuminance can be performed with one person (a vehicle driver). Additionally, there are no data limitations and the analysis of a mile long segment of roadway can be completed in approximately 30 minutes. Figure 3 shows a schematic diagram for the ALMS.

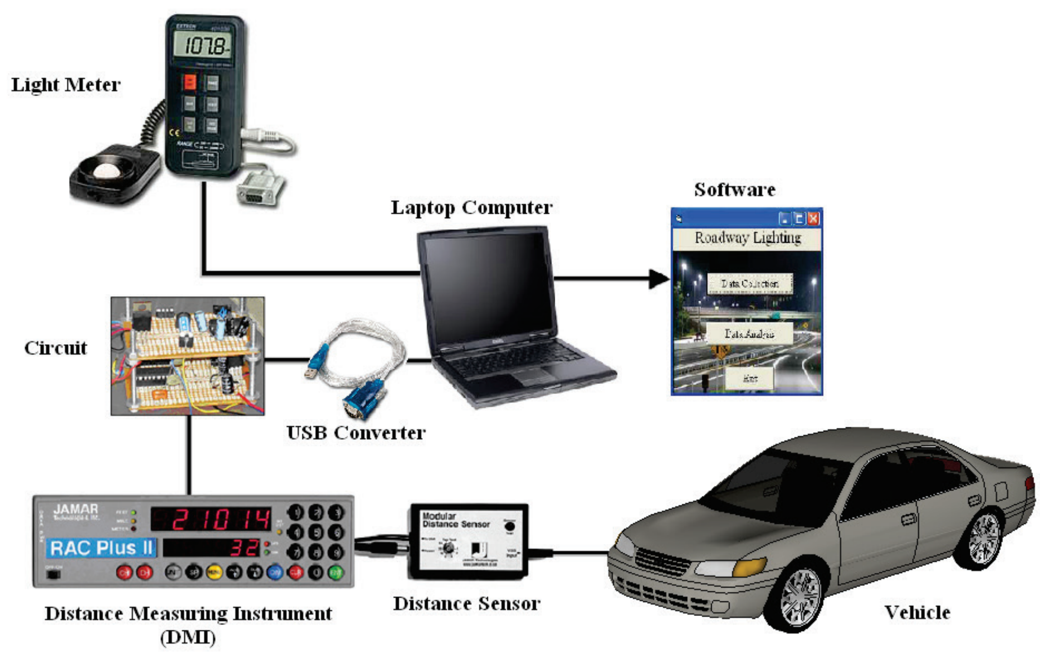

Figure 3 Advanced Lighting Measurement System

As was mentioned in the introduction, it is required by FDOT in the *Plans Preparation Manual* to have data on average illuminance levels and ratios of average/minimum and maximum/minimum for the evaluation of existing roadway lighting illuminance levels. To accomplish this analysis, the roadway lighting illuminance level was measured every 40 feet on the right side (outside lane), and left side (inside lane) for each approach by traffic direction for each segment selected. After that, the roadway lighting illuminance levels were matched with their corresponding roadway mileposts. This was accomplished based on the principle of having the beginning milepost (the intersection where data collection started) and recording the distance for each measurement, then converting each measurement into miles and adding them to the beginning mile post. This process was done for each of the segments selected.

Finally, a database was developed to manage all the information collected for the roadway lighting illuminance measurements. The database that was created included the roadway lighting illuminance measurement for every 40 feet along with the calculations of their corresponding average illuminance (every 40 feet the combination of right side (outside lane) measurements, and left side (inside lane) measurements for each approach by traffic direction was calculated) and ratio required by the FDOT *Plans Preparation Manual*.

Figure 4 shows an example of one of the segments selected for the study, a six-lane divided highway with lighting poles at both sides. The top left corner of Figure 4 shows the box that contains the distance measurement instrument (DMI) and the circuit used as the interface for the communication between the DMI and the laptop computer. The bottom left and right pictures show the light meter on top of the vehicle as it was utilized during the roadway lighting illuminance measurement process.

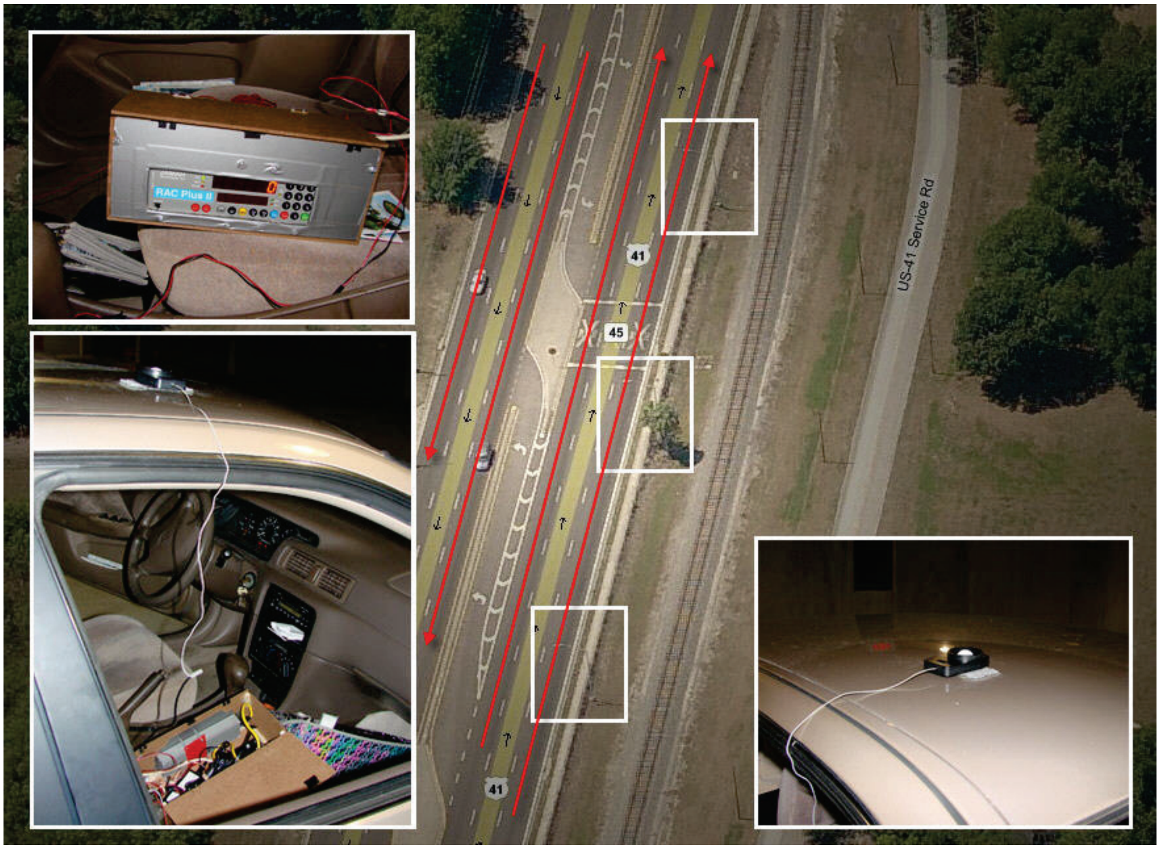

Figure 4 Data Collection Diagram

4.3 Crash Data Reports

For conducting the analysis and determining the existing relationship between nighttime injury severity and roadway lighting illuminance levels, crash data reports were required for each roadway segment selected. The crash data were obtained from FDOT Crash Analysis Reporting (CAR) System. The crash data included information on crash reports from 2005 to 2008. The crash reports were analyzed and grouped by daytime, dusk, dawn, and dark (nighttime) periods. Only crashes occurring during nighttime periods were used in this research for model development. The crash data were paired to their corresponding roadway illuminance level by matching their corresponding milepost information.

4.4 Statistical Analysis and Model Development

In order to analyze the effect and relationship between roadway lighting illuminance levels and injury severity on crashes during nighttime conditions, an Ordered Probit Model and a Negative Binomial Model were developed. The Ordered Probit Model investigates how roadway lighting illuminance levels and other roadway factors affect the injury severity on crashes during nighttime conditions. Meanwhile, the Negative Binomial Model investigates how roadway lighting illuminance levels and other roadway factors increase the probability of the occurrence of crashes resulting in injuries during nighttime conditions. The description of the models employed in this chapter was obtained from *Statistical and Econometric Methods for Transportation Data Analysis (27)*.

4.4.1 Ordered Probit Model

An ordered probit is a generalization of the popular probit analysis in case there are more than two outcomes of an ordinal and discrete dependent variable. Ordered probability models are derived by defining an unobserved variable, y, (in this research injury severity; 1 – None, 2 – Possible, 3 – Non-Incapacitating, 4 – Incapacitating, and 5 – Fatal) which is used as a basis for modeling the ordinal ranking of data. This unobserved variable is typically specified as a linear function for each observation, such that:

$$y = \beta X + \varepsilon \qquad \text{Equation 1}$$

where X is a vector of variables determining the discrete ordering for observation n, β is a vector of estimable parameters, and ε is a random disturbance. Using this equation, observed ordinal data, y, for each observation can be defined as:

$$\begin{aligned} y &= 1 \quad if\ z \leq \mu_1 \\ y &= 2 \quad if\ \mu_1 < z \leq \mu_2 \\ y &= 3 \quad if\ \mu_2 < z \leq \mu_3 \\ y &= 4 \quad if\ \mu_3 < z \leq \mu_4 \\ y &= 5 \quad if\ z > \mu_4 \end{aligned} \qquad \text{Equation 2}$$

where the μ are estimated parameters (referred as thresholds) that define y, which corresponds to integer ordering. Note that during the estimation, non-numerical orderings such as none, possible, non-incapacitating, incapacitating, and fatal were converted to integers (numbers; 1, 2, 3, 4, and 5) without loss of generality.

The μ are parameters that are estimated jointly with the model parameters (β). The estimation problem then becomes one of determining the probability of each specific ordered response (y) for each observation n. This determination is accomplished by making an assumption that ε is normally distributed across observations with mean = 0 and variance = 1, an Ordered Probit Model results with ordered selection probabilities as follows:

$$\begin{aligned} P(y=1) &= \Phi(\mu_1 - \beta X) \\ P(y=2) &= \Phi(\mu_2 - \beta X) - \Phi(\mu_1 - \beta X) \\ P(y=3) &= \Phi(\mu_3 - \beta X) - \Phi(\mu_2 - \beta X) \\ P(y=4) &= \Phi(\mu_4 - \beta X) - \Phi(\mu_3 - \beta X) \\ P(y=5) &= 1 - \Phi(\mu_4 - \beta X) \end{aligned}$$ Equation 3

where Φ() is the cumulative normal distribution,

$$\Phi(\mu) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mu} EXP\left[-\frac{1}{2}\omega^2\right] d\,\omega$$ Equation 4

Figure 5 provides an example with five possible ordered outcomes.

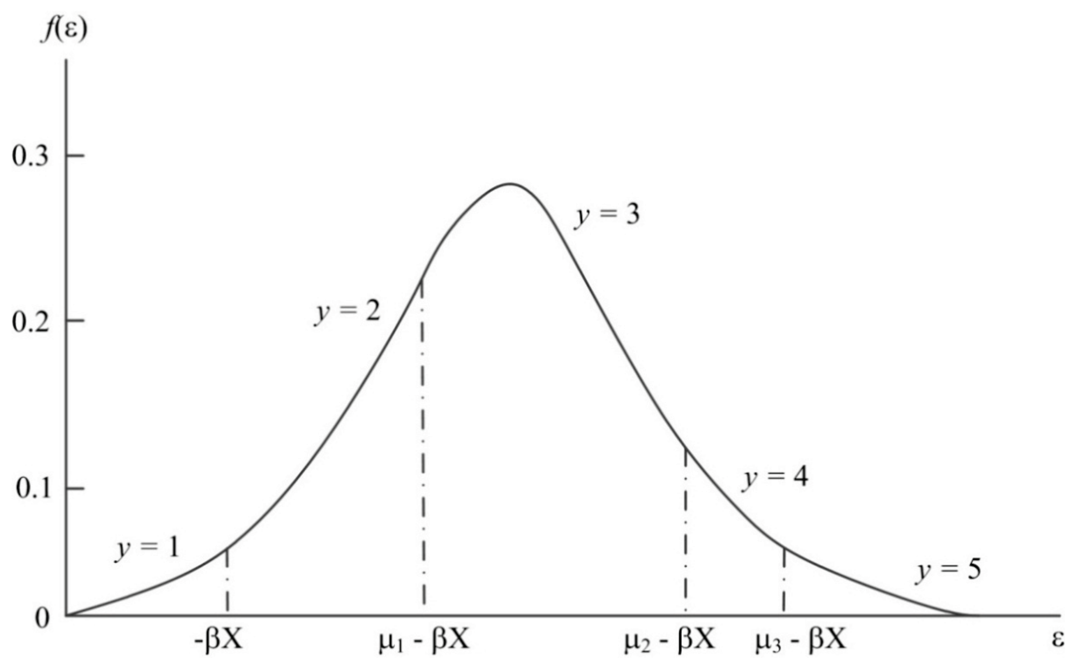

Figure 5 Example of an Ordered Probability Model with $\mu_0 = 0$

For estimation, Equation 3 is written as:

$$P(y = i) = \Phi(\mu_i - \beta X) - \Phi(\mu_{i+1} - \beta X) \qquad \text{Equation 5}$$

where μ_i and μ_{i+1} represents the upper and lower thresholds for outcome *i*. The likelihood function is:

$$L(y|\beta, \mu) = \prod_{n=1}^{N} \prod_{i=1}^{I} [\Phi(\mu_i - \beta X_n) - \Phi(\mu_{i+1} - \beta X_n)]^{\delta_{in}} \qquad \text{Equation 6}$$

where δ_{in} is equal to one if the observed discrete outcome for observation *n* is *i*, and zero otherwise. This equation leads to a log-likelihood of

$$LL = \sum_{n=1}^{N} \sum_{i=1}^{I} \delta_{in} LN[\Phi(\mu_i - \beta X_n) - \Phi(\mu_{i+1} - \beta X_n)] \qquad \text{Equation 7}$$

If it's assumed that ε in Equation 1 is logistically distributed across observations with mean = 0 and variance = 1, an Ordered Logit Model should be used, and the derivation proceeds the same as for the Ordered Probit Model. The Ordered Probit Model is widely used by the assumption of normality.

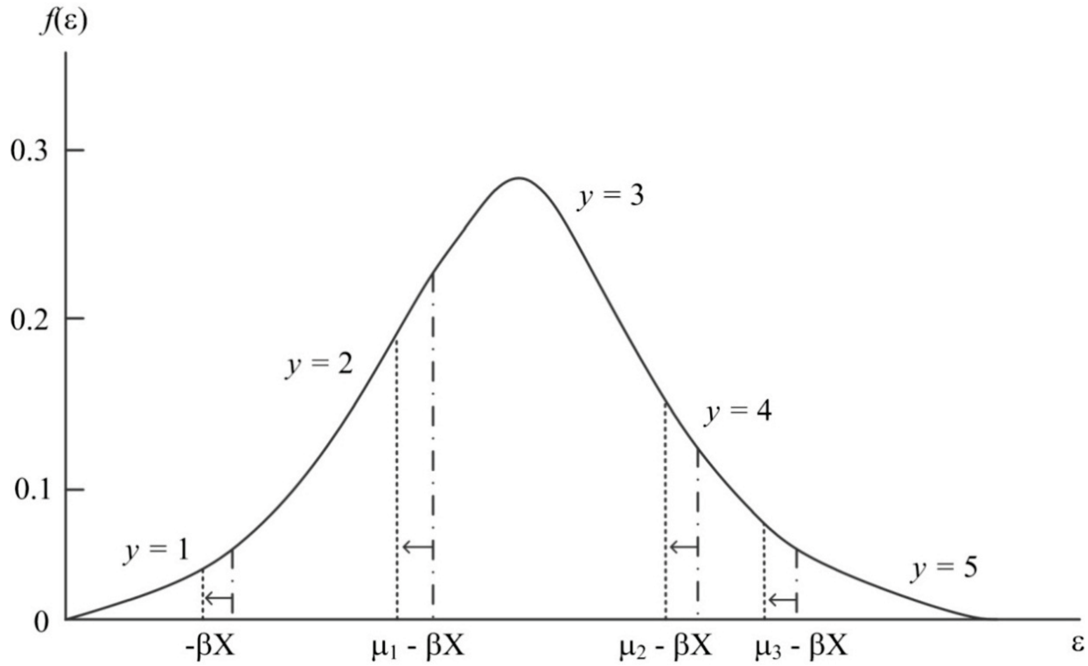

Figure 6 Example of an Ordered Probability Model with an Increase in βX (μ_0 = 0)

In terms of evaluating the effect of individual estimated parameters in ordered probability models, Figure 6 shows that a positive value of β_k implies that an increase in x_k will unambiguously increase the probability that the highest ordered discrete category results (y = 5 in Figure 6) and unambiguously decreases the probability that the lowest ordered discrete category results (*y* = 1 in Figure 6).

The problem with ordered probability models is associated with the interpretation of intermediate categories, (*y* = 2, *y* = 3, and *y* = 4 in Figure 6). Depending on the location of the thresholds, it is not necessarily clear what effect, positive or negative, β_k has on the probabilities of these categories. This difficulty arises because the areas between the shifted thresholds may yield increasing or decreasing probabilities after shifts to the left or right (see Figure 6). The correct interpretation is that an increase in x_k increases the likelihood for the highest ordered discrete category, and decreases the likelihood for the lowest ordered discrete category.

To obtain a sense of direction of the effects on the interior (y = 2, 3, and 4) categories, marginal effects are computed for each category. These marginal effects provide the direction of the probability for each category as:

$$P(y = i)/dX = [\Phi(\mu_{i-1} - \beta X) - \Phi(\mu_i - \beta X)]\beta \qquad \text{Equation 8}$$

where Φ() is the standard normal density.

4.4.2 Negative Binomial Regression Model

Count data consists of non-negative integer values and are encountered frequently in the modeling of transportation-related phenomena. An example of count data variables in transportation are the number of crashes observed on road segments per year. For this particular research the number of passengers injured during nighttime crashes was analyzed for a period of three years.

A common mistake is to model count data as continuous data by applying a standard least squares regression. This is incorrect because regression models yield predicted values that are non-integers and can predict values that are negative, both of which are inconsistent with count data. These limitations make standard regression analysis inappropriate for modeling count data without modifying dependent variables.

Count data are properly modeled by using a number of methods, the most popular of which are Poisson and Negative Binomial Regression Models. A common analysis error is failing to satisfy the property of the Poisson distribution that restricts the mean and variance to be equal, when $E[y_i] = VAR[y_i]$. If this equality does not hold, the data are said to be under dispersed ($E[y_i] > VAR[y_i]$) or over dispersed ($E[y_i] < VAR[y_i]$), and the parameter vector is biased if corrective measures are not taken.

The negative binomial model is described for each observation *i* as;

$$\lambda_i = EXP(\beta X_i + \varepsilon_i) \qquad \text{Equation 9}$$

where $EXP(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α^2. The addition of this term allows the variance to differ from the mean as indicated below:

$$VAR[y_i] = E[y_i][1 + \alpha E[y_i]] = E[y_i] + \alpha E[y_i]^2 \qquad \text{Equation 10}$$

The Poisson Regression Model is viewed as a limiting model of the Negative Binomial Regression Model as α approaches zero, which means that the selection between these two models is dependent on the value of α. The parameter α is often referred to as the over dispersion parameter. The negative binomial distribution has the form:

$$P(y_i) = \frac{\Gamma((1/\alpha)+y_i}{\Gamma((1/\alpha)y_i!}\left(\frac{1/\alpha}{(1/\alpha)+\lambda_i}\right)^{1/\alpha}\left(\frac{\lambda_i}{(1/\alpha)+\lambda_i}\right)^{y_i} \qquad \text{Equation 11}$$

where Γ( ) is a gamma function. This results in the following equation:

$$L(\lambda_i) = \prod_i \frac{\Gamma((1/\alpha)+y_i}{\Gamma((1/\alpha)y_i!}\left(\frac{1/\alpha}{(1/\alpha)+\lambda_i}\right)^{1/\alpha}\left(\frac{\lambda_i}{(1/\alpha)+\lambda_i}\right)^{y_i} \quad \text{Equation 12}$$

When the data are over dispersed, the estimated variance term is larger than under a true Poisson process. As over dispersion becomes larger so does the estimated variance, and consequently, all of the standard errors of parameter estimates become inflated.

CHAPTER 5: DATA DESCRIPTION

The emphasis of this chapter is to describe the data collected and the procedure utilized. This chapter includes the description of the West Central Florida Region for the roadway segments selected, roadway lighting illuminance levels, and their crash reports.

5.1 Roadway Segments

The West Central Florida Region refers to the Florida Department of Transportation District Seven. FDOT District Seven has a total of 1,064 centerline miles of roadway lengths with a land area of nearly 3,332 square miles. The major cities of the West Central Florida Region are: Brooksville, Clearwater, Dunedin, Largo, New Port Richey, St. Petersburg, and Tampa. This region represents five counties with an estimated population of 2.6 million residents in the Tampa Bay area (Citrus, Hernando, Hillsborough, Pasco, and Pinellas). Drivers in this district travel more than 33.6 million miles on a daily bases. Figure 7 presents the map for the entire West Central Florida Region.

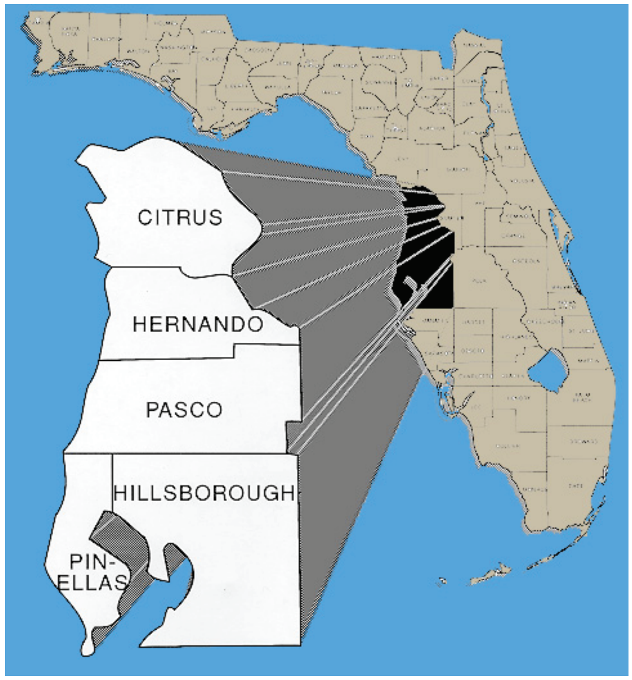

Figure 7 Map of Florida Department of Transportation District 7 Area

As previously mentioned, the selection for the segments examined in this research was based on requirements and results of previous analysis conducted by FDOT District Seven. They identify 37 segments with higher nighttime crashes per mile. In addition, these 37 segments were identified as priority for an evaluation of the roadway lighting illuminance levels. These 37 segments correspond to approximately 245 centerline miles of roadway length.

Table 2 presents the segments selected for Citrus County and also provides the corresponding description, including roadway name and length.

Table 2 Segment Selected for Citrus County

#	Roadway ID	Roadway Name	Length
1	2010000	US 41/SR 44	1.500
2	2030000	US 19	3.211

Figures 8 and 9 present the maps for the segments within Citrus County. These maps include their corresponding beginning and ending street name locations.

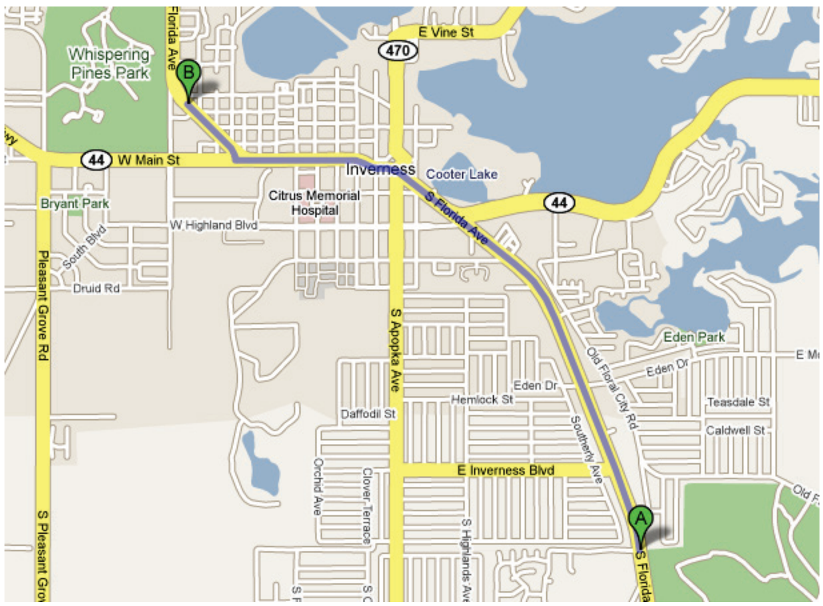

Figure 8 US-41/SR-44 ((A) US-41/44 and Relief Avenue, (B) US-41/44 and Davidson Avenue)

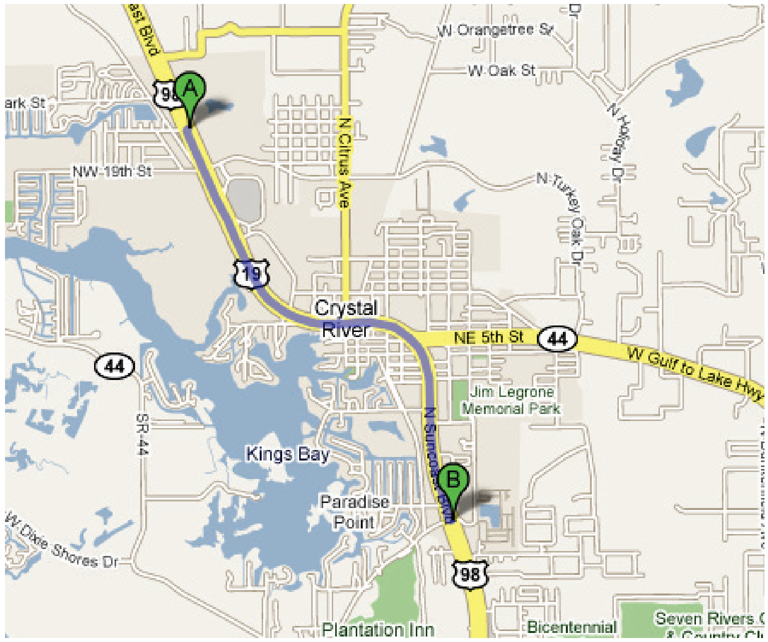

Figure 9 US-19 ((A) US-19 & NW 22nd Street, (B) US-19 and SE 8th Avenue)

Table 3 presents the segments selected within Hernando County. Table 3 also presents the description for each segment, including roadway name and length.

Table 3 Segment Selected for Hernando County

#	Roadway ID	Roadway Name	Length
3	8010000	US 41	3.386
4	8040000	SR 50	2.556

Figures 10 and 11 present the maps for the segments selected within Hernando County. Each figure provides the corresponding beginning and ending street name locations.

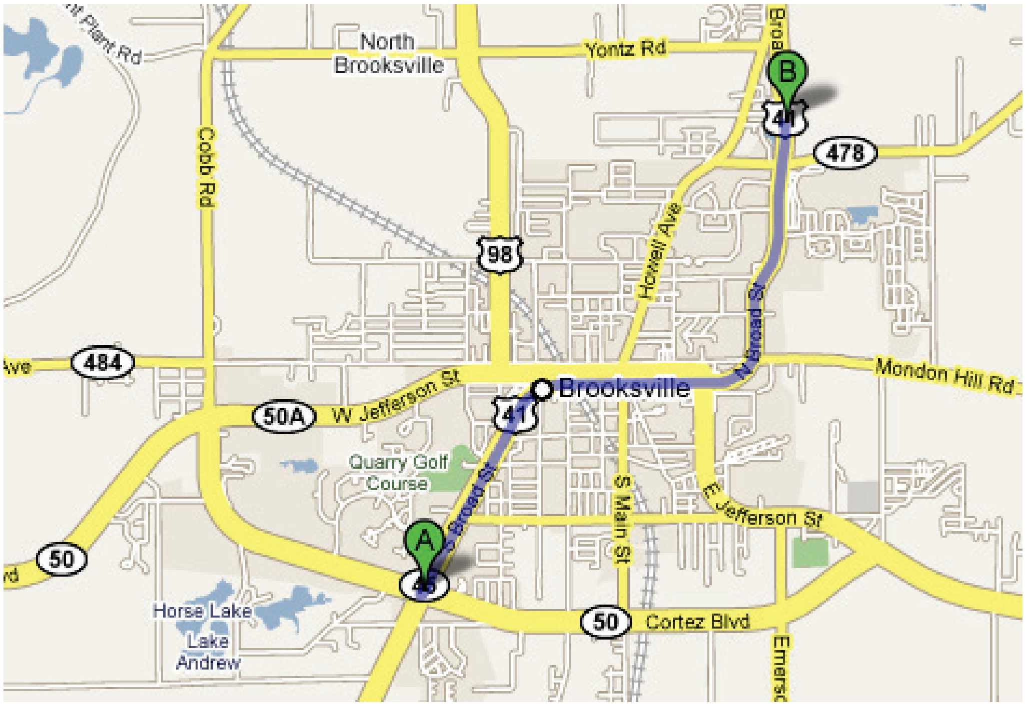

Figure 10 US-41 ((A) US-41 and SR-50, (B) US-41 and Lakeside Drive)

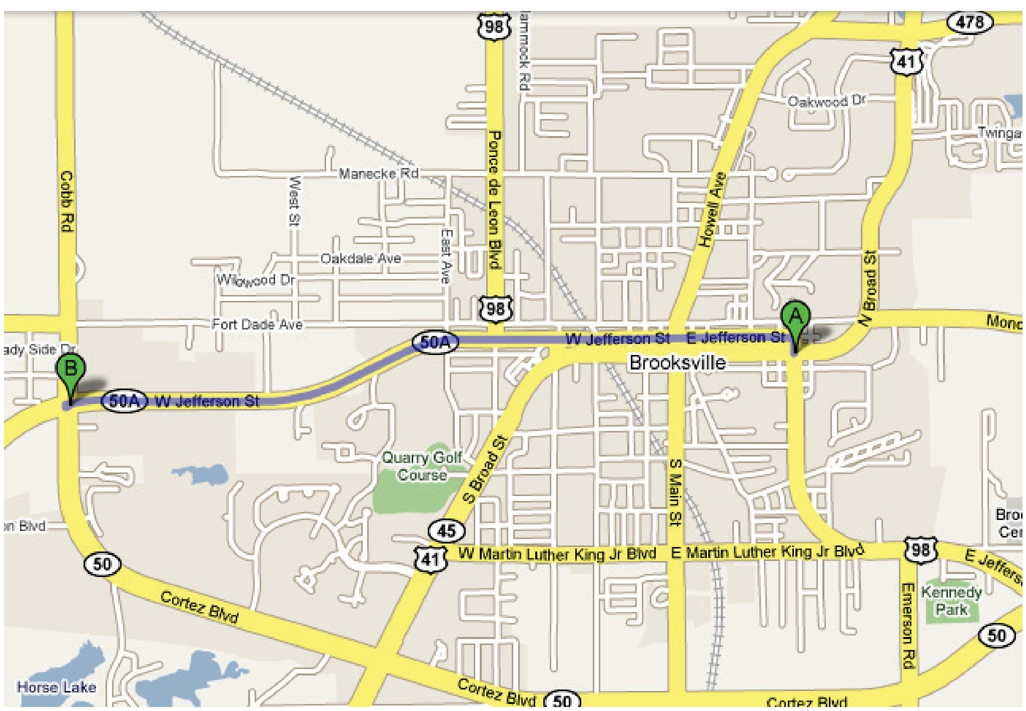

Figure 11 SR-50 ((A) SR-50 and US-98, (B) SR-50 and SR-50)

Table 4 presents the description, including roadway name and length, for the segments selected within Hillsborough County.

Table 4 Segment Selected for Hillsborough County

#	Roadway ID	Roadway Name	Length
5	10005000	40th St	2.845
6	10020000	Florida Avenue	11.211
7	10030000	Hillsborough Avenue	4.772
8	10030000	US 92 Reynolds St	2.454
9	10030101	US 92 Baker St	1.782
10	10040000	Nebraska Avenue	8.164
11	10060000	US 41	12.117
12	10080000	Kennedy Blvd	1.686
13	10110000	E Frank Adamo Dr	6.970
14	10130000	Dale Mabry Hwy	7.181
15	10140000	Courtney Campbell Cswy	5.012
16	10150000	Hillsborough Avenue	7.803
17	10160000	Dale Mabry Hwy	9.485
18	10250000	22nd St	2.782
19	10250101	21st St	0.622
20	10270000	Kennedy Blvd	1.980
21	10290000	Fowler Avenue	5.454
22	10310000	Busch Blvd	3.530
23	10330000	56th St	6.023
24	10340000	Martin Luther King Jr. Blvd	10.550

The next set of figures present the corresponding maps for the segments within Hillsborough County. Each map includes the corresponding beginning and ending street name locations.

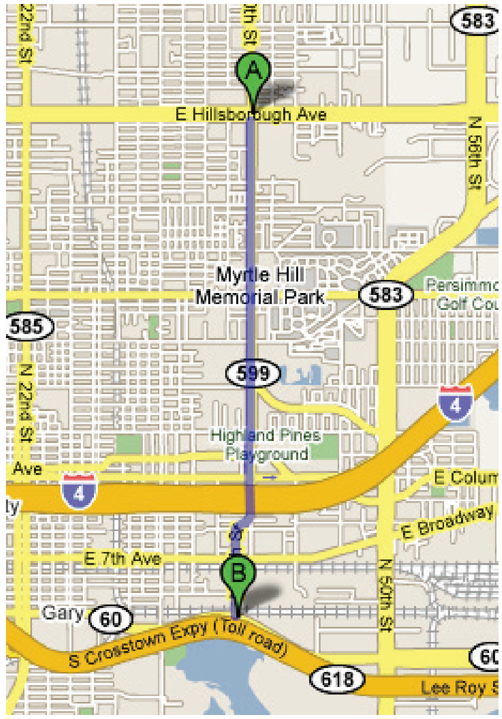

Figure 12 40th Street ((A) 40th Street and Hillsborough Avenue, (B) 40th Street and East Adamo Drive)

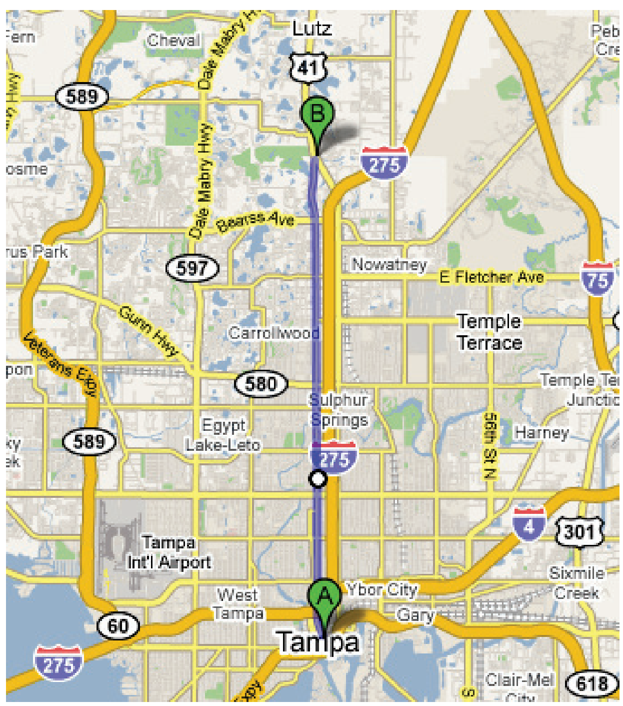

Figure 13 Florida Avenue ((A) Florida Avenue and SR-60 Kennedy Boulevard, (B) Florida Avenue and Nebraska Avenue)

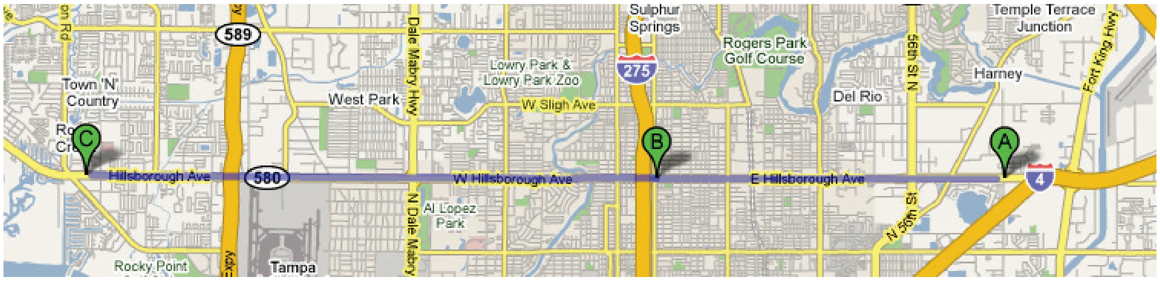

Figure 14 Hillsborough Avenue ((A) Hillsborough Avenue and Orient Road, (B) Hillsborough Avenue and Nebraska Avenue) and Hillsborough Avenue ((B) Hillsborough Avenue and Nebraska Avenue, (C) Hillsborough Avenue and Theresa Road)

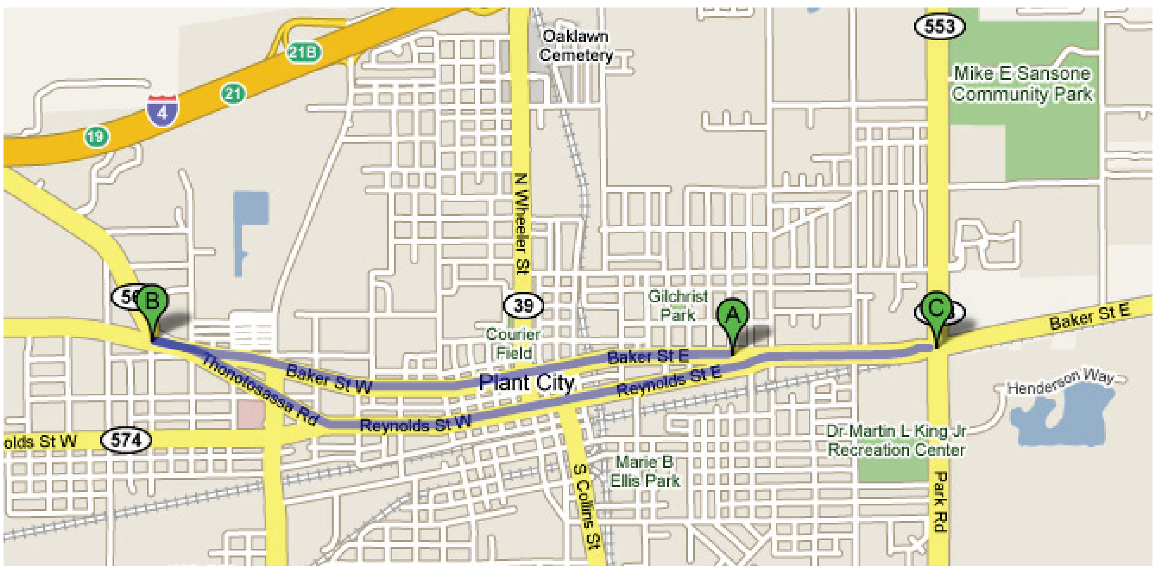

Figure 15 US-92 Reynolds Street ((B) US-92 Reynolds Street and Thonotosassa Road, (C) US-92 Reynolds Street and Park Road) and US-92 Baker ((A) US-92 Baker Street and Reynolds Street, (B) US-92 Baker Street and Thonotosassa Road)

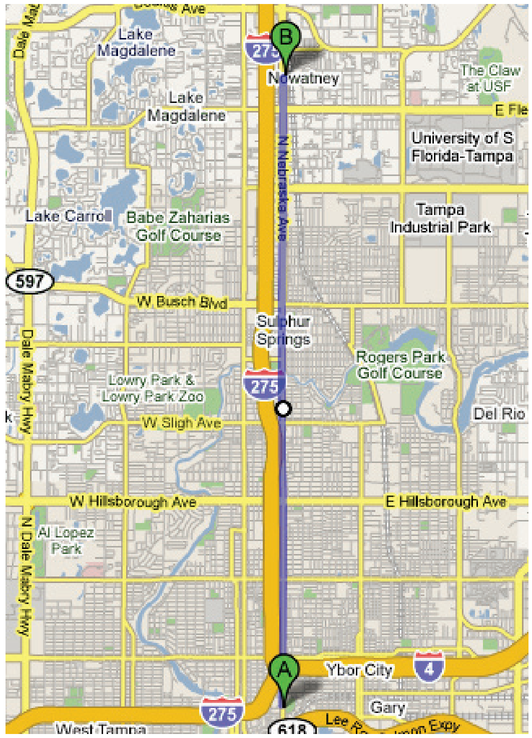

Figure 16 Nebraska Avenue ((A) Nebraska Avenue and Kay Street, (B) Nebraska Avenue and 142nd Avenue)

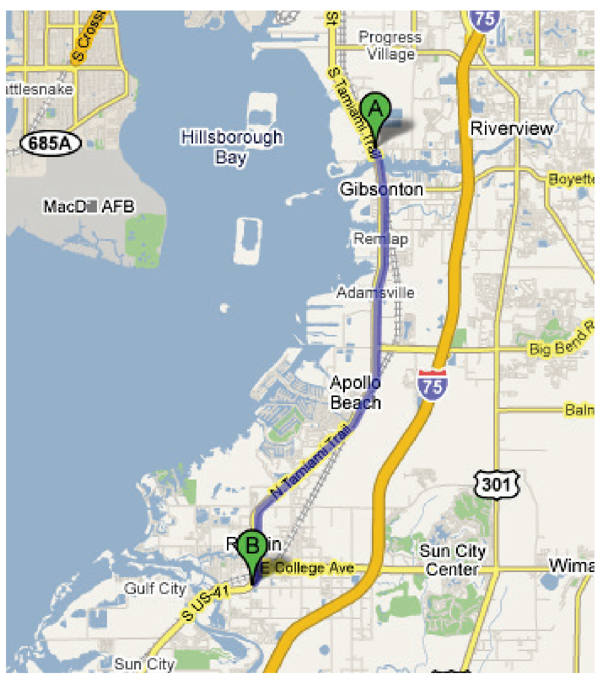

Figure 17 US-41 ((A) US-41 and Riverview Drive, (B) US-41 and 1st Street SW)

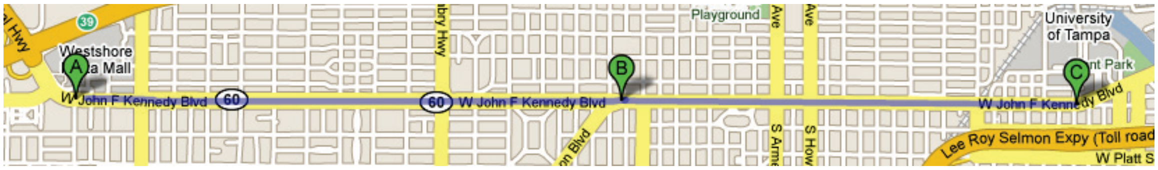

Figure 18 Kennedy Boulevard ((B) Kennedy Boulevard and Henderson Boulevard, (C) Kennedy Boulevard and Brevard Avenue) and Kennedy Boulevard ((A) Kennedy Blvd and Ward St, (B) Kennedy Blvd and Henderson Blvd)

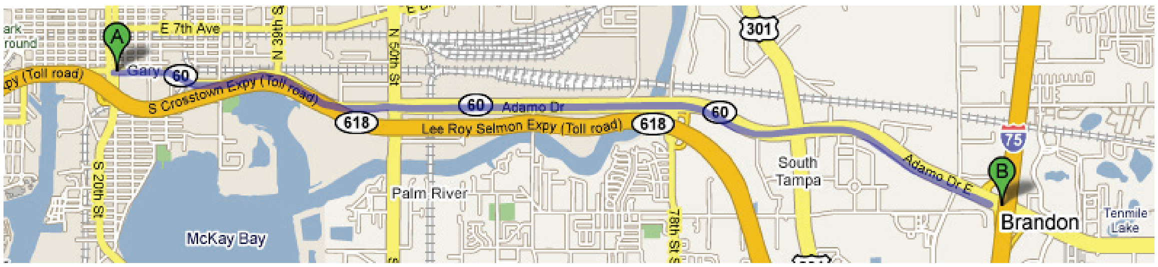

Figure 19 East Frank Adamo Drive ((A) East Frank Adamo Drive and N 22nd Street, (B) East Frank Adamo Drive and I-75)

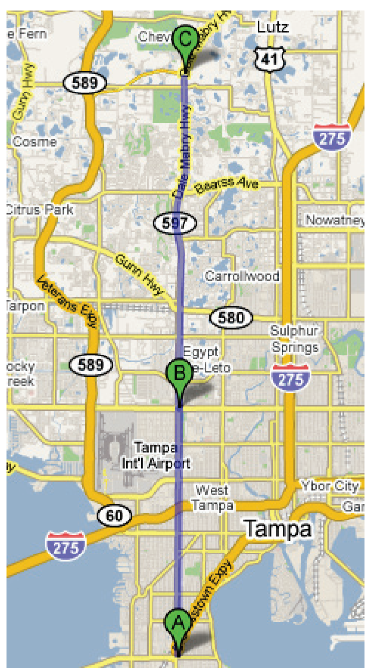

Figure 20 Dale Mabry Hwy ((A) Dale Mabry Highway and Gandy Boulevard, (B) Dale Mabry Highway and Hillsborough Avenue) and Dale Mabry Highway ((B) Dale Mabry Highway and Hillsborough Avenue, (C) Dale Mabry Highway and Veteran Expressway)

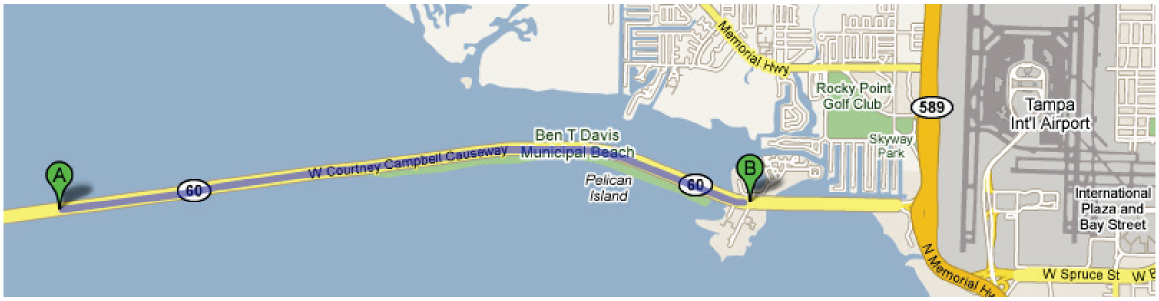

Figure 21 Courtney Campbell Causeway ((A) Courtney Campbell Causeway and Pinellas County Line, (B) Courtney Campbell Causeway and Rocky Point Drive)

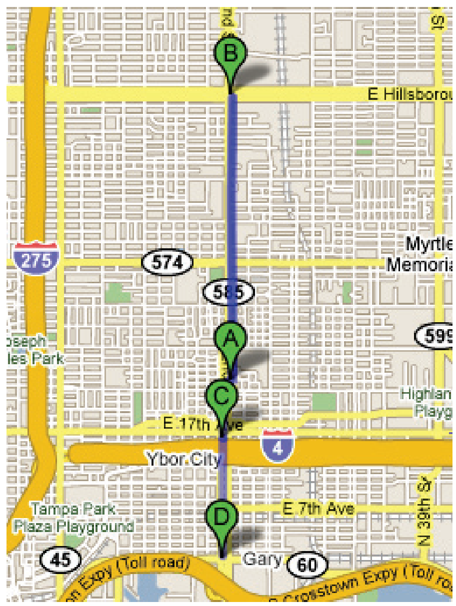

Figure 22 22nd Street ((A) 22nd Street and North 21st Street, (B) 22nd Street and Hillsborough Avenue) and 21st Street ((B) 21st Street and I-4, (C) 21st Street and Adamo Drive)

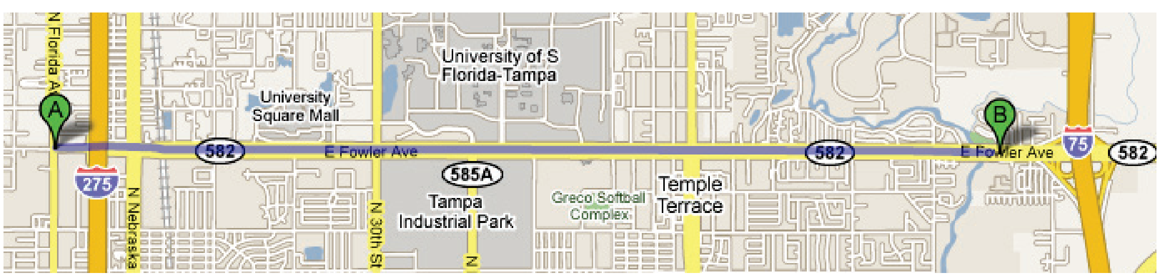

Figure 23 Fowler Avenue ((A) Fowler Avenue and Florida Avenue, (B) Fowler Avenue and Morris Bridge Road)

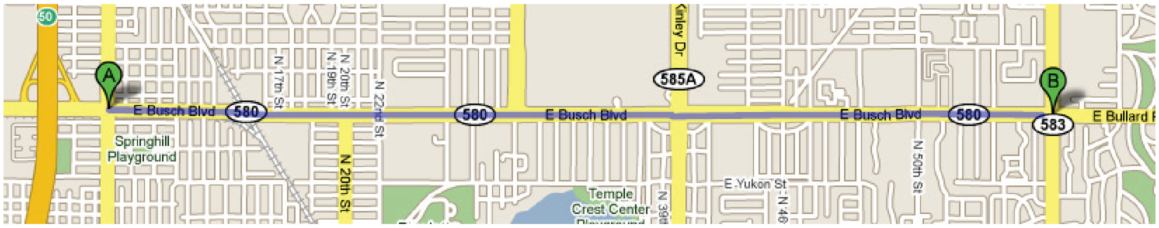

Figure 24 Busch Boulevard ((A) Busch Boulevard and Nebraska Avenue, (B) Busch Boulevard and 56th Street)

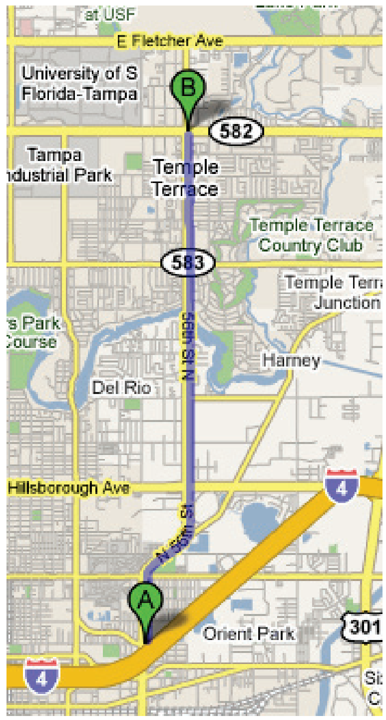

Figure 25 56th Street ((A) 56th Street and E 21st Avenue, (B) 56th Street and Fowler Avenue)

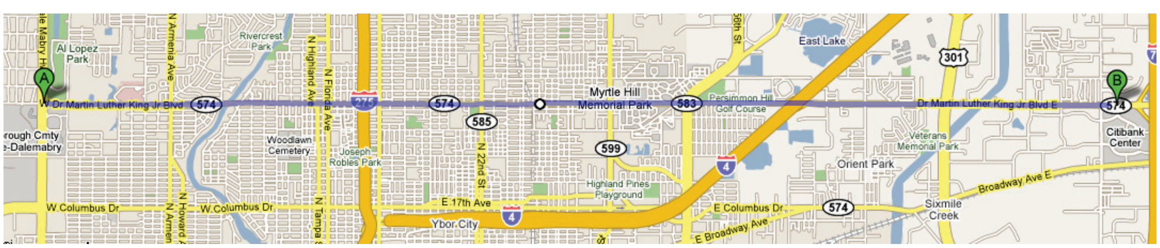

Figure 26 Martin Luther King Jr. Boulevard ((A) MLK Jr. Boulevard and Dale Mabry Hwy, (B) MLK Jr. Boulevard and Queen Palm Drive)

Table 5 presents the description, including roadway name and length, for the segments selected within Pasco County.

Table 5 Segment Selected for Pasco County

#	Roadway ID	Roadway Name	Length
25	14030000	US 19	11.105

Figure 27 presents the map for the segment within Pasco County with its corresponding beginning and ending street name location.

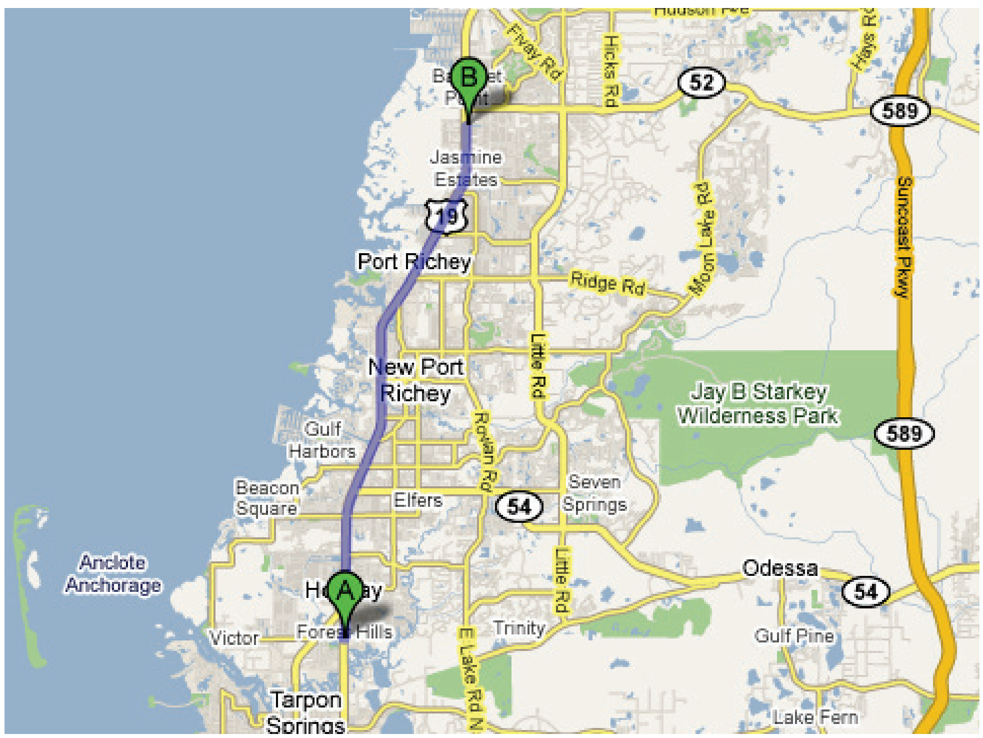

Figure 27 US-19 ((A) US-19 and Pinellas County Line, (B) US-19 and Gulf Highway Drive)

Table 6 presents the description, including roadway name and length, for the segments selected within Pinellas County.

Table 6 Segment Selected for Pinellas County

#	Roadway ID	Roadway Name	Length
26	15007000	S. Missouri Avenue	3.041
27	15010000	5th Avenue N/Tyrone Blvd/Seminole Blvd	17.066
28	15020000	Alt US 19	5.271
29	15030000	East Bay Dr	6.627
30	15040000	Gulf to Bay Blvd	4.715
31	15050000	Drew St	6.792
32	15100000	Gulf Blvd	7.858
33	15110000	Passadena Avenue	1.775
34	15120000	Ulmerton Rd	11.828
35	15140000	Gulf Blvd	6.752
36	15150000	US 19	30.962
37	15240000	Gandy Blvd/4th St	5.883

The next set of figures present the maps for the segments within Pinellas County area with their corresponding beginning and ending street name locations.

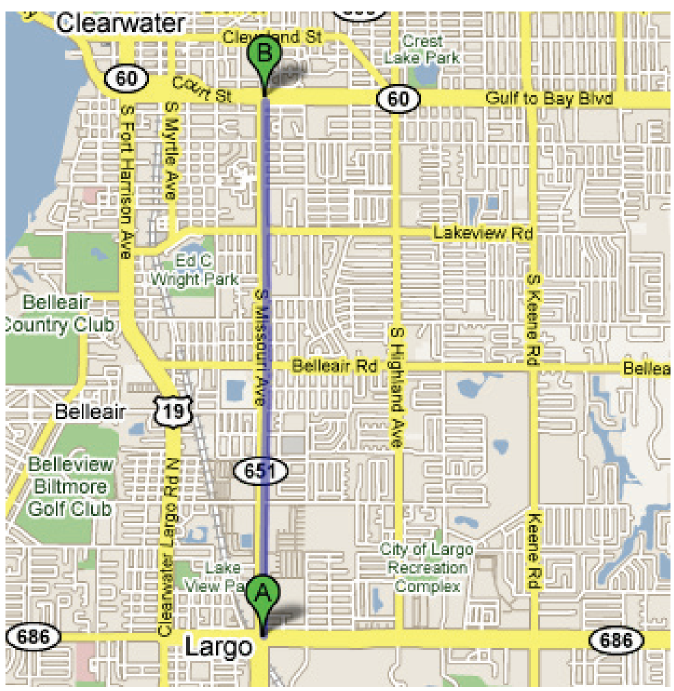

Figure 28 South Missouri Avenue ((A) S Missouri Avenue and East Bay Boulevard, (B) S Missouri Avenue and Court Street)

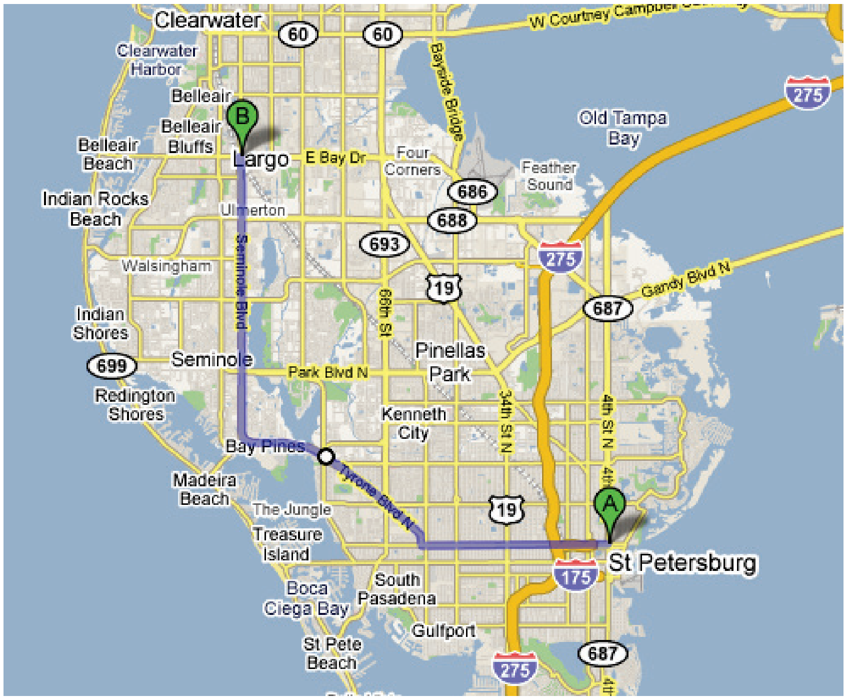

Figure 29 5th Avenue N/Tyrone Boulevard/Seminole Boulevard ((A) 5th Avenue and 4th Street North, (B) Seminole Boulevard and East Bay Drive)

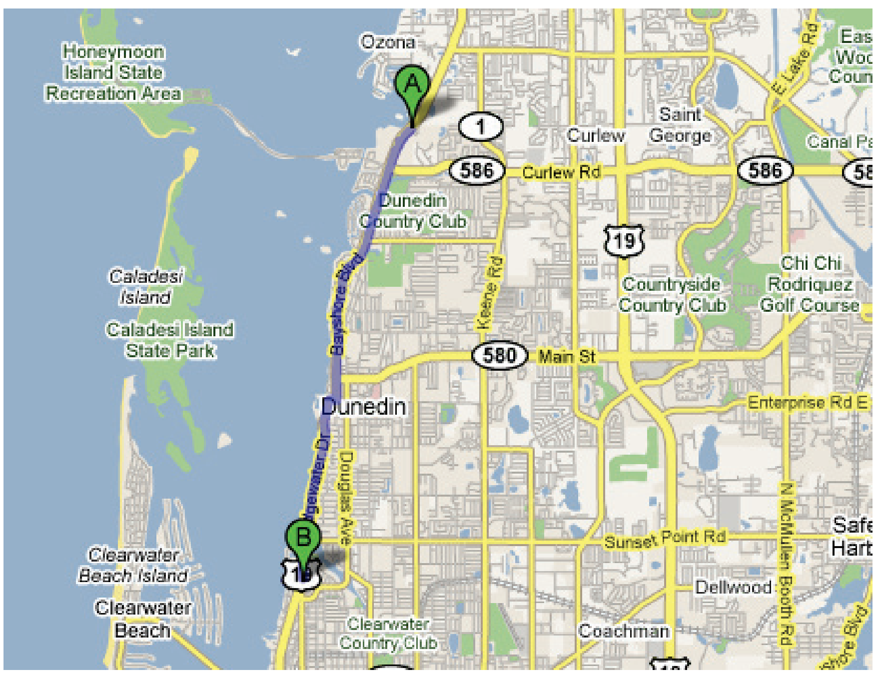

Figure 30 Alt US-19 ((A) Alt US-19 and Orange Street, (B) Alt US-19 and Myrtle Avenue)

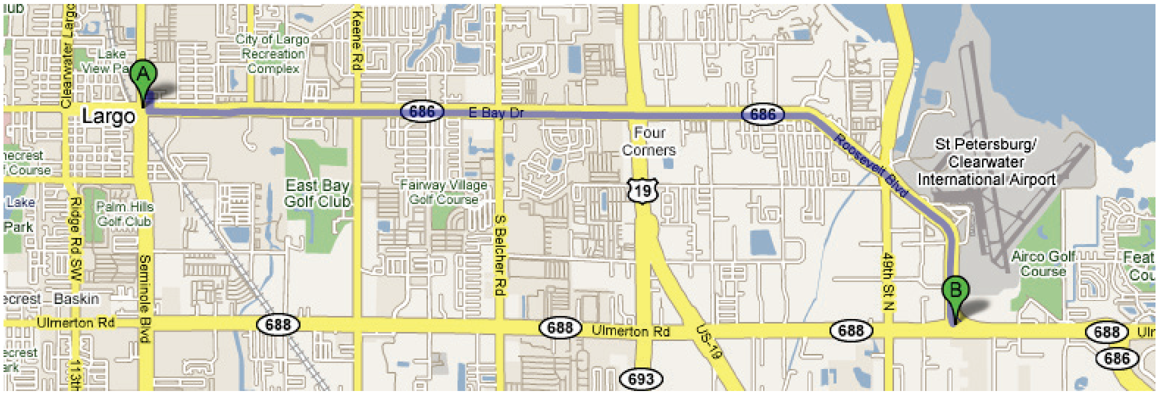

Figure 31 East Bay Drive ((A) East Bay Boulevard and Seminole Boulevard, (B) East Bay Boulevard and Ulmerton Road)

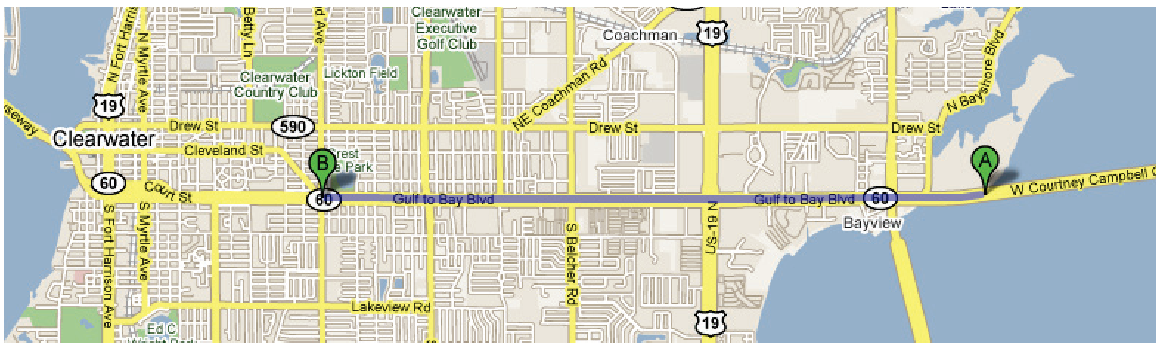

Figure 32 Gulf to Bay Boulevard ((A) Gulf to Bay Boulevard and Damascus Road, (B) Gulf to Bay Boulevard and Highland Boulevard)

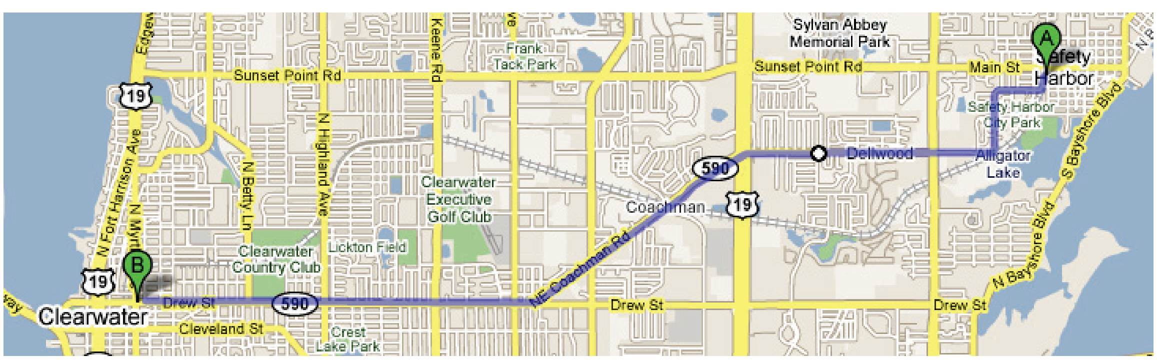

Figure 33 Drew Street ((A) 10th Avenue South and Delaware Street, (B) Drew Street and North Myrtle Avenue)

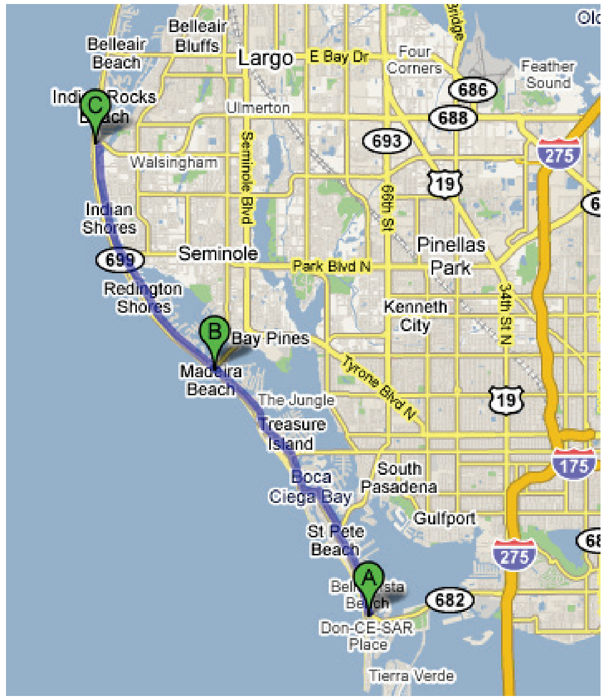

Figure 34 Gulf Boulevard ((A) Gulf Boulevard and SR-682, (B) Gulf Boulevard and SR-666) and Gulf Boulevard ((B) Gulf Boulevard and SR-666, (C) Gulf Boulevard and Walsingham Road)

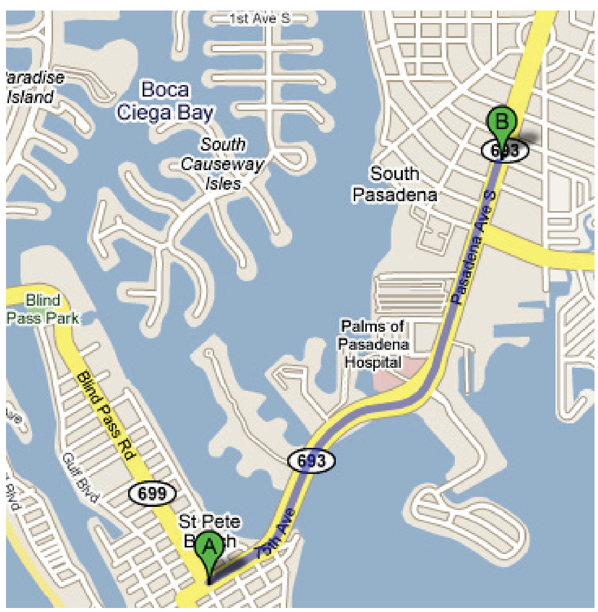

Figure 35 Pasadena Avenue ((A) Pasadena Avenue and Blind Pass Road, (B) Pasadena Avenue and Park Street)

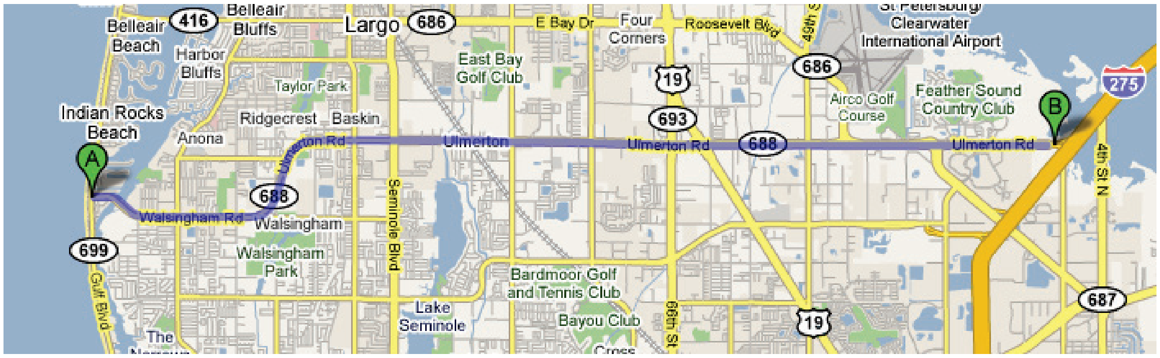

Figure 36 Ulmerton Road ((A) Ulmerton Road and Gulf Boulevard, (B) Ulmerton Road and I-275)

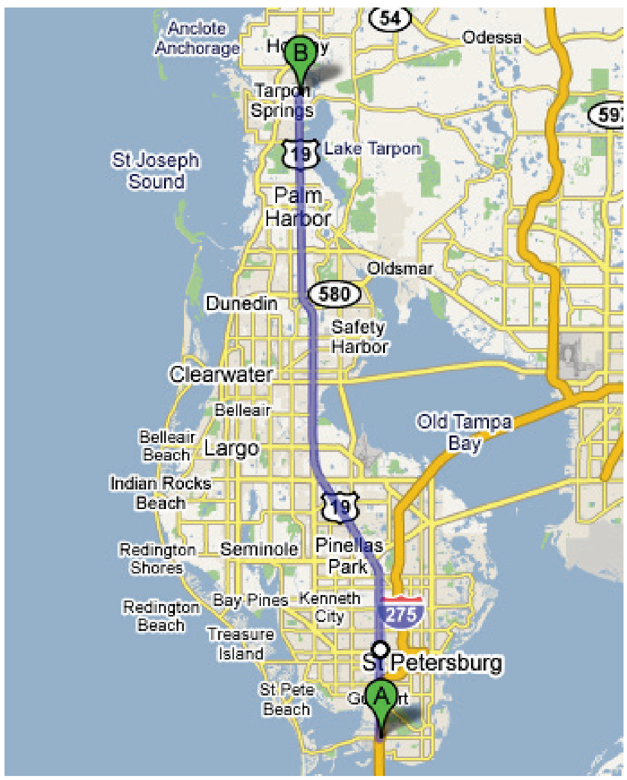

Figure 37 US-19 ((A) US-19 and 54th Avenue South, (B) US-19 and East Live Oak Street)

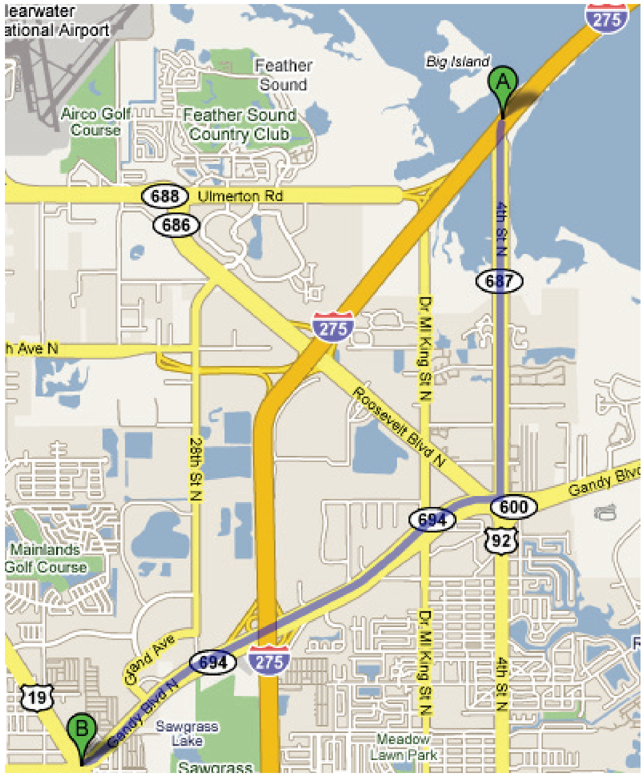

Figure 38 Gandy Boulevard/4th Street ((A) 4th Street and I-275, (B) Gandy Boulevard and US-19)

5.2 Roadway Lighting Illuminance Levels

Roadway lighting levels can be evaluated by three different methods: illuminance, luminance, and small target visibility. Luminance and small target visibility are commonly used to evaluate lighting design, as they measure the reflectance of the roadway surface. This makes them inappropriate for the evaluation of lighting systems. Therefore, the illuminance method is used in the evaluation of existing roadway lighting systems.

Currently, roadway lighting illuminance levels are often measured manually with handheld light meters. On a regional scale, this presents an enormous data collection task and offers limited or partial data. This data collection method also places the light meter operator in the middle of the roadway at night during low-light conditions, creating a safety concern for both data collection personnel and roadway users.

To address these safety issues, an Advanced Lighting Measurement System (ALMS) was developed by the Center for Urban Transportation Research. ALMS can measure lighting illuminance levels from a moving vehicle using the combination of a laptop computer, light meter, and distance measurement instrument (DMI). The illuminance value recorded by the light meter matches the location data from the DMI.

A light meter is the main unit of the ALMS. A light meter consisting of a sensor and a main unit with a built-in serial port to interface with a computer was selected. The light meter utilized has an accuracy of ±3 percent in measurement and a sampling time of 2.5 readings per second.

For data positioning, a Global Position System (GPS) and a longitudinal DMI were considered. Available portable GPS devices have an accuracy of approximately 40 feet, which is not accurate enough for the data collection requirements. In addition, the accuracy of a GPS device can be affected by factors such as weather and location (Central Business District (CBD) areas). Therefore, a longitudinal DMI was chosen for data positioning. The DMI selected has an accuracy of up to ±1 foot per mile.

A laptop computer was also an important part of the ALMS. The laptop computer was used, not only for data collection and storage, but also to establish the communication link between the light meter and DMI.

To automatically make measurements on illuminance at the desired distance intervals, a circuit was designed to detect the pulse when the DMI reached the distance selected during data collection. The circuit was designed with a small microcontroller and worked as a filter to detect the pulse from the DMI, converting it into a serial communication format.

An issue with serial connection ports was uncovered because newer laptop computers do not come equipped with serial connection ports. The laptop computer used in this project had only one serial communication port. However, two are required for the ALMS. This issue was resolved by using a USB converter device (RS-232 to USB). This USB converter creates a virtual serial port in one of the USB ports on the computer.

The lighting illuminance level was collected in both traffic directions, in the right and left lanes for all segments, with light poles on both sides of the street. Having lighting poles on both sides of the road were needed to in order to obtain maximum and minimum illuminance values per traffic direction. When a roadway segment was found with light poles on only one side of the road, the illuminance levels for that segment were measured only on the outside lanes, by traffic direction. This was done in order to obtain maximum values (under the roadway lighting poles) and minimum values (at the opposite side of the roadway lighting poles). Figure 39 shows an example of the data collection procedure for some typical traffic lanes configuration.

The top figure shows a two-lane undivided highway with fixed roadway lighting on one side of the road. For this segment only the measurements from the outside lanes were collected. The bottom two figures present a four-lane divided and four-lane undivided highway with fixed roadway lighting at both sides of the road. For this particular lane configuration, as well as for six or eight-lane divided highways, the measurements were collected on the inside and outside lanes by traffic direction.

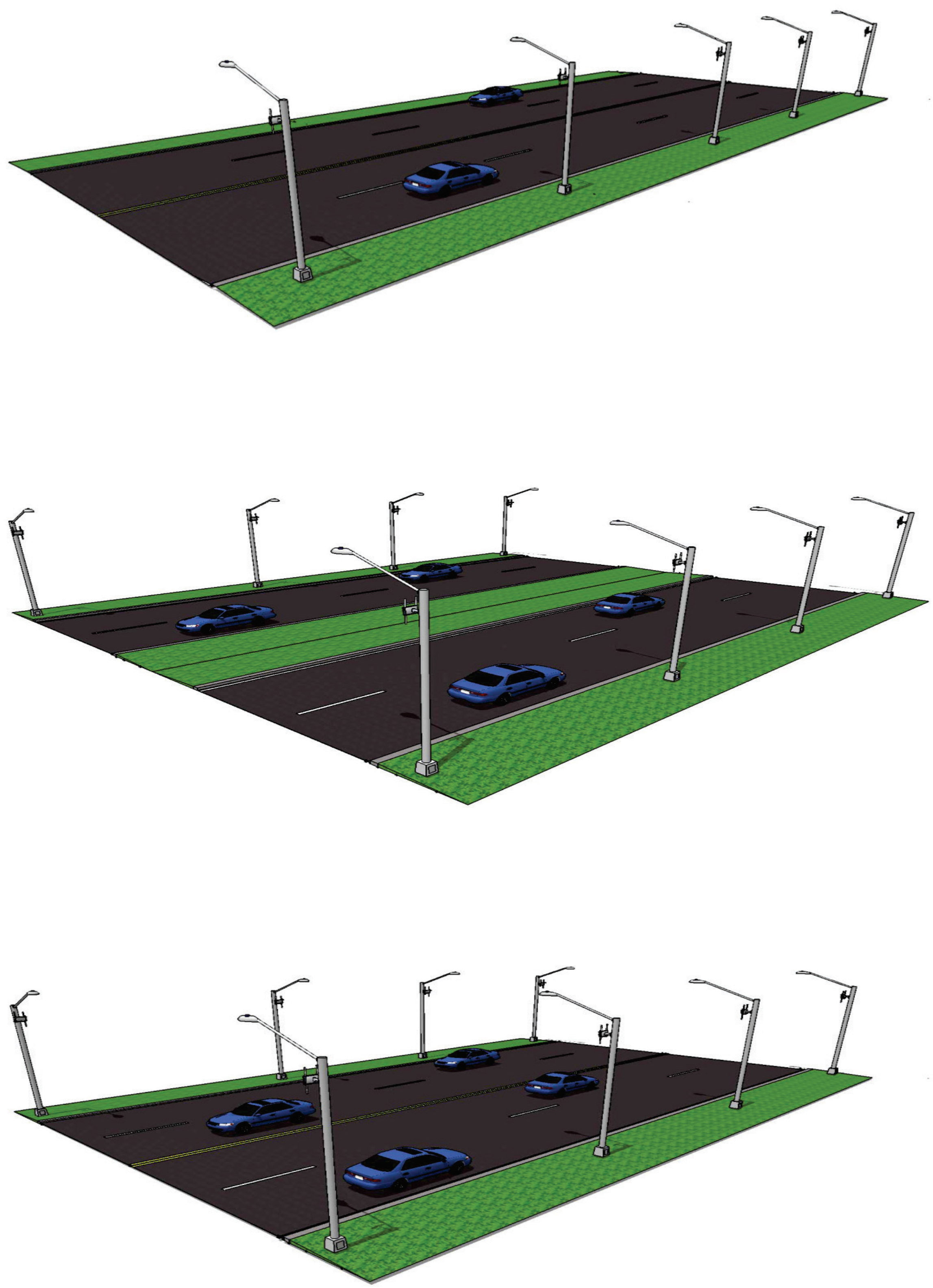

Figure 39 Data Collection Diagram

The data collections were recorded in 40 feet intervals on each lane by traffic direction. Figure 40 shows an example of the average illuminance level in foot candles obtained for one of the segments selected (56th Street).

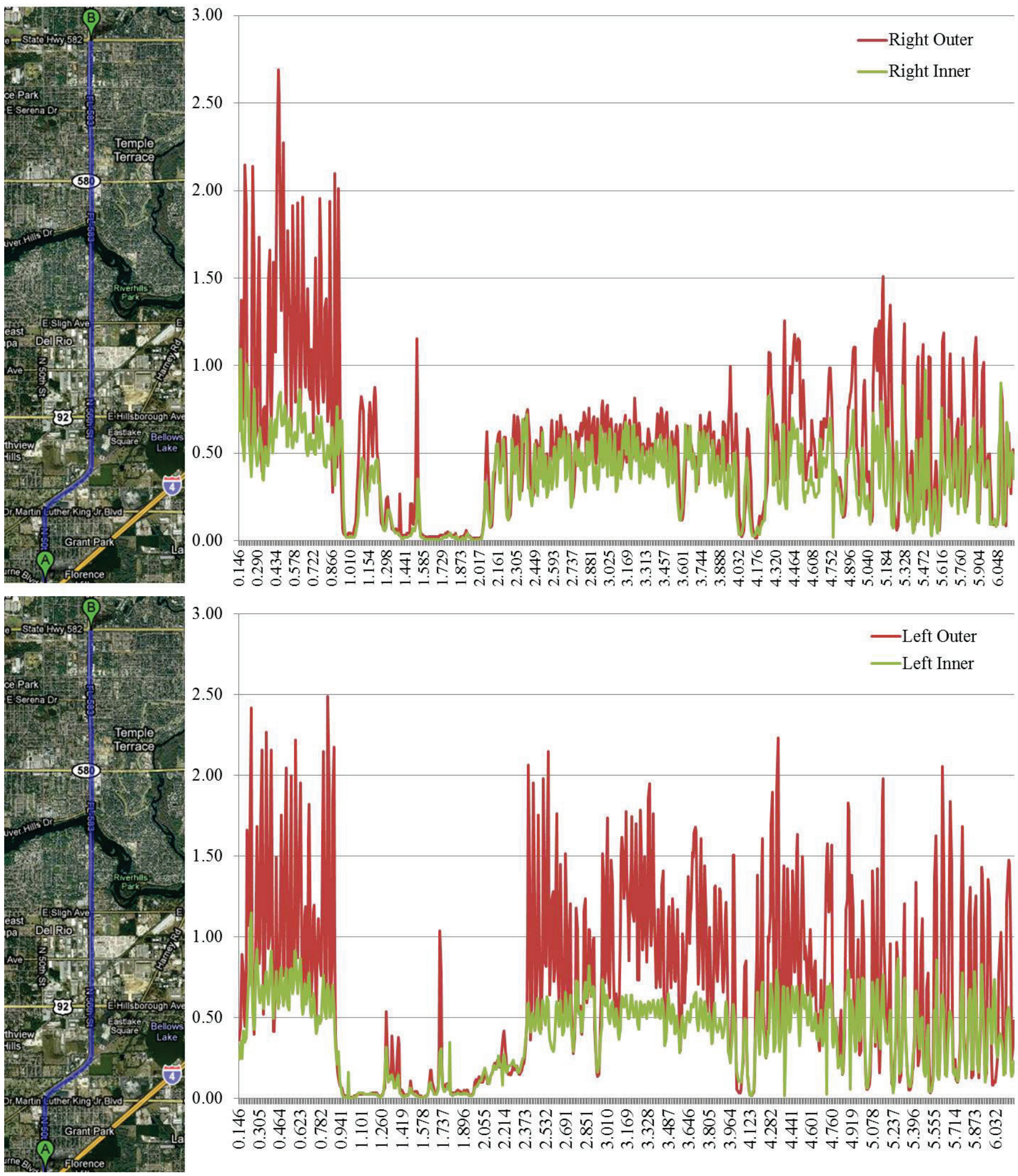

Figure 40 Roadway Illuminance Level Measured for 56th Street

In order to facilitate the analysis of the roadway lighting illuminance measured, the average for each cross section every 40 feet was computed. For the analysis performed in this research a roadway lighting average moving illuminance (AMI) was used for the crash data correlation. This roadway lighting AMI was calculated essentially by combining the average of more than one cross section's roadway lighting illuminance. A buffer was created to take into account a group of four cross section roadway lighting illuminance averages before and after the mile post where the crash occurred. This roadway lighting AMI provided the information for the surrounding roadway lighting illuminance condition that, in one way or another, affects the driver's final maneuver or action.

For the analysis of the roadway lighting AMI twelve ranges were defined: below 0.2 fc, between 0.2 and 0.4 fc, between 0.4 and 0.6, between 0.6 and 0.8 fc, between 0.8 and 1.0 fc, between 1.0 and 1.25 fc, between 1.25 and 1.5 fc, between 1.5 and 1.75 fc, between 1.75 and 2.0 fc, and more than 2.5 fc.

The roadway lighting illuminance measurements were taken on weekends and weekdays excluding Wednesdays during astronomical twilight periods. Astronomical twilight is the time when the center of the sun is between 12° and 18° below the horizon. In general, the end of astronomical twilight is the point where the sky is no longer illuminated by the sun and is dark enough for all astronomical observations. Twilight is the time between dawn and sunrise, when the entire sky is already fully dark.

5.3 Crash Data Reports

Crash data reports were required for the analysis to determine the relationship between injury severity and roadway illuminance levels. The crash data were obtained from FDOT's Crash Analysis Reporting System (CARS). A three-year time frame, 2005 to 2008, was selected for the analysis. This specific time frame was selected based on the time frame in which the roadway lighting illuminance measurements were taken (2007-2008). The crash reports were analyzed and grouped into daytime, dusk, dawn, and nighttime periods. For the scope of this research only the crashes during nighttime periods were utilized for model development and analysis. The crash data were paired to the corresponding roadway lighting illuminance levels by their corresponding mile post.

The crash data were selected using the roadway identification numbers between the beginning milepost and ending milepost for each segment. From the crash data the milepost was obtained for each of the crashes during nighttime in order to pair them with their corresponding lighting illuminance level.

Some of the characteristics from the crash reports that were analyzed during this research were milepost, date (day/month/year), time (hour), injury severity, crash location (at intersection, intersection-related, driveway-related, at railroad highway grade crossing, grade-crossing-related), light condition, weather, and pavement surface condition.

Each crash record was classified into daytime, dusk, dawn, and nighttime periods by using the sunset and sunrise time for the West Center Florida Region obtained from the US Naval Observatory *(28)*. Each crash record contained information related to the date and time where the crash occurred. Using this information as well as the sunset and sunrise time a macro was created using Microsoft Excel for the classification of each record. Table 7 presents the time classification or intervals for nighttime, dawn, day and dusk using the data obtained from the US Naval Observatory.

Table 7 Nighttime, Dawn, Day and Dusk Intervals Classification

	Night		Dawn	
January	7:00 PM	5:59 AM	6:00 AM	6:59 AM
February	7:00 PM	5:59 AM	6:00 AM	6:59 AM
March	7:00 PM	5:59 AM	6:00 AM	6:59 AM
April	9:00 PM	5:59 AM	6:00 AM	6:59 AM
May	9:00 PM	5:59 AM	6:00 AM	6:59 AM
June	9:00 PM	5:59 AM	6:00 AM	6:59 AM
July	9:00 PM	5:59 AM	6:00 AM	6:59 AM
August	9:00 PM	5:59 AM	6:00 AM	6:59 AM
September	8:00 PM	5:59 AM	6:00 AM	6:59 AM
October	8:00 PM	6:59 AM	7:00 AM	7:59 AM
November	6:00 PM	5:59 AM	6:00 AM	6:59 AM
December	6:00 PM	5:59 AM	6:00 AM	6:59 AM
	Day		Dusk	
January	7:00 AM	5:59 PM	6:00 PM	6:59 PM
February	7:00 AM	5:59 PM	6:00 PM	6:59 PM
March	7:00 AM	5:59 PM	6:00 PM	6:59 PM
April	7:00 AM	7:59 PM	8:00 PM	8:59 PM
May	7:00 AM	7:59 PM	8:00 PM	8:59 PM
June	7:00 AM	7:59 PM	8:00 PM	8:59 PM
July	7:00 AM	7:59 PM	8:00 PM	8:59 PM
August	7:00 AM	7:59 PM	8:00 PM	8:59 PM
September	7:00 AM	6:59 PM	7:00 PM	7:59 PM
October	8:00 AM	6:59 PM	7:00 PM	7:59 PM
November	7:00 AM	4:59 PM	5:00 PM	5:59 PM
December	7:00 AM	4:59 PM	5:00 PM	5:59 PM

A color coded box plot was created for a better understanding of the starting and ending times for which each classification occurred. Each particular color defines a particular category. Table 8 presents the box plot used.

Table 8 Box Plot Diagram for Crash Data Analysis

	January	February	March	April	May	June	July	August	September	October	November	December
12:00 AM												
1:00 AM												
2:00 AM												
3:00 AM												
4:00 AM												
5:00 AM												
6:00 AM												
7:00 AM												
8:00 AM												
9:00 AM												
10:00 AM												
11:00 AM												
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5:00 PM												
6:00 PM												
7:00 PM												
8:00 PM												
9:00 PM												
10:00 PM												
11:00 PM												

The gray cells correspond to the nighttime hours; the white cells correspond to the daytime hours (when the sun is in the sky). Meanwhile, for sunset, also called dusk, the pinkish cells were used. The green cells correspond to sunrise, or dawn. As it can be seen in the above table, Florida suffers a change in the sunrise period for the month of October (7:00 to 7:59 PM). The rest of the year the sunrise time is between 6:00 to 6:59 AM. For sunset the table shows four different block periods of time during the year. The first period is between the months of January to March from 6:00 to 6:59 PM. The second period is between the months of April to August (Summer) from 8:00 to 8:59 PM. The third period is between the months of September to October from 7:00 to 7:59 PM. The fourth and final period is between the months of November and December from 6:00 to 6:59 PM. The time frames were defined in one hour intervals because the information related to traffic conditions is also recorded in one hour intervals.

Research shows that the traffic volume during nighttime conditions is less than during daylight conditions. Figure 41 presents a comparison between the average vehicles per hour and the count of crashes during nighttime conditions for the study area (West Central Florida Region).

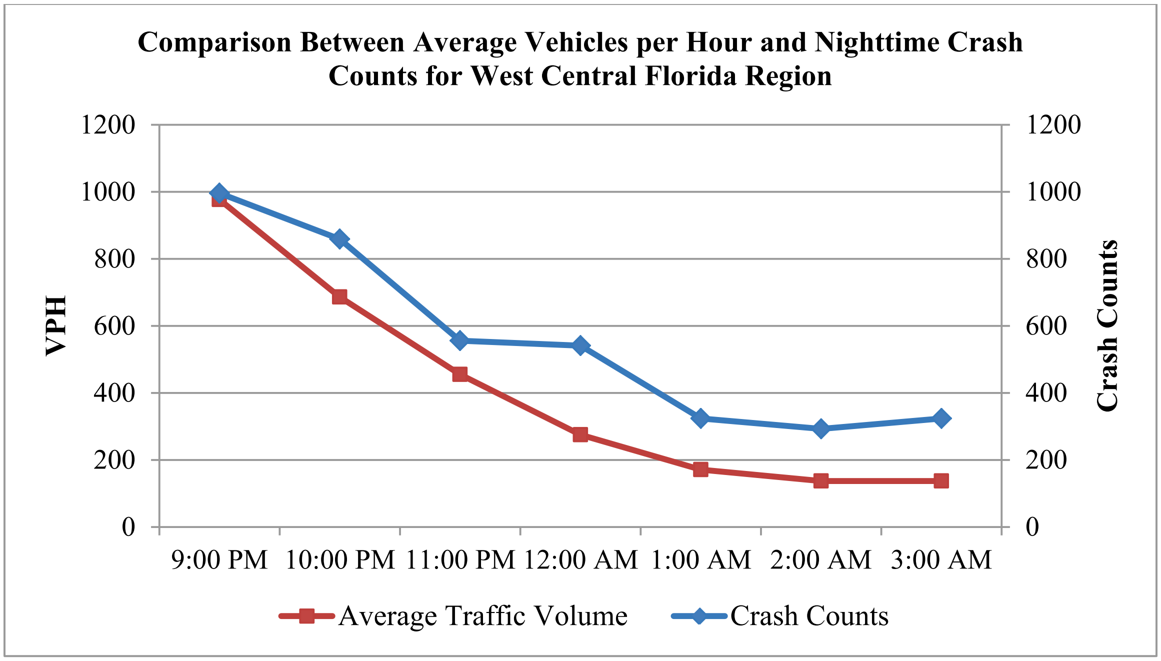

Figure 41 Average Vehicle per Hour vs. Crash Count

The figure above shows the distribution of crashes. It can be seen that the number of crashes increases with respect to the traffic volume during nighttime conditions. It can also be noticed that there is a significant, high number of crashes with respect to the nighttime traffic volume.

CHAPTER 6: MODEL RESULTS

6.1 Results Overview

The distribution of nighttime crash injury severity for the West Central Florida Region Area was as follows: (1) None Injury, N = 3,764 (52%); (2) Possible Injury, N = 1,517 (21%); (3) Non-Incapacitating Injury, N = 1,197 (17%); (4) Incapacitating Injury, N = 657 (9%); (5) Fatal, N = 67 (1%). The distribution of injury severity with respect to each roadway lighting average moving illuminance as in Case 1: All Nighttime Crashes, is presented in the appendix.

Comparisons between crashes occurring during daytime and nighttime were performed before getting into the analysis of the nighttime crash injury severity and its relationship with the roadway illuminance measured. The first consideration was the examination of the average injury severity during daytime versus nighttime for the study area. Table 9 presents the total crash counts during the study period (2005-2008) and the average injury severity with respect to each lighting condition.

Table 9 Lighting Condition and Average Injury Severity

Light Condition	Injury Counts	Average Injury Severity
Dark	7008	2
Dawn	414	2
Daylight	24990	2
Dusk	798	2

The table above shows that there is no difference in the average injury severity between all lighting conditions (dark, dawn, daylight, and dusk). The average injury severity was found to be Possible Injury (2) for all lighting conditions. Table 10 presents the first four, first harmful events for each of the different lighting conditions.

Table 10 Lighting Condition and First Harmful Event

Rank	First Harmful Event	Dark	Daylight	Dusk & Dawn
1	Rear-end	2514(38%)	11003(47%)	473(41%)
2	Angle	1305(20%)	5027(21%)	236(21%)
3	Left-turn	654(10%)	2150(9%)	133(12%)
4	Sideswipe	587(9%)	2074(9%)	87(8%)

The table above shows that there is no difference in the first harmful event for all lighting conditions. The highest rank (highest count for the first harmful events) was rear-end collisions for all lighting conditions. The results presented in Tables 9 and 10 tell us that there is no evidence of geometric factors or roadway characteristics that could make nighttime conditions different from daylight conditions.

6.2 All Nighttime Crashes Results

6.2.1 Variables Description

This section presents and describes the variables used for the analysis of the existing relationship between roadway lighting illuminance levels and injury severity for the West Central Florida Region. All of the variables presented in this section were utilized on either the Ordered Probit Model or Negative Binomial Model. The data collected and used in this research corresponds to crash reports for 2005 to 2008. The sample size data for all nighttime crashes corresponds to 7,202 observations. Table 11 presents and describes the variables used on the models.

Table 11 Description of the Model Variables

Variable	Description
Road Surface Condition	
RSDry	Dry
RSWet	Wet
RSSlippery	Slippery
RSIcy	Icy
RSAllOther	All Other Explain
Site Location	
FsiteLocIntOrNearby	At Intersection or Influenced By Intersection
FnotInt	Not At Intersection / RR-X-ing / Bridge
Fdriveway	Driveway Access
First Harmful Events	
FAllOther	Other
Fangle	Collision With MV in Transport (Angle)
FBackedInto	Collision With MV in Transport (Backed Into)
FCargoLossOrShift	Cargo Loss or Shift
FCollWPedBike	Collision With Pedestrian or Bicycle
FCollWOther	Collision With Other
Ffire	Fire
FHeadOn	Collision With MV in Transport (Head On)
FHitFixedOther	MV Hit Fixed Object
FLeftTurn	Collision With MV in Transport (Left Turn)
FMedianCrossover	Median Crossover
FOccupantFelt	Occupant Felt From Vehicle
FOverturned	Overturned
FRanOff	MV Ran Off
FRearEnd	Collision With MV in Transport (Rear End)
FRightTurn	Collision With MV in Transport (Right Turn)
FSeparationOfUnits	Separation of Units
FSidesWipe	Collision With MV in Transport (Sideswipe)
FUtilityLightPole	MV Hit Utility Pole / Light Pole
Funknown	Unknown
Fnone	None

Table 11 Continued

Variable	Description
Functional Classification	
FCUrbanMinorArt	Urban Minor Arterial
FurbanPrinArtExpr	Urban Principal Arterial / Expressway
FCUrbanOtherPrinArt	Urban Other Principal Arterial
Land Use	
LUCentralBusinessDistrict	Central Business District (CBD)
LUHighDensityBusCommercial	High Density Bus Commercial
LUHighDensityResidential	High Density Residential
LUHighDensity	High Density
LULowDensityCommercial	Low Density Commercial
LULowDensityResidential	Low Density Residential
LULowDensity	Low Density
LUOther	Other
LUCommercial	Commercial
LUResidential	Residential
LUNoInfo	No Information
Roadway Posted Speed	
FSpeedA	Less than 35 mph
FSpeedB	40 to 45 mph
FSpeedC	More than 50 mph
Number of Lanes	
NL1Lane	1 Lane
NL2Lanes	2 Lanes
NL3Lanes	3 Lanes
NL4Lanes	4 Lanes
NL34Lanes	More than 3 Lanes
Vehicles per Hour (VPH)	
VPHA	Less than 500 VPH
VPHB	Between 500 to 1000 VPH
VPHAB	Less than 1000 VPH
VPHC	Between 1000 to 1500 VPH
VPHD	Between 1500 to 2000 VPH
VPHCD	Between 1000 to 2000 VPH
VPHE	Between 2000 to 2500 VPH
VPHF	More than 2500 VPH
VPHEF	More than 2000 VPH

Table 11 Continued

Variable	Description
Roadway Average Moving Illuminance	
AMIA	Less than 0.20 fc
AMIB	Between 0.20 to 0.40 fc
AMIC	Between 0.40 to 0.60 fc
AMID	Between 0.60 to 0.80 fc
AMIE	Between 0.80 to 1.00 fc
AMIF	Between 1.00 to 1.25 fc
AMIG	Between 1.25 to 1.50 fc
AMIH	Between 1.50 to 1.75 fc
AMII	Between 1.75 to 2.00 fc
AMIJ	Between 2.00 to 2.25 fc
AMIK	Between 2.25 to 2.50 fc
AMIL	More than 2.50 fc

Table 12 exemplifies a statistical description for the variables presented above. The frequency and proportion description for each variable are provided below.

Table 12 Variables Statistical Description

Description	Frequency	Proportion
Road Surface Condition		
Dry	6134	85%
Wet	989	14%
Slippery	47	1%
Icy	4	0%
All Other Explain	28	0%
Site Location		
At Intersection or Influenced By Intersection	4845	67%
Not At Intersection / RR-X-ing / Bridge	1821	25%
Driveway Access	480	7%
Injury Severity		
Fatal	67	1%
Incapacitating	657	9%
Non-Incapacitating	1197	17%
Possible	1517	21%
None	3764	52%

Table 12 Continued

Description	Frequency	Proportion
First Harmful Events		
Other	465	6%
Collision With MV in Transport (Angle)	1342	19%
Collision With MV in Transport (Backed Into)	66	1%
Cargo Loss or Shift	2	0%
Collision With Pedestrian or Bicycle	321	4%
Collision With Other	310	4%
Fire	12	0%
Collision With MV in Transport (Head On)	174	2%
MV Hit Fixed Object	248	3%
Collision With MV in Transport (Left Turn)	672	9%
Median Crossover	24	0%
Occupant Felt From Vehicle	9	0%
Overturned	36	0%
MV Ran Off	42	1%
Collision With MV in Transport (Rear End)	2598	36%
Collision With MV in Transport (Right Turn)	141	2%
Separation of Units	1	0%
Collision With MV in Transport (Sideswipe)	597	8%
MV Hit Utility Pole / Light Pole	128	2%
Unknown	13	0%
None	1	0%
Functional Classification		
Urban Minor Arterial	1172	16%
Urban Principal Arterial / Expressway	42	1%
Urban Other Principal Arterial	5988	83%
Land Use		
Central Business District (CBD)	36	0%
High Density Bus Commercial	0	0%
High Density Residential	232	3%
High Density	232	3%
Low Density Commercial	1579	22%
Low Density Residential	110	2%
Low Density	1689	23%
Other	62	1%
Commercial	1579	22%
Residential	342	5%
No Information	30	0%

Table 12 Continued

Description	Frequency	Proportion
Roadway Posted Speed		
Less than 35 mph	807	11%
40 to 45 mph	4601	64%
More than 50 mph	1794	25%
Number of Lanes		
1 Lane	93	1%
2 Lanes	2178	30%
3 Lanes	4170	58%
4 Lanes	761	11%
More than 3 Lanes	4931	68%
Vehicles per Hour (VPH)		
Less than 500 VPH	1722	24%
Between 500 to 1000 VPH	1252	17%
Less than 1000 VPH	2974	41%
Between 1000 to 1500 VPH	1148	16%
Between 1500 to 2000 VPH	908	13%
Between 1000 to 2000 VPH	2056	29%
Between 2000 to 2500 VPH	860	12%
More than 2500 VPH	1312	18%
More than 2000 VPH	2172	30%
Roadway Average Moving Illuminance		
Less than 0.20 fc	910	13%
Between 0.20 to 0.40 fc	693	10%
Between 0.40 to 0.60 fc	880	12%
Between 0.60 to 0.80 fc	863	12%
Between 0.80 to 1.00 fc	829	12%
Between 1.00 to 1.25 fc	669	9%
Between 1.25 to 1.50 fc	1009	14%
Between 1.50 to 1.75 fc	647	9%
Between 1.75 to 2.00 fc	346	5%
Between 2.00 to 2.25 fc	139	2%
Between 2.25 to 2.50 fc	80	1%
More than 2.50 fc	137	2%

In order to obtain a better understanding about the explanatory variables, a cross tabulation for each of the variables with respect to crash severity were developed. This is provided in Tables 13 and 14. Table 13 presents the variables selected for the Order Probit Model analysis. Meanwhile, Table 14 presents the variables selected for the Negative Binomial Model analysis.

Table 13 Cross Tabulations of the Variables Used for the Order Probit Model

Variables	Fatal	Incapacitating	Non-Incapacitating	Possible	None	Total
Road Surface Condition (Base - Wet, Slippery, All Other)						
Base	7(1%)	80(7%)	153(14%)	220(21%)	608(57%)	1068(100%)
Dry	60(1%)	577(9%)	1044(17%)	1297(21%)	3156(51%)	6134(100%)
Site Location (Base - At Intersection or Influenced By Intersection, Driveway Access, All Other)						
Base	37(1%)	457(8%)	895(17%)	1166(22%)	2826(53%)	5381(100%)
Not At Intersection / RR-X-ing / Bridge	30(2%)	200(11%)	302(17%)	351(19%)	938(52%)	1821(100%)
Number of Lanes (Base - Less than 3 Lanes)						
Base	19(1%)	200(9%)	361(16%)	450(20%)	1241(55%)	2271(100%)
More than 3 Lanes	48(1%)	457(9%)	836(17%)	1067(22%)	2523(51%)	4931(100%)
Roadway Posted Speed (Base - More than 35 mph)						
Base	62(1%)	617(10%)	1064(17%)	1352(21%)	3300(52%)	6395(100%)
Less than 35 mph	5(1%)	40(5%)	133(16%)	165(20%)	464(57%)	807(100%)
Vehicles per Hour (VPH) (Base - More than 1000 VPH)						
Base	43(1%)	361(9%)	684(16%)	955(23%)	2185(52%)	4228(100%)
Less than 1000 VPH	24(1%)	296(10%)	513(17%)	562(19%)	1579(53%)	2974(100%)
Roadway Average Moving Illuminance (Base - Less than 0.40 fc, and More than 0.80 fc)						
Base	58(1%)	512(9%)	884(16%)	1174(22%)	2831(52%)	5459(100%)
Between 0.40 to 0.60 fc	4(0%)	59(7%)	145(16%)	160(18%)	512(58%)	880(100%)
Between 0.60 to 0.80 fc	5(1%)	86(10%)	168(19%)	183(21%)	421(49%)	863(100%)

Table 14 Cross Tabulations of the Variables Used for the Negative Binomial Model

Variables	Fatal	Incapacitating	Non-Incapacitating	Possible	None	Total
First Harmful Events (Base - Other, Cargo Loss or Shift, Collision With Other, Fire, MV Hit Fixed Object, Median Crossover, Occupant Felt From Vehicle, Overturned, MV Ran Off, Separation of Units, Unknown)						
Base	9(1%)	130(9%)	268(19%)	265(19%)	760(53%)	1432(100%)
Collision With MV in Transport (Angle)	14(1%)	132(10%)	221(16%)	289(22%)	686(51%)	1342(100%)
Collision With MV in Transport (Backed Into)	0(0%)	0(0%)	0(0%)	6(9%)	60(91%)	66(100%)
Collision With Pedestrian or Bicycle	26(8%)	142(44%)	100(31%)	37(12%)	16(5%)	321(100%)
Collision With MV in Transport (Head On)	1(1%)	24(14%)	41(24%)	40(23%)	68(39%)	174(100%)
Collision With MV in Transport (Left Turn)	7(1%)	59(9%)	147(22%)	140(21%)	319(47%)	672(100%)
Collision With MV in Transport (Rear End)	9(0%)	151(6%)	375(14%)	673(26%)	1390(54%)	2598(100%)
Collision With MV in Transport (Sideswipe)	1(0%)	19(3%)	45(8%)	67(11%)	465(78%)	597(100%)
Functional Classification (Base - Urban Principal Arterial / Expressway, Urban Other Principal Arterial)						
Base	54(1%)	559(9%)	994(16%)	1301(22%)	3122(52%)	6030(100%)
Urban Minor Arterial	13(1%)	98(8%)	203(17%)	216(18%)	642(55%)	1172(100%)
Land Use (Base - Residential, Other, No Information)						
Base	51(1%)	513(9%)	934(17%)	1224(22%)	2901(52%)	5623(100%)
Commercial	16(1%)	144(9%)	263(17%)	293(19%)	863(55%)	1579(100%)

Table 14 Continued

Variables	Fatal	Incapacitating	Non-Incapacitating	Possible	None	Total
Roadway Posted Speed (Base - More than 35 mph)						
Base	62(1%)	617(10%)	1064(17%)	1352(21%)	3300(52%)	6395(100%)
Less than 35 mph	5(1%)	40(5%)	133(16%)	165(20%)	464(57%)	807(100%)
Vehicles per Hour (VPH) (Base -Less than 1500 VPH, More than 2000 VPH)						
Base	56(1%)	567(9%)	1060(17%)	1319(21%)	3292(52%)	6294(100%)
Between 1500 to 2000 VPH	11(1%)	90(10%)	137(15%)	198(22%)	472(52%)	908(100%)
Roadway Average Moving Illuminance (Base - Less than 0.40 fc, Between 0.80 to 1.00 fc, and More than 1.25 fc)						
Base	47(1%)	406(9%)	743(17%)	915(21%)	2339(53%)	4450(100%)
Between 0.40 to 0.60 fc	4(0%)	59(7%)	145(16%)	160(18%)	512(58%)	880(100%)
Between 0.60 to 0.80 fc	5(1%)	86(10%)	168(19%)	183(21%)	421(49%)	863(100%)
Between 1.00 to 1.25 fc	11(1%)	106(11%)	141(14%)	259(26%)	492(49%)	1009(100%)

6.2.2 Ordered Probit Model Estimation

The estimation of results for the Ordered Probit Model is specified in Table 15 and Table 16. The sample size was 7,202 observations (injury severity as it applies to drivers involved in crashes during nighttime conditions from 2005 to 2008), and the likelihood ratio (LR) test statistic falls into the rejection area (p – value = 0 < 0.05). This means that the overall explanatory variables of the model have significant influence on the responses (injury severity) at a statistical significance level of 95 percent.

Table 15 Ordered Probit Model Summary Description

Number of observations =	7202
Log likelihood at Zero =	-8839.8796
Log likelihood at Convergence =	-8808.8033
LR $chi^2(7)$ =	62.15
Prob > chi^2 =	0
Pseudo R^2 =	0.0035

Table 16 Ordered Probit Model Parameter Estimates

Variables	Coefficient	Standard Error	Z	P>|z|	95% C.I.	
Road Surface Dry	0.150	0.038	3.93	0.000	0.075	0.224
Not At Intersection	0.068	0.031	2.22	0.026	0.008	0.129
3 Lanes or More	0.057	0.030	1.92	0.055	-0.001	0.115
Less than 35 mph	-0.186	0.045	-4.13	0.000	-0.275	-0.098
1000 vph or Less	0.050	0.029	1.74	0.081	-0.006	0.106
Between 0.40 to 0.60 fc	-0.154	0.042	-3.64	0.000	-0.237	-0.071
Between 0.60 to 0.80 fc	0.068	0.041	1.65	0.100	-0.013	0.148
Threshold 1 (μ_1)	0.230	0.046			0.139	0.320
Threshold 2 (μ_2)	0.798	0.047			0.707	0.890
Threshold 3 (μ_3)	1.459	0.048			1.364	1.554
Threshold 4 (μ_4)	2.541	0.064			2.417	2.666

Table 16 shows the estimation results of an Ordered Probit Model for injury severity as it applies to drivers involved in crashes during nighttime conditions from 2005 to 2008. Since the dependent variable, injury severity, increases as the numbers increase from None Injury (1) to Fatal Injury (5), positive estimate values suggest an increase in the probability of being involved in a crash resulting in a more severe injury.

Table 16 shows that all variables with a *z*-statistic of ± 1.96 or greater will significantly affect the injury severity for all nighttime crashes at a 95 percent confidence level or greater. Furthermore, variables with a *z*-statistic of ± 1.64 or greater but less than ± 1.96 will significantly affect the injury severity for all nighttime crashes between the 90 and 95 percent confidence level. For example, any vehicle driving on a dry roadway surface at night and not at an intersection is more likely to be involved in a crash resulting in higher injury severity. Table 17 presents the influence of the variables with respect to the likelihood of an increase or decrease in crash injury severity.

Table 17 Analysis of the Coefficient Signs

Independent Variable	Sign	Influence on Crash Injury Severity
Road Surface Dry	+	Increase
Not At Intersection	+	Increase
3 Lanes or More	+	Increase
Less than 35 mph	-	Decrease
1000 vph or Less	+	Increase
Between 0.40 to 0.60 fc	-	Decrease
Between 0.60 to 0.80 fc	+	Increase

Table 17 demonstrates that driving on roadway segments with less than 1,000 vph during nighttime and with roadway illuminance levels between 0.6-0.8 fc would increase the likelihood of being involved in a crash resulting in higher injury severity. In fact, if there are fewer cars on the road some drivers may be more likely to increase their driving speed. Exceeding the posted speed can make them lose the control of their vehicles, resulting in a higher impact and more serious injury crash. Furthermore, if a driver of a vehicle has a crash during nighttime periods while on a dry roadway surface and in roadways segments with more than three lanes, the driver would be more likely to be involved in a crash resulting in higher injury severity. In essence, driving during nighttime conditions on dry pavement, with low traffic volume and with open road ahead is more likely to feel more relegated of any pressure. This can sometimes create an excess of relaxation, and a significant lack of attention to the driver's surroundings.

The results from the Ordered Probit Model showed that a roadway lighting illuminance level between 0.4 and 0.6 fc (less than the amount of roadway lighting illumination than required by the *Florida Plans Preparation Manual*, see Table 1) would have a positive impact on roadway user's safety. In other words, it seems that roadway users drive more cautiously under smaller amounts of roadway lighting illumination. In addition, driving speeds less than 35 mph seem to have a positive effect on roadway user's safety.

The marginal effect of each explanatory variable utilized in the Ordered Probit Model is presented in Table 18. Marginal effects show how the probability of increasing or decreasing injury severity changes with respect to the explanatory variables. The advantage of using the Ordered Probit Model is that the marginal effect allows the determination of the impact of each explanatory variable on the probability of each injury severity level.

Table 18 Marginal Effects

Variables	Coefficient	Standard Error	Z	P>|z|	95% C.I.	
None Injury						
Road Surface Dry	-0.059	0.015	-3.96	0.000	-0.089	-0.030
Not At Intersection	-0.027	0.012	-2.22	0.026	-0.051	-0.003
3 Lanes or More	-0.023	0.012	-1.92	0.055	-0.046	0.000
Less than 35 mph	0.074	0.018	4.18	0.000	0.039	0.108
1000 vph or Less	-0.020	0.011	-1.74	0.081	-0.042	0.002
Between 0.40 to 0.60 fc	0.061	0.017	3.68	0.000	0.028	0.094
Between 0.60 to 0.80 fc	-0.027	0.016	-1.64	0.100	-0.059	0.005
Variables	**Coefficient**	**Standard Error**	**Z**	**P>|z|**	**95% C.I.**	
Possible Injury						
Road Surface Dry	0.012	0.003	3.50	0.000	0.005	0.019
Not At Intersection	0.005	0.002	2.32	0.020	0.001	0.008
3 Lanes or More	0.004	0.002	1.86	0.063	0.000	0.008
Less than 35 mph	-0.015	0.004	-3.59	0.000	-0.024	-0.007
1000 vph or Less	0.003	0.002	1.76	0.079	0.000	0.007
Between 0.40 to 0.60 fc	-0.012	0.004	-3.23	0.001	-0.020	-0.005
Between 0.60 to 0.80 fc	0.004	0.003	1.77	0.077	0.000	0.009

Table 18 Continued

Variables	Coefficient	Standard Error	Z	P>|z|	95% C.I.	
Non-Incapacitating Injury						
Road Surface Dry	0.023	0.006	3.91	0.000	0.011	0.035
Not At Intersection	0.010	0.005	2.22	0.026	0.001	0.020
3 Lanes or More	0.009	0.005	1.91	0.056	0.000	0.018
Less than 35 mph	-0.029	0.007	-4.13	0.000	-0.042	-0.015
1000 vph or Less	0.008	0.004	1.74	0.082	-0.001	0.016
Between 0.40 to 0.60 fc	-0.024	0.007	-3.64	0.000	-0.036	-0.011
Between 0.60 to 0.80 fc	0.010	0.006	1.65	0.098	-0.002	0.023
Variables	**Coefficient**	**Standard Error**	**Z**	**P>|z|**	**95% C.I.**	
Incapacitating Injury						
Road Surface Dry	0.021	0.005	4.16	0.000	0.011	0.031
Not At Intersection	0.010	0.005	2.18	0.029	0.001	0.020
3 Lanes or More	0.008	0.004	1.94	0.053	0.000	0.017
Less than 35 mph	-0.026	0.006	-4.48	0.000	-0.037	-0.015
1000 vph or Less	0.008	0.004	1.73	0.083	-0.001	0.016
Between 0.40 to 0.60 fc	-0.022	0.006	-3.89	0.000	-0.033	-0.011
Between 0.60 to 0.80 fc	0.010	0.007	1.60	0.110	-0.002	0.023
Variables	**Coefficient**	**Standard Error**	**Z**	**P>|z|**	**95% C.I.**	
Fatal Injury						
Road Surface Dry	0.003	0.001	4.03	0.000	0.002	0.005
Not At Intersection	0.002	0.001	2.09	0.036	0.000	0.003
3 Lanes or More	0.001	0.001	1.92	0.055	0.000	0.003
Less than 35 mph	-0.004	0.001	-4.37	0.000	-0.006	-0.002
1000 vph or Less	0.001	0.001	1.70	0.089	0.000	0.003
Between 0.40 to 0.60 fc	-0.003	0.001	-3.84	0.000	-0.005	-0.002
Between 0.60 to 0.80 fc	0.002	0.001	1.53	0.126	0.000	0.004

As it can be observed from Table 18 the marginal effects indicate that the variables; dry road surface, not at intersection, having more than 3 lanes, and driving in traffic conditions of less than 1,000 vph result mainly in nighttime crashes with high injury severity. Meanwhile, a roadway segment with a roadway lighting illuminance level ranging from 0.6 to 0.8 fc seems to have a significant influence (at a 90 percent confidence interval or higher) in crashes resulting in none injury, possible injury and non-incapacitating injury severity. For crashes resulting with incapacitating injury or fatal injury severity the value of the *z*-statistic was less than ±1.64. Therefore, this means that the roadway lighting illuminance level ranging from 0.6 to 0.8 fc does not have any significant influence. Table 19 presents a comparison for each variable with respect to their marginal effects for all possible injury severities.

Table 19 Marginal Effects Comparison

Variables	**Injury Severity**				
	None	**Possible**	**Non-Incapacitating**	**Incapacitating**	**Fatal**
Road Surface Dry	-	+	+	+	+
Not At Intersection	-	+	+	+	+
3 Lanes or More	-	+	+	+	+
Less than 35 mph	+	-	-	-	-
1000 vph or Less	-	+	+	+	+
Between 0.40 to 0.60 fc	+	-	-	-	-
Between 0.60 to 0.80 fc	-	+	+	+	+

As it is illustrated in Table 19, roadway lighting illuminance ranges between 0.4 to 0.6 fc can have a positive safety impact on drivers during nighttime conditions. At the same time the variable that describes the posted speed of 25 to 35 mph for any roadway segment seems to have a positive safety impact on drivers during nighttime conditions. These two variables, a roadway lighting illuminance range between 0.4 to 0.6 fc and a posted speed less than 35 mph can reduce the probability of being involved in crashes resulting in fatal injuries. However, these two variables can increase the probability for crashes resulting in none injury severity category.

6.2.3 Negative Binomial Model Estimation

The estimation of results for the Negative Binomial Model is specified in Tables 20 and Table 21. The sample size data were 7,202 observations (count of crashes resulting in injury severity as applied to drivers involved in nighttime crashes from 2005 to 2008), and the likelihood ratio (LR) test statistic falls into the rejection area (p – value = 0 < 0.05). This means that the overall explanatory variables of the model have significant influence on the responses (count of crashes resulting on injury severity) at a statistical significance level 95 percent.

Table 20 Negative Binomial Model Summary Description

Number of observations =	7202
Log likelihood at Zero =	-8532.0615
Log likelihood at Convergence =	-8524.0155
LR $chi^2(14)$ =	314.74
Prob > chi^2 =	0
Pseudo R^2 =	0.0181
Alpha =	0.531

Table 21 Negative Binomial Model Parameter Estimates

Variables	Coefficient	Standard Error	Z	P>|z|	95% C.I.	
Angle Collision	0.280	0.052	5.36	0.000	0.178	0.383
Backed Into Collision	-1.634	0.367	-4.45	0.000	-2.354	-0.915
Collision With Pedestrian or Bicycle	0.444	0.079	5.61	0.000	0.289	0.599
Head On Collision	0.543	0.100	5.45	0.000	0.347	0.738
Left Turn Collision	0.390	0.062	6.29	0.000	0.269	0.512
Rear End Collision	0.220	0.047	4.73	0.000	0.129	0.311
Sideswipe Collision	-0.694	0.087	-8.02	0.000	-0.864	-0.525
Urban Minor Arterial	-0.103	0.048	-2.14	0.032	-0.197	-0.009
Land Use Commercial	-0.117	0.040	-2.93	0.003	-0.196	-0.039
Less than 35 mph	-0.125	0.057	-2.21	0.027	-0.236	-0.014
Between 1500 to 2000 VPH	-0.087	0.050	-1.76	0.079	-0.185	0.010
Between 0.40 to 0.60 fc	-0.156	0.053	-2.93	0.003	-0.260	-0.052
Between 0.60 to 0.80 fc	0.085	0.050	1.70	0.090	-0.013	0.182
Between 1.00 to 1.25 fc	0.095	0.046	2.04	0.041	0.004	0.186
Constant	-0.378	0.043	-8.88	0.000	-0.461	-0.294

The estimation results for a Negative Binomial Model on the count of crashes resulting in injury severity as applied to drivers involved in nighttime crashes from 2005 to 2008 are provided in Table 21.

As shown in Table 21, all variables with a *z*-statistic of ± 1.96 or greater will significantly affect the injury severity for all nighttime crashes at the 95 percent confidence level or higher. Furthermore, variables with a *z*-statistic of ± 1.64 or greater but less than ± 1.96 will significantly affect the injury severity for all nighttime crashes between the 95 percent and 90 percent confidence level. Table 22 presents the effect of all the variables with respect to the likelihood of an increase or decrease in the probability of crashes resulting in injuries during nighttime conditions.

Table 22 Analysis of the Coefficient Signs

Independent Variable	Sign	Influence on Crash occurrence
Angle Collision	+	Increase
Backed Into Collision	-	Decrease
Collision With Pedestrian or Bicycle	+	Increase
Head On Collision	+	Increase
Left Turn Collision	+	Increase
Rear End Collision	+	Increase
Sideswipe Collision	-	Decrease
Urban Minor Arterial	-	Decrease
Land Use Commercial	-	Decrease
Less than 35 mph	-	Decrease
Between 1500 to 2000 VPH	-	Decrease
Between 0.40 to 0.60 fc	-	Decrease
Between 0.60 to 0.80 fc	+	Increase
Between 1.00 to 1.25 fc	+	Increase

Table 22 shows the effect of each variable on the increasing or decreasing probability of the occurrence of a nighttime crash resulting in injury severity. As an example, if a rear-end collision occurs during nighttime periods there is an increased likelihood of occupants becoming injured during the crash. Usually the driver of a vehicle involved in a rear-end collision complains of neck pain after the impact.

It can be observed from Table 22 that other collision types such as angle (T bone), head on, left turn and collision with a pedestrian or bicycle are types of crashes with higher probabilities of occupants resulting with injures or traumas. As an example, when a bicyclist rides in a residential area gets hit by a motor vehicle, the probability of that bicyclist resulting with injuries is high. The severity of the injury would depend on two factors; protection gear of the bicyclist and the speed of which the motor vehicle hits the bicyclist.

Meanwhile, sideswipes and backed into collisions are crashes that are less likely to result in injured occupants. On the other hand, it seems that roadway segments with urban minor arterial classification and with commercial land use have less of a probability for the occurrence of crashes during nighttime conditions resulting in injury severity. The results for the land use commercial classification can be explained by the fact that not many stores or businesses are open during night periods, therefore generating fewer trips during those hours.

As it was found from the Ordered Probit Model, in the Negative Binomial Model factors such as low VPH, low speed, and a roadway illuminance level ranging between 0.4 to 0.6 fc seems to have a positive impact on nighttime roadway safety. Meanwhile, higher roadway lighting illuminance levels (ranges between 0.6 to 0.8 fc and 1.0 to 1.25 fc) seem to have a negative effect on roadway safety, thus increasing the probability of the occurrence of crashes resulting in injury severity.

As a conclusion, after completing the analysis for all nighttime crashes using an Ordered Probit Model and a Negative Binomial Model it was found that roadway lighting illuminance levels fluctuating between 0.4 to 0.6 fc are more beneficial and would help increase nighttime roadway safety.

6.3 Rear-End Crashes Results

6.3.1 Variables Description

The distribution of rear-end nighttime crash injury severity for the West Central Florida Region Area was as follows: (1) None Injury, N = 1,390 (54%); (2) Possible Injury, N = 673 (26%); (3) Non-Incapacitating Injury, N = 375 (14%); (4) Incapacitating Injury, N = 151 (6%); (5) Fatal, N = 9 (0%). The distribution of injury severity with respect to each roadway lighting average moving illuminance as in Case 2: All Rear-end Nighttime Crashes, is presented in the appendix.

This section presents and describes the variables used for the analysis of the existing relationship between roadway lighting illuminance levels and injury severity for rear-end crashes within the West Central Florida Region. All of the variables presented in this section were utilized in either the Ordered Probit Model or Negative Binomial Model. The data collected and used in this research corresponds to crash reports from 2005 to 2008. The sample size data for rear-end nighttime crashes corresponds to 2,598 observations. Table 23 exemplifies a statistical description for the variables used on the analysis of the models. The frequency and proportion description for each variable are provided below.

Table 23 Variables Statistical Description

Description	Frequency	Proportion
Site Location		
At Intersection or Influenced By Intersection	1777	69%
Not At Intersection / RR-X-ing / Bridge	742	29%
Driveway Access	58	2%

Table 23 Continued

Description	Frequency	Proportion
Road Surface Condition		
Dry	2158	83%
Wet	408	16%
Slippery	18	1%
Icy	1	0%
All Other Explain	13	1%
Injury Severity		
Fatal	9	0%
Incapacitating	151	6%
Non-Incapacitating	375	14%
Possible	673	26%
None	1390	54%
Functional Classification		
Urban Minor Arterial	290	11%
Urban Principal Arterial / Expressway	14	1%
Urban Other Principal Arterial	2294	88%
Land Use		
Central Business District (CBD)	3	0%
High Density Bus Commercial	0	0%
High Density Residential	71	3%
High Density	71	3%
Low Density Commercial	560	27%
Low Density Residential	56	3%
Low Density	616	29%
Other	20	1%
Commercial	560	27%
Residential	127	6%
No Information	6	0%
Roadway Posted Speed		
Less than 35 mph	166	6%
40 to 45 mph	1700	65%
More than 50 mph	732	28%
Number of Lanes		
1 Lane	29	1%
2 Lanes	661	15%
3 Lanes	1659	37%
4 Lanes	249	6%
More than 3 Lanes	1908	42%

Table 23 Continued

Description	Frequency	Proportion
Vehicles per Hour (VPH)		
Less than 500 VPH	444	17%
Between 500 to 1000 VPH	396	15%
Less than 1000 VPH	840	32%
Between 1000 to 1500 VPH	396	15%
Between 1500 to 2000 VPH	374	14%
Between 1000 to 2000 VPH	770	30%
Between 2000 to 2500 VPH	366	14%
More than 2500 VPH	622	24%
More than 2000 VPH	988	38%
Roadway Average Moving Illuminance		
Less than 0.20 fc	358	14%
Between 0.20 to 0.40 fc	271	10%
Between 0.40 to 0.60 fc	330	13%
Between 0.60 to 0.80 fc	272	10%
Between 0.80 to 1.00 fc	253	10%
Between 1.00 to 1.25 fc	226	9%
Between 1.25 to 1.50 fc	408	16%
Between 1.50 to 1.75 fc	263	10%
Between 1.75 to 2.00 fc	124	5%
Between 2.00 to 2.25 fc	33	1%
Between 2.25 to 2.50 fc	22	1%
More than 2.50 fc	38	1%

In order to obtain a better understanding about the explanatory variables, a cross tabulation for each of the variables, with respect to crash severity, were developed and are provided in Tables 24 and 25. Table 24 presents the variables selected for the Order Probit Model analysis. Meanwhile, Table 25 presents the variables selected for the Negative Binomial Model analysis.

Table 24 Cross Tabulations of the Variables Used for the Rear-end Crash Order Probit Model

Variables	Fatal	Incapacitating	Non-Incapacitating	Possible	None	Total
Road Surface Condition (Base - Wet, Slippery, Icy, All Other)						
Base	1(0%)	29(7%)	52(12%)	103(23%)	255(58%)	440(100%)
Dry	8(0%)	122(6%)	323(15%)	570(26%)	1135(53%)	2158(100%)
Site Location (Base - At Intersection or Influenced By Intersection, Driveway Access, All Other)						
Base	5(1%)	70(9%)	130(16%)	207(25%)	409(50%)	821(100%)
Not At Intersection / RR-X-ing / Bridge	4(0%)	81(5%)	245(14%)	466(26%)	981(55%)	1777(100%)
Number of Lanes (Base - Less than 3 Lanes)						
Base	2(0%)	44(6%)	80(12%)	158(23%)	406(59%)	690(100%)
More than 3 Lanes	7(0%)	107(6%)	295(15%)	515(27%)	984(52%)	1908(100%)
Roadway Posted Speed (Base - More than 35 mph)						
Base	9(0%)	147(6%)	354(15%)	635(26%)	1287(53%)	2432(100%)
Less than 35 mph	0(0%)	4(2%)	21(13%)	38(23%)	103(62%)	166(100%)
Vehicles per Hour (VPH) (Base - More than 1000 VPH)						
Base	7(0%)	86(5%)	249(14%)	484(28%)	932(53%)	1758(100%)
Less than 1000 VPH	2(0%)	65(8%)	126(15%)	189(23%)	458(55%)	840(100%)
Roadway Average Moving Illuminance (Base - Less than 0.40 fc, and More than 0.60 fc)						
Base	8(0%)	142(6%)	329(15%)	604(27%)	1185(52%)	2268(100%)
Between 0.40 to 0.60 fc	1(0%)	9(3%)	46(14%)	69(21%)	205(62%)	330(100%)

Table 25 Cross Tabulations of the Variables Used for the Rear-end Crash Negative Binomial Model

Variables	Fatal	Incapacitating	Non-Incapacitating	Possible	None	Total
Functional Classification (Base - Urban Principal Arterial / Expressway, Urban Other Principal Arterial)						
Base	7(0%)	141(6%)	333(14%)	616(27%)	1211(52%)	2308(100%)
Urban Minor Arterial	2(1%)	10(3%)	42(14%)	57(20%)	179(62%)	290(100%)
Land Use (Base - Residential, Other, No Information)						
Base	8(0%)	116(6%)	295(14%)	547(27%)	1072(53%)	2038(100%)
Commercial	1(0%)	35(6%)	80(14%)	126(23%)	318(57%)	560(100%)
Roadway Posted Speed (Base - Less than 50 mph)						
Base	7(0%)	95(5%)	257(14%)	485(26%)	1022(55%)	1866(100%)
More than 50 mph	2(0%)	56(8%)	118(16%)	188(26%)	368(50%)	732(100%)
Vehicles per Hour (VPH) (Base -Less than 1500 VPH, More than 2000 VPH)						
Base	6(0%)	131(6%)	324(15%)	574(26%)	1189(53%)	2224(100%)
Between 1500 to 2000 VPH	3(1%)	20(5%)	51(14%)	99(26%)	201(54%)	374(100%)
Roadway Average Moving Illuminance (Base - Less than 0.40 fc, and More than 0.60 fc)						
Base	8(0%)	142(6%)	329(15%)	604(27%)	1185(52%)	2268(100%)
Between 0.40 to 0.60 fc	1(0%)	9(3%)	46(14%)	69(21%)	205(62%)	330(100%)

6.3.2 Ordered Probit Model Estimation

The estimation of results for the Ordered Probit Model are specified in Table 26 and Table 27. The sample size dataset was 2,598 observations (injury severity as it applies to drivers involved in rear-end crashes during nighttime conditions from 2005 to 2008), and the likelihood ratio (LR) test statistic falls into the rejection area (p – value = 0 < 0.05). This means that the overall explanatory variables of the model have significant influence on the responses (injury severity) at a statistical significance level of 95 percent.

Table 26 Ordered Probit Model Summary Description

Number of observations =	2598
Log likelihood at Zero =	-2984.8695
Log likelihood at Convergence =	-2964.0314
LR $chi^2(6)$ =	41.68
Prob > chi^2 =	0
Pseudo R^2 =	0.007

Table 27 Ordered Probit Model Parameter Estimates

Variables	Coefficient	Standard Error	z	P>|z|	95% C.I.	
Road Surface Dry	0.102	0.061	1.68	0.093	-0.017	0.220
Not At Intersection	0.173	0.050	3.50	0.000	0.076	0.271
3 Lanes or More	0.114	0.053	2.15	0.031	0.010	0.219
Less than 35 mph	-0.245	0.098	-2.49	0.013	-0.438	-0.052
1000 vph or Less	0.110	0.050	2.19	0.029	0.011	0.209
Between 0.40 to 0.60 fc	-0.219	0.070	-3.13	0.002	-0.356	-0.082
Threshold 1 (μ_1)	0.299	0.075			0.151	0.447
Threshold 2 (μ_2)	1.039	0.077			0.888	1.190
Threshold 3 (μ_3)	1.768	0.082			1.607	1.929
Threshold 4 (μ_4)	2.941	0.133			2.680	3.202

In Table 27 the estimation results of an Ordered Probit Model for injury severity as it applies to drivers involved in rear-end crashes during nighttime conditions from 2005 to 2008 are provided. Since the dependent variable, injury severity, increases as the numbers increase from None Injury (1) to Fatal Injury (5), positive estimate values suggest an increased probability of being involved in a rear-end crash resulting in a more severe injury.

In Table 27 all variables with a *z*-statistic of ± 1.96 or greater will significantly affect the injury severity for rear-end nighttime crashes at the 95 percent confidence level or more. Furthermore, variables with a *z*-statistic of ± 1.64 or greater but less than ± 1.96 will significantly affect the injury severity for rear-end nighttime crashes between the 90 and 95 percent confidence level. For example, a vehicle driving on a dry roadway surface at night and not at an intersection is more likely to be involved in a rear-end crash resulting in higher injury severity. Table 28 presents the influence of the variables with respect to the likelihood of an increased or decreased crash injury severity.

Table 28 Analysis of the Coefficient Signs

Independent Variable	Sign	Influence on Crash Injury Severity
Road Surface Dry	+	Increase
Not At Intersection	+	Increase
3 Lanes or More	+	Increase
Less than 35 mph	-	Decrease
1000 vph or Less	+	Increase
Between 0.40 to 0.60 fc	-	Decrease

Table 28 demonstrates that driving on roadway segments with less than 1,000 vph during nighttime, and on roadways with three or more lanes are more likely to be involved in a rear-end crash resulting in higher injury severity. In fact, if there are fewer cars on the road, some drivers may be more likely to increase their driving speed. Exceeding the posted speed can make them lose the control of their vehicle, resulting in a higher impact crash. Any crash at a higher speed can result in a more serious injury crash. In essence, a driver driving during nighttime conditions on dry pavement, with low traffic volume and with open road ahead of him/her is more likely to feel relegated of any pressure on the road. This can sometimes create an excess of relaxation, and a significant lack of attention to their surroundings.

The results from the Ordered Probit Model showed that a roadway lighting illuminance level between 0.4 to 0.6 fc (less than the amount of roadway lighting illumination than required by the *Florida Plans Preparation Manual*, see Table 1) would have a positive impact on roadway user's safety. In other words, it seems that roadway users drive more cautiously under less roadway lighting illumination. In addition, driving speeds less than 35 mph also seem to have a positive effect on roadway user's safety.

The marginal effect of each explanatory variable utilized in the Ordered Probit Model is presented in Table 29. Marginal effects show how the probability of increasing or decreasing injury severity changes with respect to the explanatory variables. The advantage of the Ordered Probit Model is that the marginal effect allows the determination of the impact of each explanatory variable on the probability of each injury severity level.

Table 29 Marginal Effects

Variables	Coefficient	Standard Error	z	P>|z|	95% C.I.	
None Injury						
Road Surface Dry	-0.040	0.024	-1.69	0.091	-0.087	0.006
Not At Intersection	-0.069	0.020	-3.50	0.000	-0.108	-0.030
3 Lanes or More	-0.045	0.021	-2.16	0.030	-0.086	-0.004
Less than 35 mph	0.096	0.037	2.56	0.011	0.022	0.169
1000 vph or Less	-0.044	0.020	-2.18	0.029	-0.083	-0.005
Between 0.40 to 0.60 fc	0.086	0.027	3.18	0.001	0.033	0.139
Variables	**Coefficient**	**Standard Error**	**z**	**P>|z|**	**95% C.I.**	
Possible Injury						
Road Surface Dry	0.012	0.008	1.59	0.111	-0.003	0.027
Not At Intersection	0.018	0.005	3.69	0.000	0.009	0.028
3 Lanes or More	0.014	0.007	2.05	0.040	0.001	0.027
Less than 35 mph	-0.033	0.015	-2.21	0.027	-0.061	-0.004
1000 vph or Less	0.012	0.005	2.25	0.024	0.002	0.023
Between 0.40 to 0.60 fc	-0.028	0.010	-2.81	0.005	-0.048	-0.009

Table 29 Continued

Variables	Coefficient	Standard Error	z	P>|z|	95% C.I.	
Non-Incapacitating Injury						
Road Surface Dry	0.017	0.010	1.70	0.089	-0.003	0.036
Not At Intersection	0.029	0.008	3.43	0.001	0.012	0.045
3 Lanes or More	0.019	0.009	2.17	0.030	0.002	0.035
Less than 35 mph	-0.039	0.015	-2.62	0.009	-0.067	-0.010
1000 vph or Less	0.018	0.008	2.16	0.031	0.002	0.035
Between 0.40 to 0.60 fc	-0.035	0.011	-3.23	0.001	-0.056	-0.014
Variables	**Coefficient**	**Standard Error**	**z**	**P>|z|**	**95% C.I.**	
Incapacitating Injury						
Road Surface Dry	0.011	0.006	1.76	0.079	-0.001	0.022
Not At Intersection	0.020	0.006	3.26	0.001	0.008	0.032
3 Lanes or More	0.012	0.005	2.22	0.026	0.001	0.023
Less than 35 mph	-0.023	0.008	-2.92	0.003	-0.038	-0.008
1000 vph or Less	0.012	0.006	2.11	0.035	0.001	0.024
Between 0.40 to 0.60 fc	-0.021	0.006	-3.48	0.001	-0.033	-0.009
Variables	**Coefficient**	**Standard Error**	**z**	**P>|z|**	**95% C.I.**	
Fatal Injury						
Road Surface Dry	0.001	0.001	1.60	0.109	0.000	0.002
Not At Intersection	0.002	0.001	2.32	0.020	0.000	0.003
3 Lanes or More	0.001	0.001	1.88	0.060	0.000	0.002
Less than 35 mph	-0.002	0.001	-2.34	0.019	-0.003	0.000
1000 vph or Less	0.001	0.001	1.77	0.077	0.000	0.002
Between 0.40 to 0.60 fc	-0.002	0.001	-2.50	0.012	-0.003	0.000

As it can be observed in Table 29 the marginal effects indicate that the variables; dry road surface, not at intersection, having more than three lanes, and driving in traffic conditions of less than 1,000 vph result mainly in nighttime rear-end crashes with high injury severity. Table 30 presents a comparison for each variable with respect to their marginal effects for all possible injury severities.

Table 30 Marginal Effects Comparison

Variables	Injury Severity				
	None	Possible	Non-Incapacitating	Incapacitating	Fatal
Road Surface Dry	-	+	+	+	+
Not At Intersection	-	+	+	+	+
3 Lanes or More	-	+	+	+	+
Less than 35 mph	+	-	-	-	-
1000 vph or Less	-	+	+	+	+
Between 0.40 to 0.60 fc	+	-	-	-	-

As illustrated in Table 30, roadway lighting illuminance levels ranging between 0.4 to 0.6 fc can have a positive safety impact on drivers during nighttime conditions. At the same time the variable that describes the posted speed less than 35 mph for any roadway segment seems to have a positive safety impact on drivers during nighttime conditions. These two variables, roadway lighting illuminance levels ranging between 0.4 to 0.6 fc and posted speeds less than 35 mph can reduce the probability of being involved in rear-end crashes resulting in fatal injuries. Meanwhile, these two variables can increase the probability of rear-end crashes resulting in none injury severity.

6.3.3 Negative Binomial Model Estimation

The estimation of results for the Negative Binomial Model are specified in Tables 31 and 32. The sample size dataset was 2,598 observations (count of crashes resulting in injury severity as applied to drivers involved in nighttime rear-end crashes from 2005 to 2008) and the likelihood ratio (LR) test statistic falls into the rejection area (p – value = 0 < 0.05). That means that the overall explanatory variables of the model have significant influence on the responses (count of crashes resulting in injury severity) at a statistical significance level of 95 percent.

Table 31 Negative Binomial Model Summary Description

Number of observations =	2598
Log likelihood at Zero =	-3228.7124
Log likelihood at Convergence =	-3228.4588
LR $chi^2(5)$ =	31.99
Prob > chi^2 =	0
Pseudo R^2 =	0.0049
Alpha =	0.832

Table 32 Negative Binomial Model Parameter Estimates

Variables	Coefficient	Standard Error	z	P>|z|	95% C.I.	
Urban Minor Arterial	-0.203	0.098	-2.08	0.038	-0.394	-0.011
Land Use Commercial	-0.147	0.072	-2.06	0.039	-0.287	-0.007
More than 50 mph	0.130	0.063	2.07	0.038	0.007	0.253
Between 1500 to 2000 VPH	-0.166	0.083	-1.98	0.047	-0.329	-0.002
Between 0.40 to 0.60 fc	-0.299	0.092	-3.26	0.001	-0.479	-0.119
Constant	-0.137	0.041	-3.35	0.001	-0.217	-0.057

In Table 32 the estimation results for the Negative Binomial Model for count of crashes resulting in injury severity as applied to drivers involved in rear-end crashes during nighttime conditions from 2005 to 2008 are provided.

In Table 32 all variables with a *z*-statistic of ± 1.96 or greater will significantly affect the injury severity for rear-end nighttime crashes at the 95 percent confidence level or more. Furthermore, variables with a *z*-statistic of ± 1.64 or greater but less than ± 1.96 will significantly affect the injury severity for rear-end nighttime crashes between the 90 and 95 percent confidence level. Table 33 presents the influence of the variables with respect to the likelihood of an increased or decreased probability of the occurrence of crashes resulting in injuries during nighttime conditions.

Table 33 Analysis of the Coefficient Signs

Independent Variable	Sign	Influence on Crash occurrence
Urban Minor Arterial	-	Decrease
Land Use Commercial	-	Decrease
More than 50 mph	+	Increase
Between 1500 to 2000 VPH	-	Decrease
Between 0.40 to 0.60 fc	-	Decrease

Table 33 shows the effect of each variable on increasing or decreasing the probability of the occurrence of a nighttime rear-end crash resulting in injury severity. It can be observed from Table 33 that a roadway segment with a classification of urban minor arterial and land use commercial are segments with a lower probability of being involved in rear-end crashes during nighttime conditions resulting in injury severity. The result for the land use commercial can be explained by the fact that not too many stores or businesses are open late at night, thus generating fewer trips during those hours.

As was obtained from the Ordered Probit Model, in the Negative Binomial Model a roadway illuminance level between 0.4 to 0.6 fc seems to have a positive impact on nighttime roadway safety. Meanwhile, the factor of low VPH (between 1500 to 2000) seems to have a positive impact on nighttime roadway safety. Therefore, driving on roadway segments with posted speeds higher than 50 mph seems to have a higher probability of being involved in rear-end crashes during nighttime conditions resulting in injury severity.

In conclusion, after completing the analysis of the Ordered Probit Model and the Negative Binomial Model, a roadway lighting illuminance level ranging between 0.4 to 0.6 fc seems to be more suitable to improving nighttime roadway safety.

CHAPTER 7: CONCLUSION

The research performed in this study focused on determining and understanding the existing relationship between roadway lighting illuminance levels and injury severity for the West Central Florida Region during nighttime crashes. As part of this investigation a comprehensive literature review was also conducted. It was found that all previous longitudinal studies focus on the presence of roadway lighting systems (lit or unlit roadways analysis). It was observed that with the introduction of roadway lighting a significant decrease in the number of nighttime crashes can be obtained. In addition it was noticed that continuous roadway lighting illuminance data collection and analysis have not been previously performed due to current limitations on roadway lighting illuminance measurement procedures. Furthermore, it was also observed that with the introduction of new roadway lighting illuminance drivers were more likely to increase their driving speed and reduce their concentration. In this study, roadway lighting illuminance levels were measured every 40 feet using an Advanced Lighting Measurement System (ALMS) on a total of 245 centerline miles of roadway segments within the West Central Florida Region. The field measurements were paired with crash data reports for the study area. During the process of crash data analysis, it was found that the primary first harmful event in a crash, regardless of the light condition was a rear-end collision. Meanwhile, the average injury severity for all crashes within the scope of this research was found to be possible injury for all four light conditions (day, dark, dusk, and dawn).

An Ordered Probit Model was developed to investigate how roadway lighting illuminance levels and other roadway factors affect the injury severity on crashes during nighttime conditions. Meanwhile, a Negative Binomial Model was developed to investigate how roadway lighting illuminance levels and other roadway factors affect the probability of the occurrence of crashes resulting in injuries during nighttime conditions. These two models were developed for the analysis of all nighttime crashes and for rear-end nighttime collisions. The results from these two models can be used to select appropriate countermeasures that can help decrease the likelihood of injury severity and at the same time the number of crashes resulting in injuries during nighttime periods. Based on the model's results the following conclusions can be obtained:

- It was identified that a roadway lighting average moving illuminance level between 0.4 to 0.6 fc seems beneficial in reducing the likelihood of crashes during nighttime conditions, as well as the likelihood in them resulting in injury severity.
- With the reduction of roadway lighting illuminance levels, other aspects such as light pollution (glare, lighting trespass, and sky glow) can be alleviated.
- Additional to the mitigation of lighting pollution problems, the reduction of roadway lighting illuminance levels offers benefits such as economical savings on energy consumption.

- The Florida Department of Transportation saved an excess of $1 million with the evaluation of the roadway lighting illuminance levels on approximately 245 center line miles of roads within the West Central Florida Region using an Advanced Lighting Measurement System.

The ultimate purpose of roadway lighting is to provide safety to all roadway users. The correct use of the proper quantity of roadway lighting illumination can provide safer roads while reducing lighting pollution. Additionally, it can also contribute to reduced energy consumption.

The results of this research suggest that simply adding more lighting does not make roadways safer. The fact is that a reduction on the amount of roadway lighting illuminance can produce savings in energy consumption and help the environment by reducing light pollution. Moreover, what these results present is that designing roadway lighting goes beyond the initial design process; it also requires continuous maintenance. Furthermore, regulations for new developments and the introduction of additional lighting sources near roadway facilities (that are not created with the intention of being used for roadway facilities, but for business purposes near roadway facilities) need to be created. This study was conducted from data within a limited geographical boundary. The crashes themselves may include specific geographical characteristics that can only be applied to the study area.

7.1 Contributions to the Field

The interpretations of the nighttime crash injury severity model can be used to understand the impacts of roadway lighting illuminance levels and other roadway factors on nighttime safety. Knowing the relationship of roadway lighting illuminance levels and nighttime crash injury severity is beneficial for addressing safety concerns during nighttime and selecting proper countermeasures to reduce the likelihood of crashes with injury severity with a final goal of improving nighttime roadway safety. Furthermore, understanding the relationship of roadway lighting illuminance levels and nighttime crash injury severity would provide a better understanding to practitioners and help them in the elaboration of new roadway lighting design manuals and standards.

7.2 Recommendations

After conducting this research it is determined that the development of guidelines, standards and regulatory documentation to monitor and evaluate how the introduction of roadway lighting (business site facilities, business electronic signs, electronic billboard, among others) affect the safety of the roadway facilities needs to be created. The introduction of additional roadway illumination can be beneficial for roadway users. More evaluation and maintenance of the roadway facilities and roadway lighting illuminance need to be conducted. Proper evaluation of the facilities should or need to be provided every couple of years in order to identify which areas need priority and what countermeasures are needed to increase the safety of roadway users.

CHAPTER 8: FUTURE RESEARCH

A full understanding of the factors affecting nighttime crash injury severity still needs to be developed.

- To achieve a statewide (Florida) conclusion and understanding of the existing relationship between roadway lighting illuminance levels and nighttime crashes more data collection needs to occur. To accomplish this goal, USF and CUTR need to partner with other FDOT Districts so that research can be collected and analyzed in the same way as utilized in this research study.
- Evaluate new roadway lighting facilities using new light-emitting diode (LED) lights, with the objective of understanding if this new lighting system provides the same amount of safety, or more, to roadway users under the current lighting system.
- Improvements to the data collection system (ALMS) are suggested:
  - Inclusion of a Global Positioning System (GPS) device to record the position of the measurements and additional information such as the location of light poles, intersections, etc.
  - The utilization of more than one light measurement device to avoid doubts of any measurement and at the same time enabling more information.
- Analysis and identification of businesses that generate nighttime trips and traffic activities. This can help identify locations of other factors that may be prompting nighttime crashes.

- Utilize roadway lighting simulation software to identify which software is the most suitable for the evaluation of existing roadway lighting facilities, with respect to field roadway lighting illuminance measurements.
- Perform an analysis of all Intelligent Transportation System (ITS) devices that are available and that can be used in Florida's roadway facilities to help achieve a better roadway lighting system; one that can be reliable, energy efficient, and provide maintenance information.

I would like to conclude with a phrase by Dr. Peter R. Boyce from his book *Lighting for Driving: Roads, Vehicles, Signs, and Signals*: "It is necessary to ensure that lighting makes its full contribution to road safety at night".

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APPENDICES

Appendix A: Roadway Lighting Average Moving Illuminance and Nighttime Crash Injury Severity Overview

A.1: All Nighttime Crashes

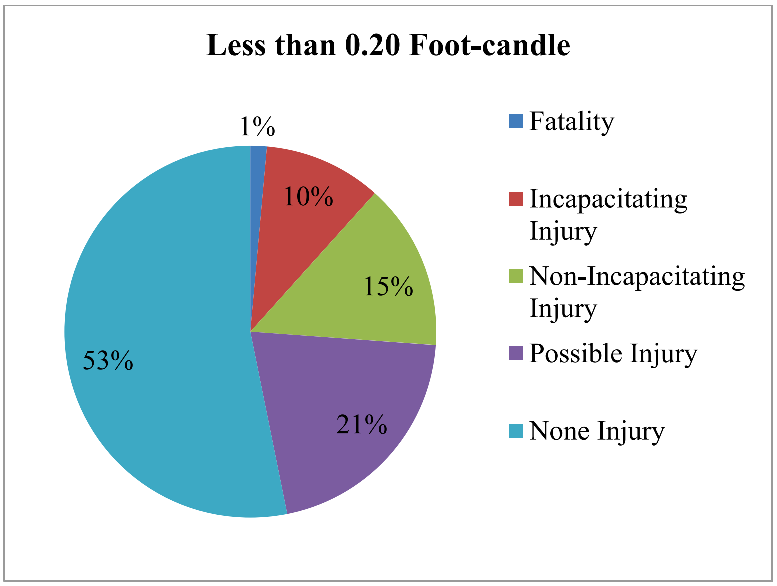

Figure A.1.1 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Less Than 0.20 fc

Appendix A: Continued

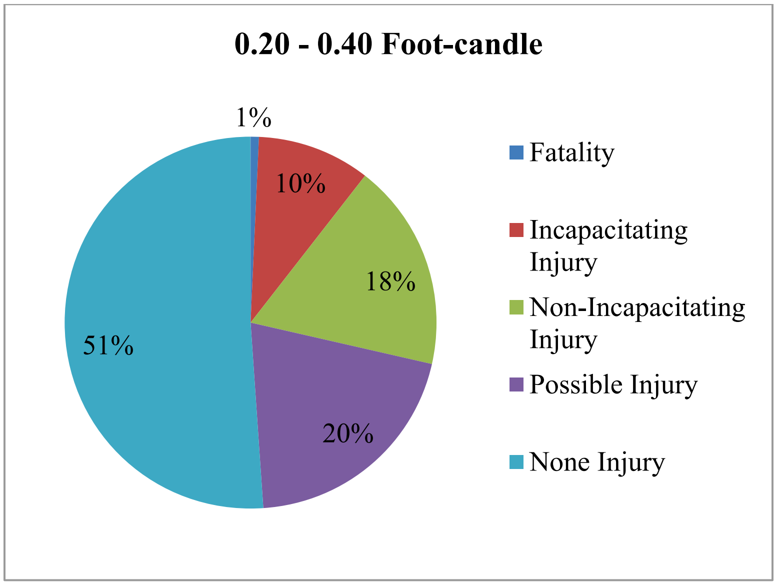

Figure A.1.2 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.20 to 0.40 fc

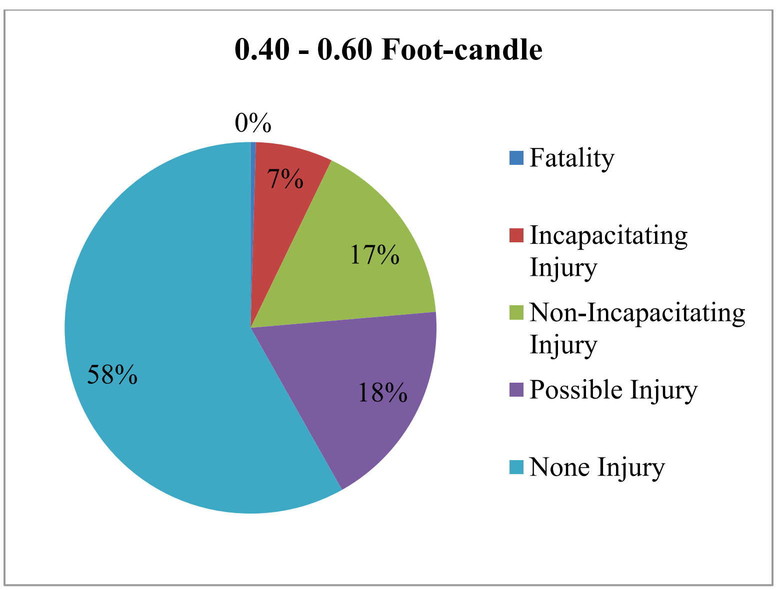

Figure A.1.3 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.40 to 0.60 fc

Appendix A: Continued

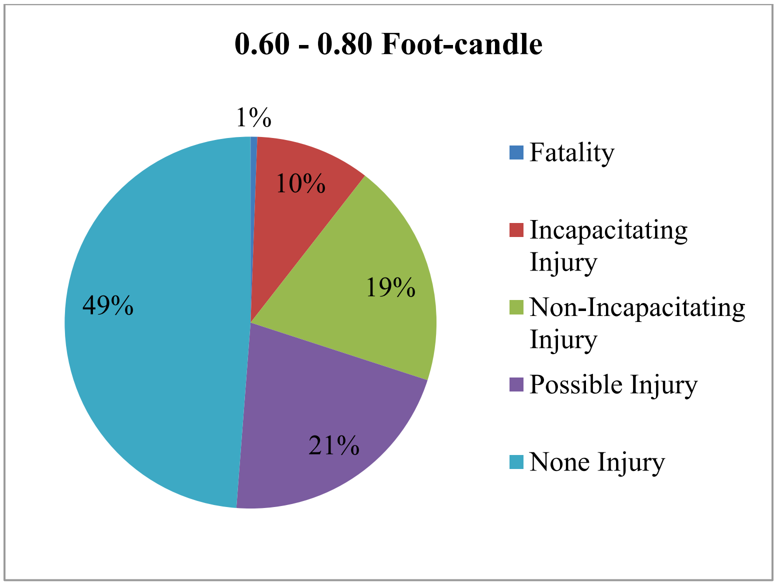

Figure A.1.4 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.60 to 0.80 fc

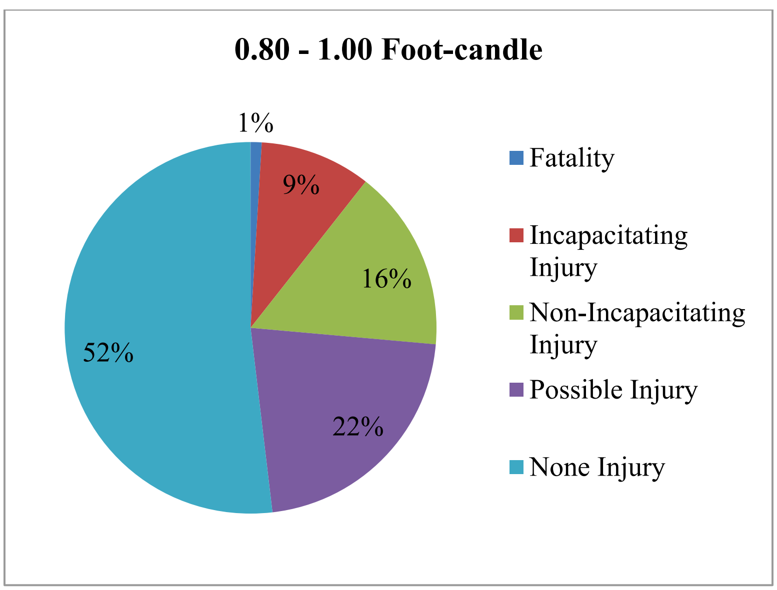

Figure A.1.5 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.80 to 1.00 fc

Appendix A: Continued

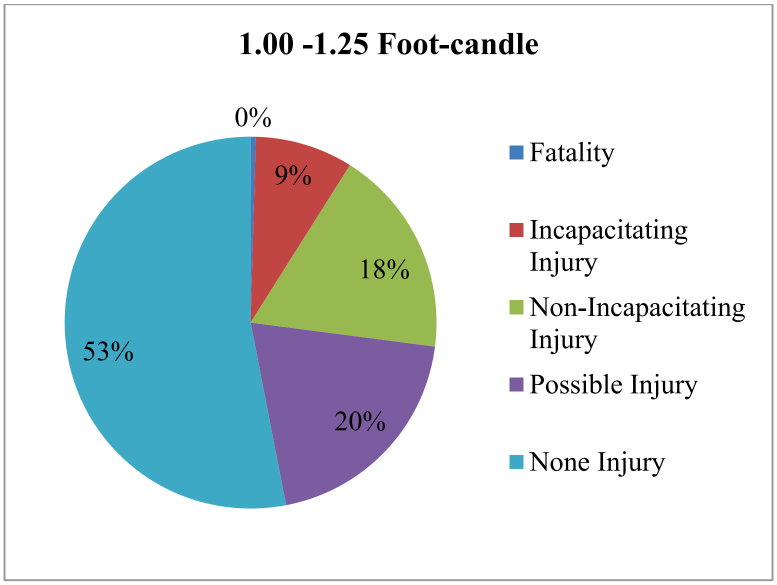

Figure A.1.6 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.00 to 1.25 fc

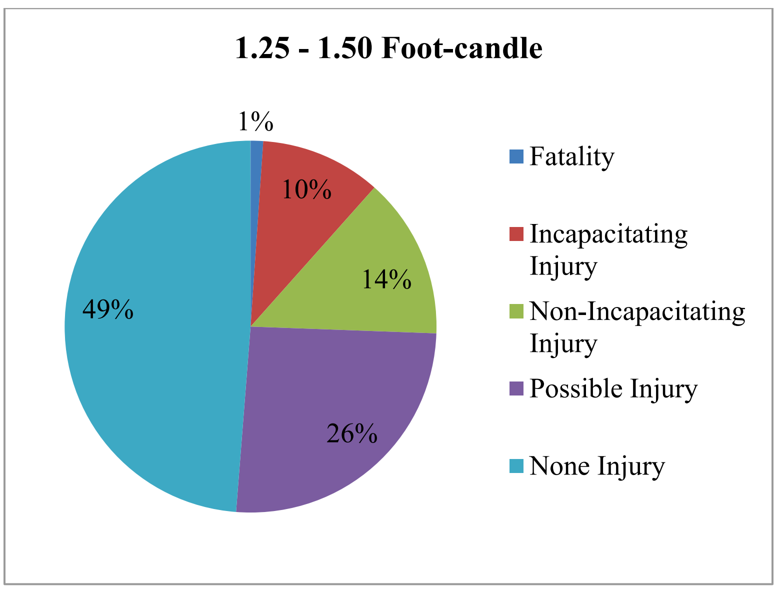

Figure A.1.7 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.25 to 1.50 fc

Appendix A: Continued

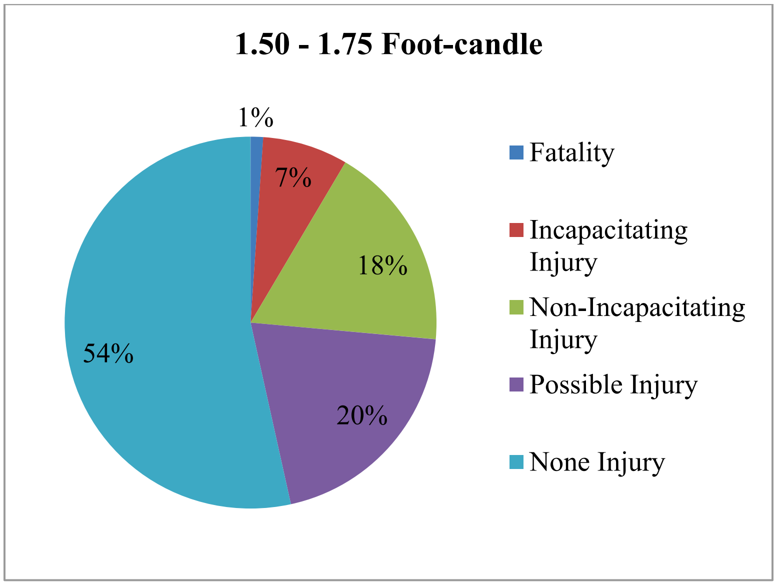

Figure A.1.8 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.50 to 1.75 fc

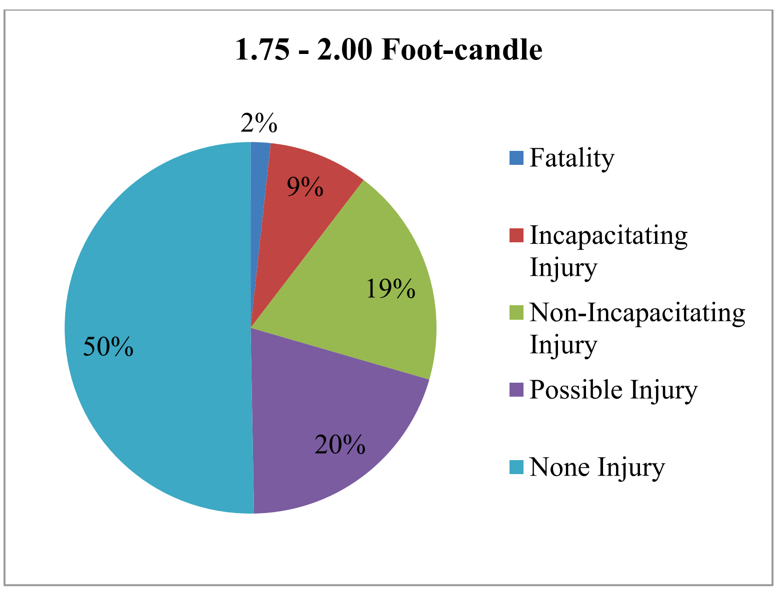

Figure A.1.9 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.75 to 2.00 fc

Appendix A: Continued

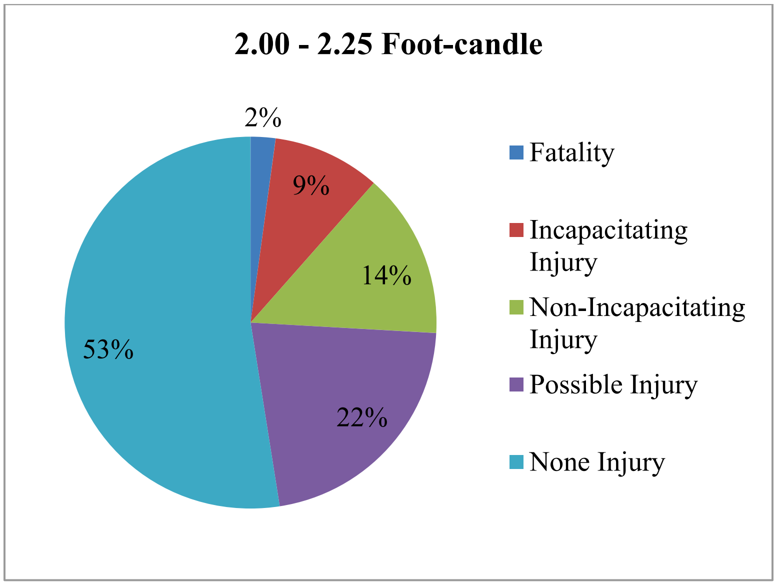

Figure A.1.10 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 2.00 to 2.25 fc

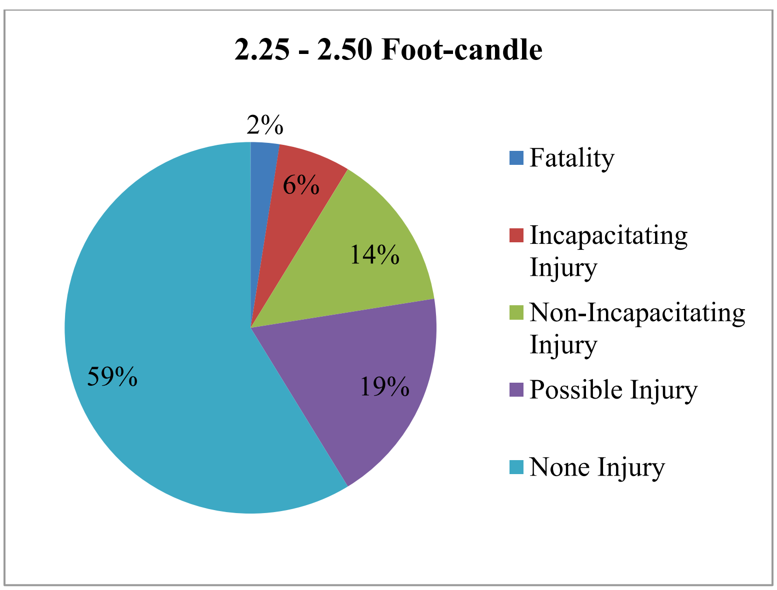

Figure A.1.11 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 2.25 to 2.50 fc

Appendix A: Continued

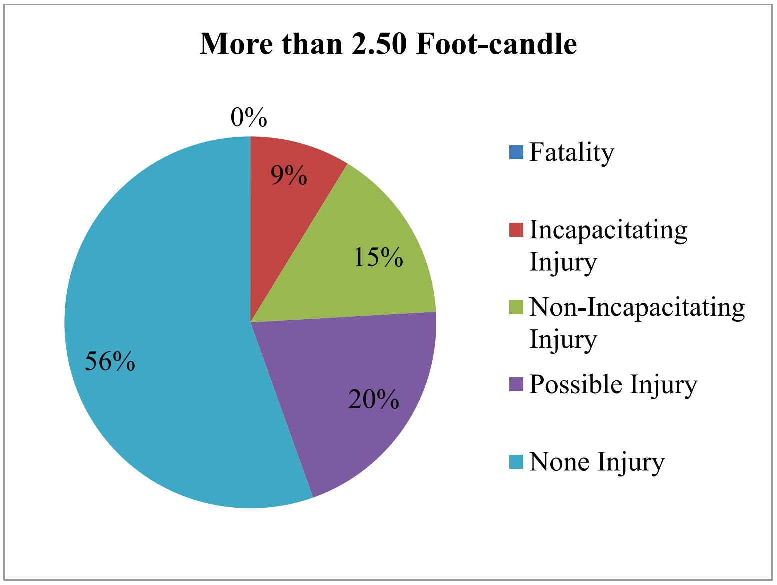

Figure A.1.12 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance More than 2.50 fc

Appendix A: Continued

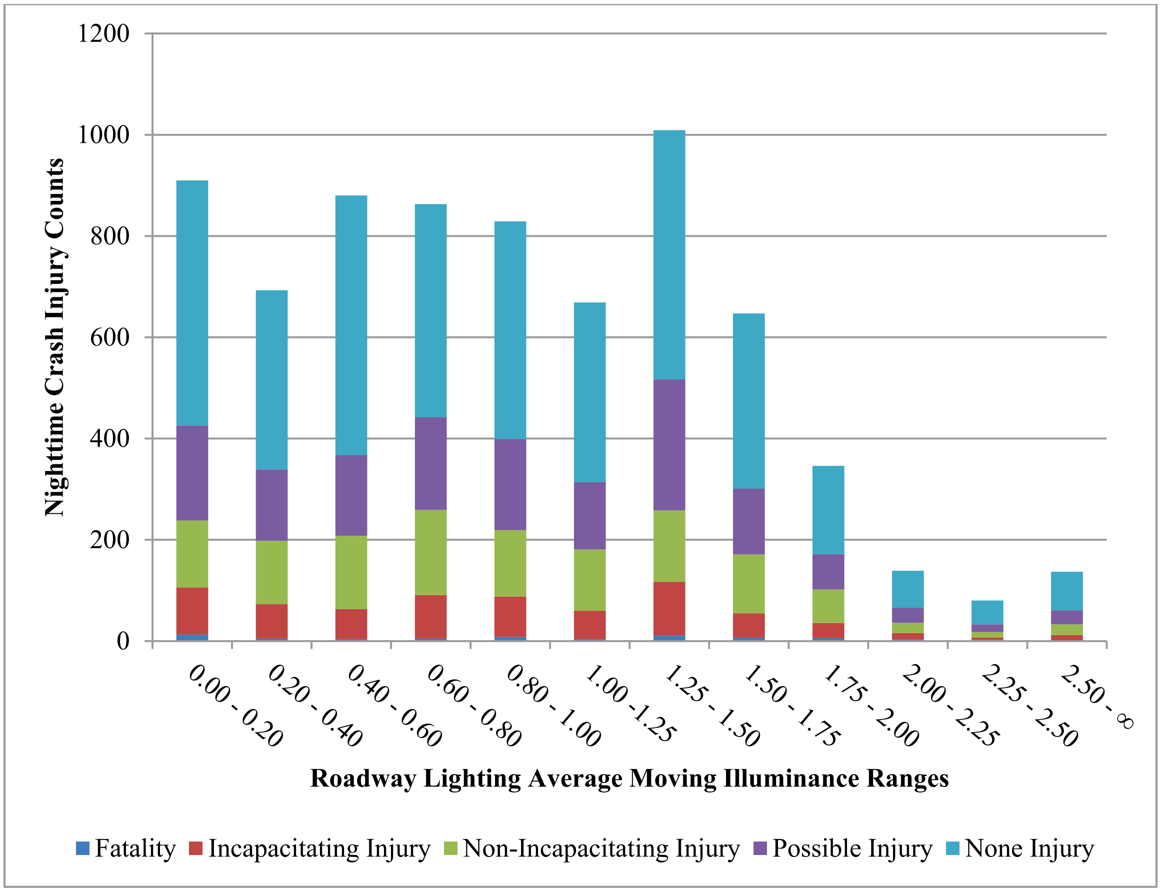

Figure A.1.13 Injury Severity for Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance

Appendix A: Continued

A.2: All Rear-End Nighttime Crashes

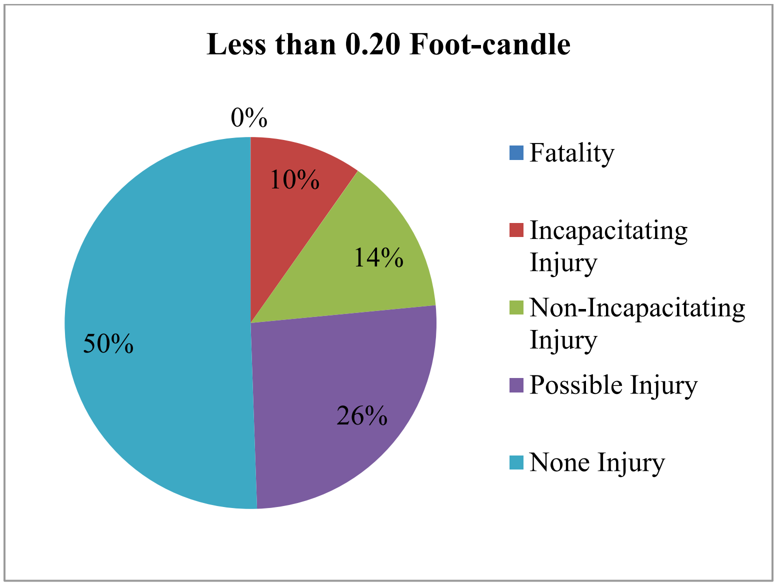

Figure A.2.1 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Less than 0.20 fc

Appendix A: Continued

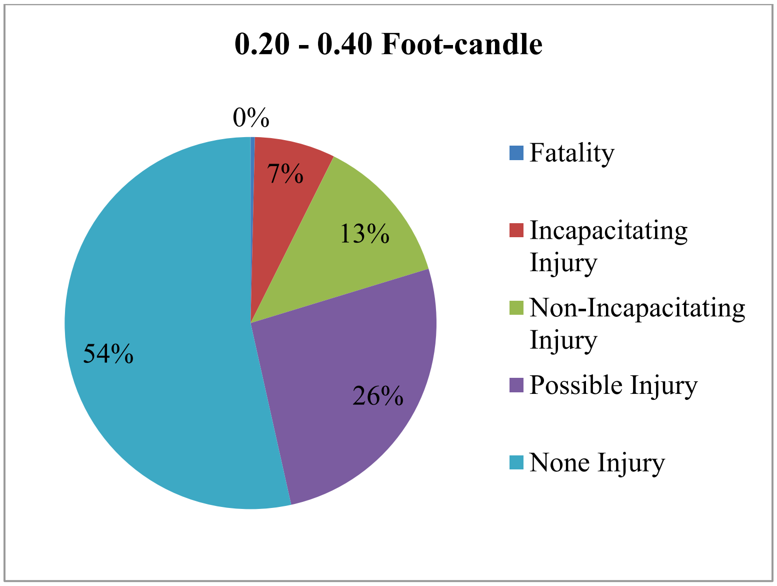

Figure A.2.2 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.20 to 0.40 fc

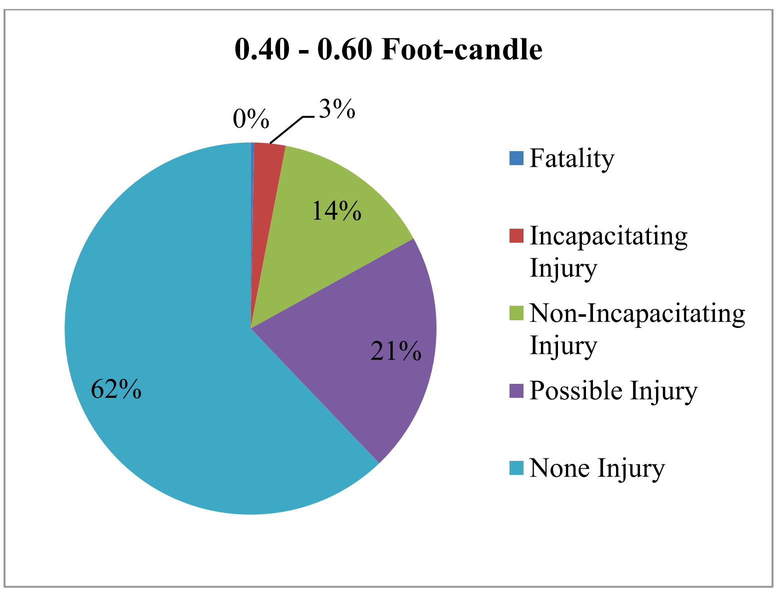

Figure A.2.3 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.40 to 0.60 fc

Appendix A: Continued

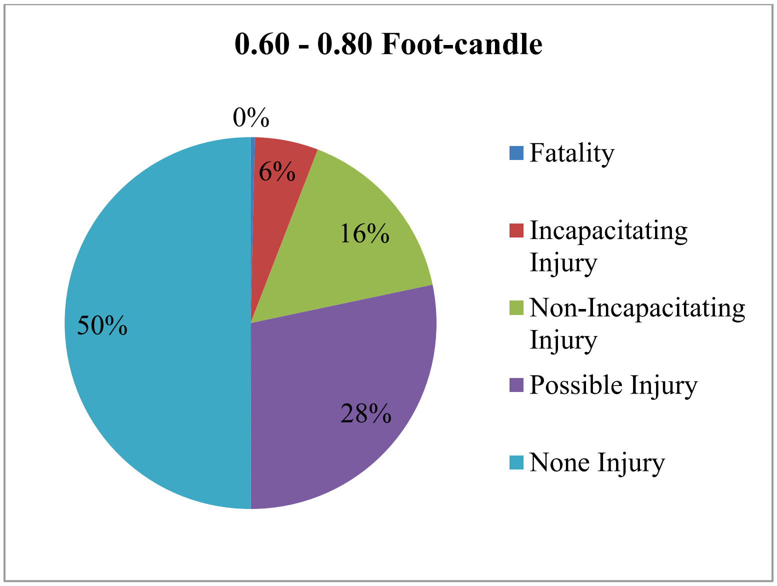

Figure A.2.4 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.60 to 0.80 fc

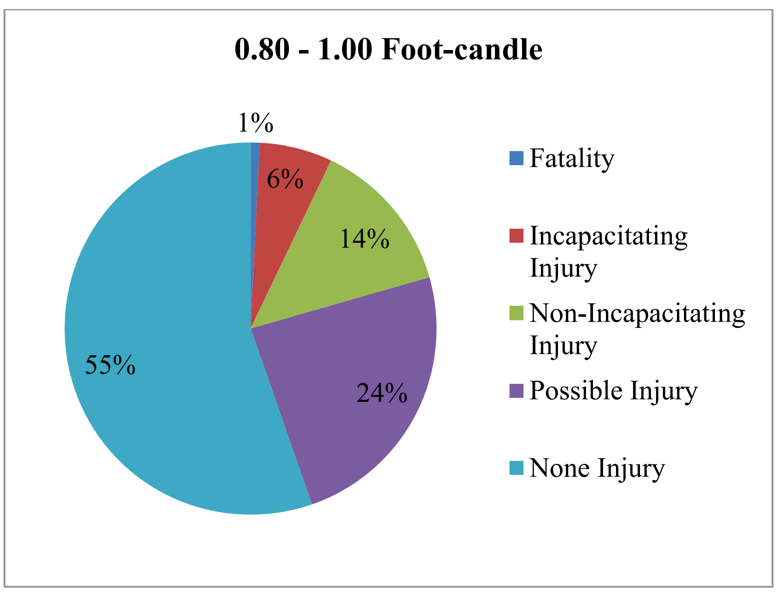

Figure A.2.5 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 0.80 to 1.00 fc

Appendix A: Continued

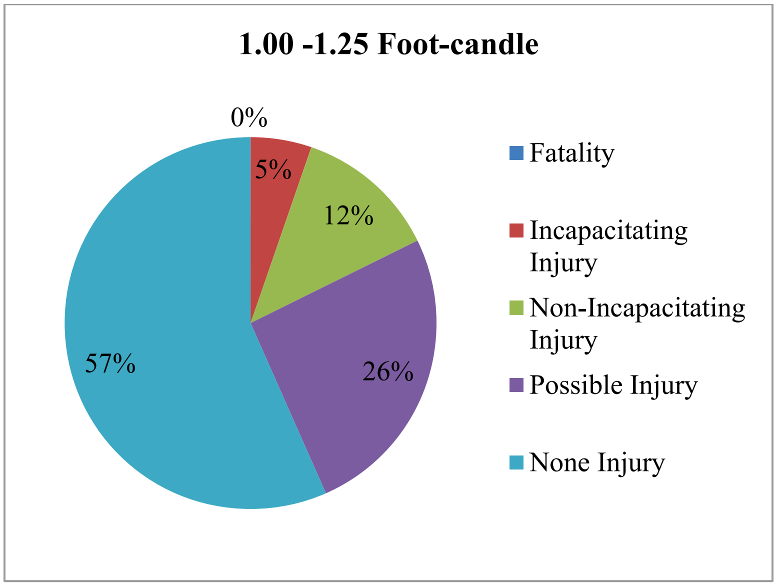

Figure A.2.6 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.00 to 1.25 fc

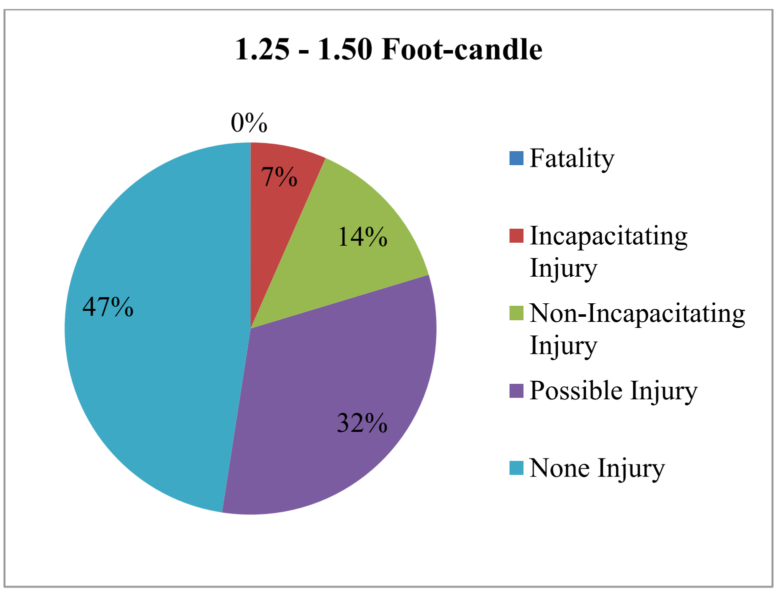

Figure A.2.7 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.25 to 1.50 fc

Appendix A: Continued

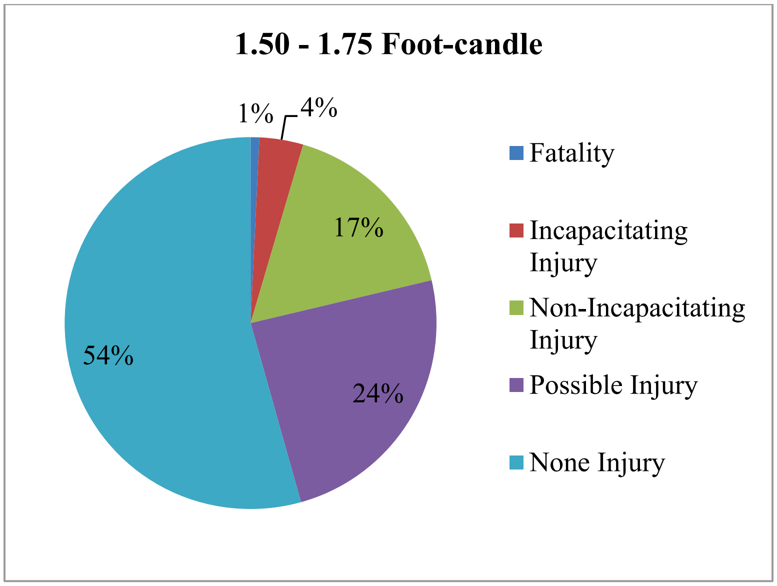

Figure A.2.8 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.50 to 1.75 fc

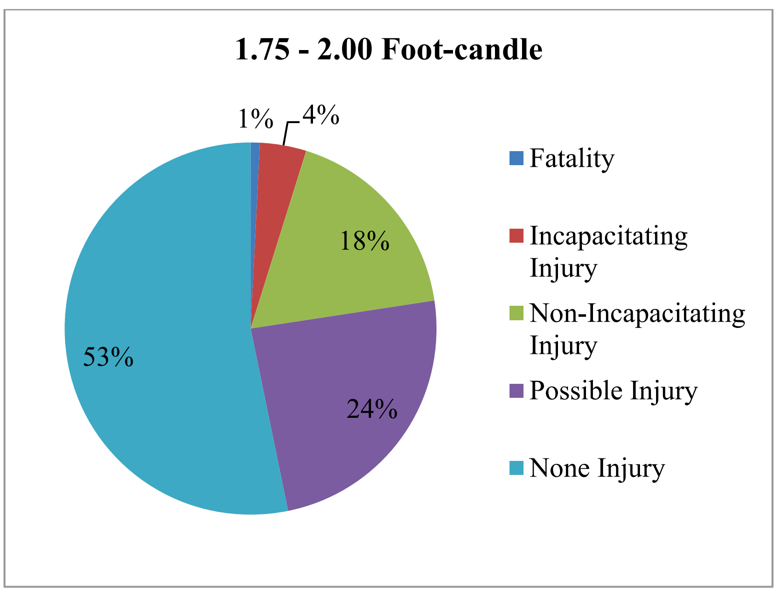

Figure A.2.9 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 1.75 to 2.00 fc

Appendix A: Continued

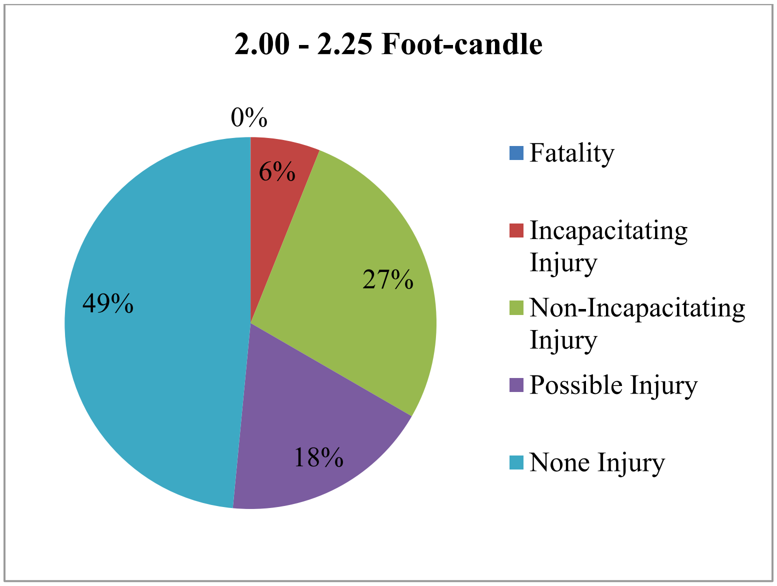

Figure A.2.10 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 2.00 to 2.25 fc

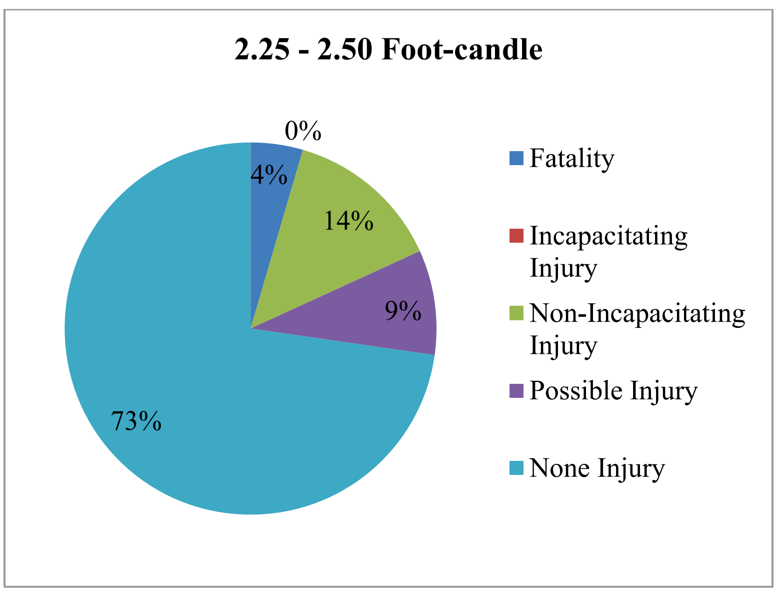

Figure A.2.11 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance Between 2.25 to 2.50 fc

Appendix A: Continued

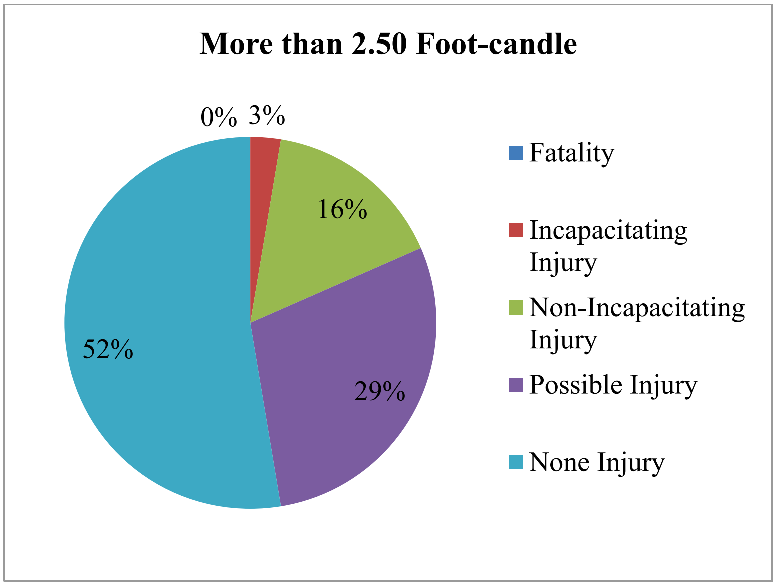

Figure A.2.12 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance More than 2.50 fc

Appendix A: Continued

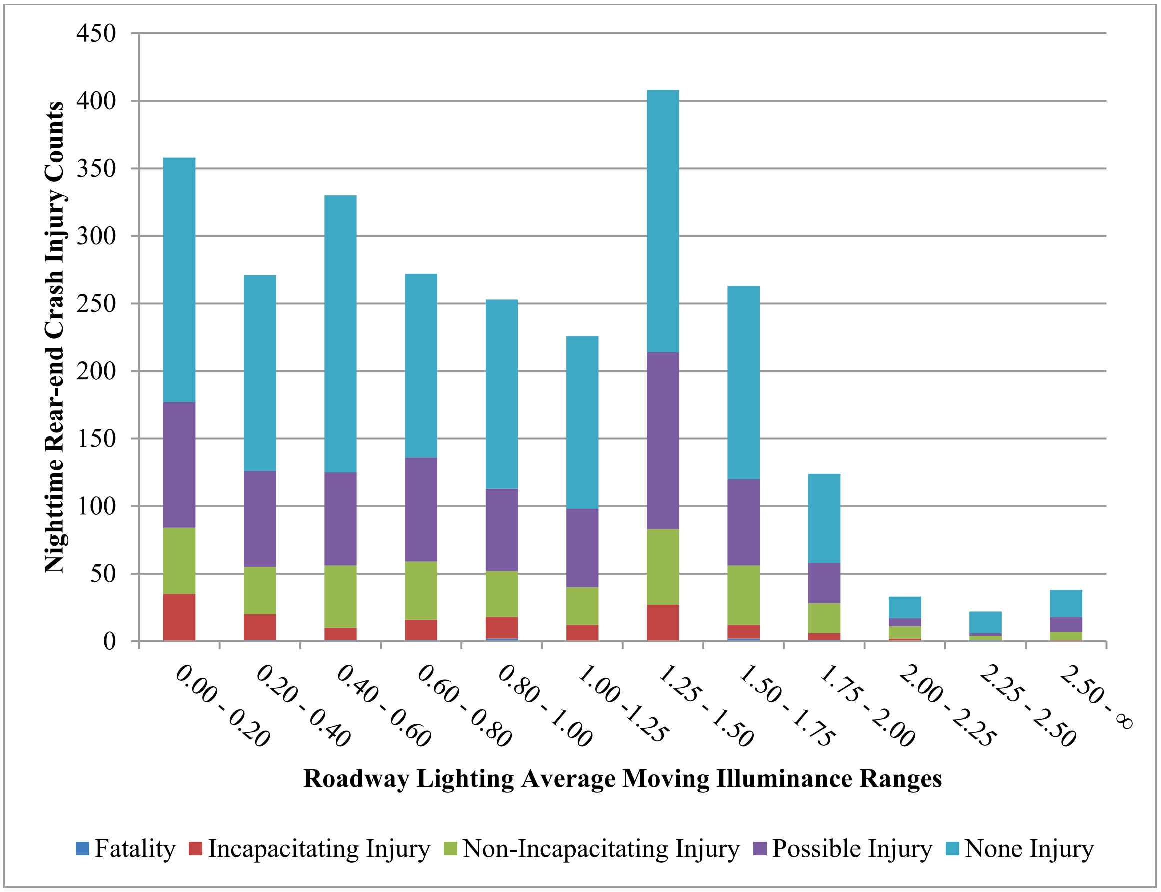

Figure A.2.13 Injury Severity for Rear-end Nighttime Crashes from 2005 to 2008 with Respect to Roadway Lighting Average Moving Illuminance