THE IMPACTS OF ILLUMINATION LEVELS ON NIGHTTIME SAFETY AT ROUNDABOUTS

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By

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To all those who after pursuing knowledge, arrived only to realize that there is yet more to be learnt!

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GLOSSARY OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
AIC	Akaike Information Criterion
AS/NZS	Australian and New Zealand Standards
BCF	Bayesian Correction Factor
BEG_MP	Beginning Milepost
BIC	Bayesian Information Criterion
cd/m2	Candela per square meter
CEDR	Conference of European Directors of Roads
CEN	European Committee for Standardization
CEN/TR	European Committee for Standardization Technical Report
CIE	International Commission on Illumination
CMF	Crash Modification Factor
DEV	Daily Entering Volume
DOT	Department of Transportation
DSLR	Digital Single Lens Reflex
Eavg	Average Maintained Horizontal Illuminance
EB	Empirical Bayes
EL	Exposure Level

Emin	Minimum Horizontal Illuminance
EN	European Normal/European Standard
END_MP	Ending Milepost
FC	Foot Candles
FHWA	Federal Highway Administration
FIPS	Federal Information Processing Standard
GDOT	Georgia Department of Transportation
GEE	Generalized Estimating Equation
GIS	Geographical Information System
GPS	Global Positioning System
HDR	High Dynamic Range
HPS	High Pressure Sodium
HSIP	Highway Safety Improvement Program
HSIS	Highway Safety Information System
HSM	Highway Safety Manual
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IIHS	Insurance Institute for Highway Safety
INT_CESC	Intersection Description
ISYE	Industrial Systems Engineering
JPEG	Joint Photographic Experts Group
LCO_TYPE	Location Type
LED	Light Emitting Diode

MEV	Million Entering Vehicles
MGSC	Middle Georgia State College
MN	Minnesota
MNDOT	Minnesota Department of Transportation
NCHRP	National Cooperative Highway Research Program
NCTSPM	National Center for Transportation System Productivity and Management
ND	Night/Day
Nd	Pixel Intensity
NM	Negative Multinomial
NYSDOT	New York State Department of Transportation
PDO	Property Damage Only
QAQC	Quality Control and Quality Assurance
RENB	Random Effects Negative Binomial
RHS	Product of Exposure Time and ISO and Luminance, divided by Square of Aperture
RR	Risk Ratio
RTE_NBR	Route Number
RTE_SYS	Route System
SEB	Sustainable Education Building
SEDR	Service d'Etudes Techniques des Routes et Autoroutes
SPF	Safety Performance Function
STV	Small Target Visibility

T3	Canon EOS Rebel T3 DSLR Camera
T5	Canon EOS Rebel T5 DSLR Camera
TIFF	Tagged Image File Format
TRRL	Transport and Road Research Laboratory
VMT	Vehicle Miles Traveled
W	Watts
WisDOT	Wisconsin Department of Transportation

SUMMARY

Roundabout installations are becoming common practice among DOTs and other local governments due to their superior safety attributes compared to other conventional at-grade intersections, especially stop-control and uncontrolled intersections. Current U.S. national guidelines for roundabout illumination recommend systematic illumination for all roundabouts. This recommendation might become a potential hindrance to desired widespread installations due to implied financial costs, especially in rural areas because the competing stop-control and uncontrolled intersections can be kept unlit. Interestingly rural roundabouts in most countries around the world are not illuminated. Also, review of intersection safety literature does not identify any publication that supports a systematic illumination policy of U.S. roundabouts. In fact, despite this recommendation there is no quantitative research on influence of illumination levels on nighttime safety at roundabouts and little on conventional intersections. Conversely, the literature shows a significant number of published studies which have indicated that currently recommended illumination levels on roadways can be reduced without compromising nighttime safety.

At the beginning of this dissertation research, there was no available repository of quantitative intersection illumination levels which could be used in highway safety research. Also, existing protocols for measurement require expensive light meters and are extremely time consuming to follow, making them impractical to use to study a large number of intersections. Consequently, the status-quo for highway safety research regarding the impacts of illumination has been to treat road lighting as a binary

(Lit/Unlit) variable. However, even in most places without purposely-built road lighting there is usually ambient lighting from abutting facilities such as a gas stations or a store. Existing research has not been able to account for this ambient lighting.

Consequently, this dissertation proposed to first evaluate the relationship between illumination and nighttime safety at roundabouts using the best available data. The best available intersection illumination data was obtained from the Minnesota data contained in the Highway Safety Information System (HSIS). Minnesota crash and illumination data from 2003 to 2010 were analyzed. This illumination data was a qualitative description of intersection illuminating schemes and/or luminaire arrangement. A naïve analysis indicated among other findings that the presence of lighting can provide approximately 61 percent lower total nighttime crash rate compared to the unlit condition. Also, providing illumination to the roundabout circle alone can yield about 80 percent of the benefits (55 percent reduction from unlit condition) of illuminating both the roundabout circle and approaches (66 percent reduction from unlit condition). This analysis was pioneering for roundabout illumination and safety studies. However, it was unsatisfying because it did not use quantitative illumination data.

Therefore, this dissertation proposed to secondly (a) develop a cost-effective, accurate, and rapid method for measurement of quantitative intersection illumination data, and (b) to apply the developed protocol to a case study in Georgia. The goal of this case study is to highlight an existing deficiency in current knowledge which has been imposed by the lack of quantitative illumination data for both conventional intersections and roundabouts. Specifically, to showcase the potential for developing an illumination level crash modification factor, an important safety parameter which is missing in the current version of the highway safety manual.

To this end, a cost-effective, accurate, and rapid measurement protocol based on the photographic method was developed and two digital single lens reflex cameras were calibrated and field tested for measurement of nighttime luminance at intersections. Field test results indicate the average intersection illuminance derived from the protocol is within 3.6 percent difference of the actual average intersection illumination estimated from following the existing protocols. Also, the potential for using the protocol to generate illuminance uniformity (contour) plots was demonstrated. The developed protocol was used to collect intersection illumination levels from a hundred conventional intersections and roundabouts. The measured intersection illumination was analyzed together with crash data obtained from GDOT for 2009 to 2014. Despite limited roundabout data and potential issues of selection bias which could not be addressed in this dissertation, a cautious roundabout illumination specific crash modification factor has been estimated. Specifically, the analysis showed that an increase of 1 lux in average roundabout illuminance will result in a 4.72 percent reduction in expected number nighttime crashes.

The results of this work are useful in creating a sound framework for DOTs and other transportation agencies to determine the most appropriate level of illumination for roundabouts. This study also makes a number of significant contributions to highway safety research. First, this work is the first quantitative study on the impact of illumination on safety at roundabouts. Second, this dissertation is the first documented application of the photographic method to roundabouts. It is also the first documented application of the photographic method’s camera specific constant calibration approach to transportation field measurements. Previous documented application of the photographic method to transportation field measurements (Jackett and Frith 2013) used an exposure specific calibration approach. Unlike the camera specific constant calibration approach, the exposure specific approach is rigid and field measurements must always be done at the exposure settings used in calibrating the camera. Thirdly, this work demonstrates the first developed procedure to developing uniformity (contour) plots from the photographic method. Next, this work can serve as the basis for initial efforts to create an illumination specific quantitative crash modification factor. Last, but not the least this work offers procedures for collecting luminance data from the field and also documents a database of intersection illumination levels and intersection characteristics which can be used by future research.

CHAPTER 1: INTRODUCTION

An intersection is the area of the road network, including roadways and side facilities, where two or more roadways meet (AASHTO 2010). Intersections can be broadly classified as either at-grade or grade-separated. The main difference being that the latter usually have at least one of the crossing roads elevated above the other crossing roads.

1.1 At-Grade Intersections

At-grade intersections out number grade-separated intersections across the road transportation network because they offer cheaper capital costs for managing conflicting streams of vehicular traffic. However, they also pose one of the most complex traffic situations encountered (FHWA 2009) and present various operating challenges to transportation agencies such as maintaining high intersection capacity and reducing crashes and related injury severities .The Highway Safety Manual (AASHTO 2010) indicates that 50 percent of all urban crashes and 25 percent of all rural crashes are related to at-grade intersections.

In the U.S., signalized and stop-control intersections are the most common types of at-grade intersections (Retting et al. 2001) despite being plagued with a lot of safety issues. Signalized intersections are prone to accidents (Al-Ghamdi 2003) as highlighted by their contribution of 46 percent of all accidents in British Columbia (Miska et al. 1998) and one-third of all U.S. intersection fatalities (FHWA 2012). Conversely, stop-control intersections have a comparatively lower total crash rate but possess a higher fatality rate, a fact evidenced by their association with over 60 percent of intersection fatalities (Bryer 2011) in the Fatal Accident Reporting System (FARS) even though they accounted for only about 25 percent of all reported fatalities.

Due to these safety issues and other secondary factors such operating challenges and construction costs (Kusuma and Koutsopoulos 2011), the modern roundabout – a previously seldom used at-grade intersection in the U.S. (Retting et al. 2001), is gradually becoming a favorite among various state Department of Transportation (DOTs) with many now considering roundabouts as a viable alternative to uncontrolled intersections and stop-control intersections, and, in some cases, signalized intersections and complex freeway interchanges (Flannery 2001). The Federal Highway Administration states that roundabouts must be considered as an alternative for all new intersections as well as for reconstruction, and/or rehabilitation of existing intersections that are federally funded (FHWA 2012). The Insurance Institute for Highway Safety (IIHS) reports that roundabouts are safer than typical 4-leg intersections and typically experience 40 percent fewer vehicle collisions, 80 percent fewer injuries and 90 percent fewer serious injuries and fatalities than their conventional counterparts in both urban and rural settings (IIHS 2000).

Furthermore, it has been shown that vehicles use less fuel going through roundabouts than similar signalized intersection (Garder 2012); projections of fuel consumptions made within 0.1 miles upstream and downstream indicated that roundabouts would offer fuel savings of about 14 gallons per person per year. Similarly, another study (Alisoglu 2010) which evaluated operating costs for roundabouts and signalized intersections indicated that over a design life of 30 years roundabouts would provide tax payers with more than $60,000 in cost savings.

1.2 Growth in U.S. Roundabout Installations

There has been tremendous growth in the number of roundabout installations since year 2000, when the FHWA published the first *Roundabout: An Informational Guide* (Rodegerdts 2008). Currently, there are at least 21 states actively pursuing planning and implementation of roundabouts. Figure 1 shows the cumulative number of U.S. roundabouts from 1990 to 2013. The data used in the chart was sourced from the Kittleson^{TM} Roundabout Database (Kittleson & Associates). The increase in roundabouts is not just due to new constructions alone because many conventional intersections have also been converted to roundabouts (Rodegerdts et al. 2007a). Key drivers for this growth include high intersection capacity (Rodegerdts et al. 2007a) and reduction in injury severities through elimination of some vehicle conflict points (FHWA 2000; Highways Agency 2007; Lenters 2005; Rodegerdts et al. 2010; SETRA 1998; Spacek 2004). Figure 2 compares the conflict points at a conventional four-leg intersection and a four-leg single-lane roundabout.

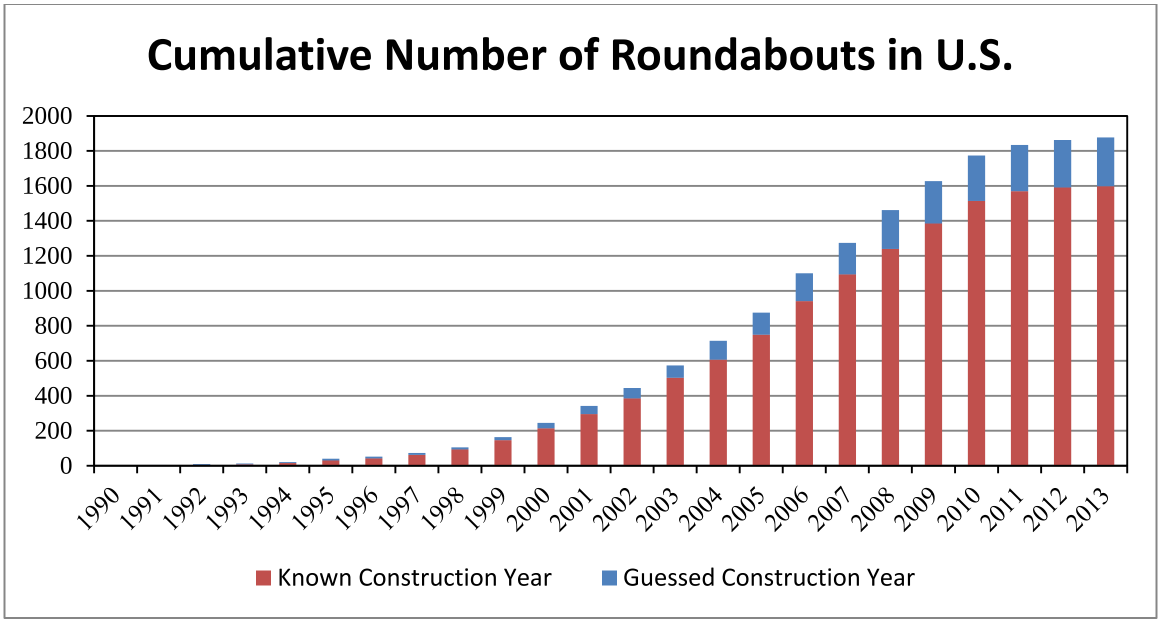
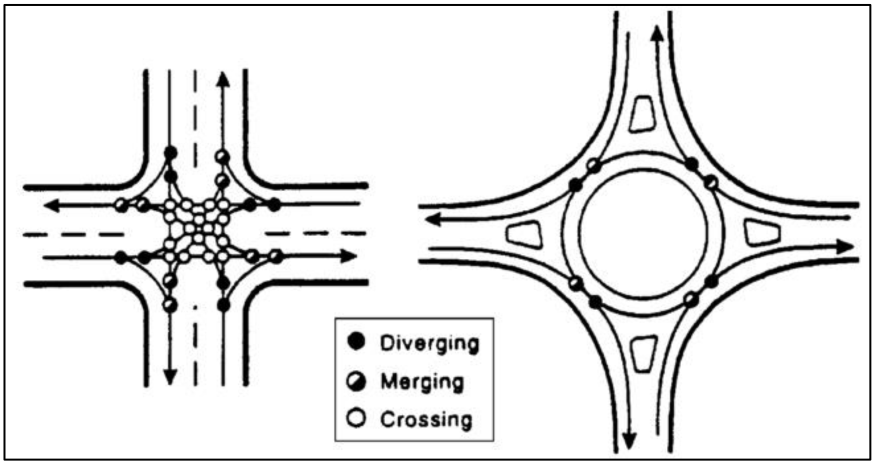


Figure 1 Cumulative Number of Roundabouts in the U.S.



(Source: Flannery 2001)

Figure 2 Conflict Points at Conventional Intersections and Roundabout Intersections

1.3 The Modern Roundabout

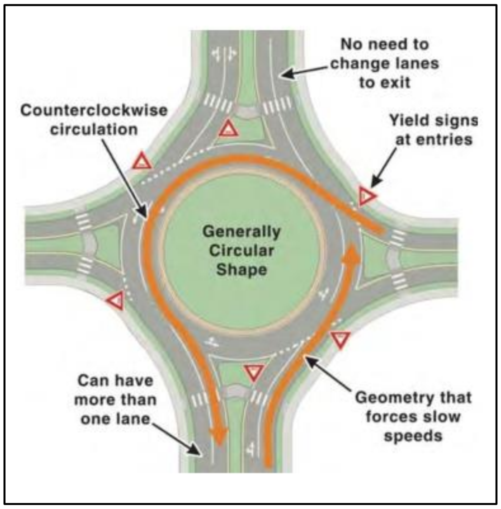
This is a channelized intersection where traffic moves in a circular path around a central island (Kusuma and Koutsopoulos 2011; O'Flaherty 1997). It has three distinguishing operating principles (FHWA 2012):

(a) A low speed environment which is the result of a unique geometry.

(b) Circulating vehicles have priority while entering vehicles have to yield.

(c) Channelization at the entrance and deflection around the central island.

Figure 3 highlights these operating principles. The low speed environment reduces impact force of crashes and also reduces the required stopping sight distance at similar conventional intersections by about half (Wisconsin Department of Transportation 2001). The channelization leads to avoidance of left-turn and angle crashes, which produces the most serious injuries at intersections (Lenters 2005).



(Source: Rodegerdts et al. 2000)

Figure 3 Distinguishing Features of Roundabouts

1.3.1 Historical Overview

The modern roundabout is a third generation circular intersection following after rotaries and traffic circles. One of the earliest recorded traffic circles was installed at The Circus, in Somerset, England in 1768 (Manco 2004) by Architect John Wood (Jnr). Nationally, traffic circles have been part of the transportation system from 1905 when Architect William Phelps Eno designed the Columbus Circle, in Manhattan, New York (Rodegerdts et al. 2010). After this successful installation, many large circles or rotaries were built across the United States. Rotaries assigned priority to entering vehicles and permitted high-speed merging and weaving with a consequent high congestion and crash experience which eventually led to the unpopularity of rotaries in the mid-1950s. Figure 4 shows a typical rotary induced grid-lock.

(Source: Cam 2011)

Figure 4 Example of Congestion at a Traffic Circle

In the 1960s, U.K.'s Transport and Road Research Laboratory (TRRL) developed the modern roundabout in response to safety concerns at rotaries. The modern roundabout gave priority to circulating vehicles and this helped to avoid intersection grid-locks. The development of this priority rule was led by Frank Blackmore. In addition to this operating rule, the modern roundabout used smaller diameters and this eliminated merging and weaving in the circular path. .

Amidst much public skepticism and resistance, the modern roundabout (here after called roundabout) made its U.S. debut in the early 1990s (Ourston Roundabout Engineering 2010) through efforts of Leif Ourston – one of the pioneer proponents and founder of the Ourston Roundabout Engineering Company (Ourston Roundabout Engineering 2010). Mr. Ourston was introduced to roundabouts by Frank Blackmore in 1979 at a TRRL training meeting in Berkshire, England. On his return to America, Mr. Ourston tried to convince California agencies about roundabouts but faced repeated setbacks on many proposed installations which were all abandoned, including locations at Goleta and Santa Barbara in 1985, at Oxnard in 1986, at Ojai and Valencia in 1988 and several other locations along Long Beach (Ourston Roundabout Engineering 2010).

Unfazed, Mr. Ourston brought in two renowned international experts in 1986 in an effort to further persuade California agencies. Professor Ragnvald Sagen of Norway was the first expert, and later that year Frank Blackmore also came to help. Mr. Ourston's efforts finally paid off in 1990 when the first modern roundabout in the United States was built in Nevada. Since then public resistance has been thawing gradually and there has been tremendous growth in installations albeit unequally among states due to state policies. In a recent review of statewide policies on roundabouts (Pochowski 2011) identified six different types of roundabout policies including:

(a) None – where a state neither encourages nor discourages roundabouts.

(b) Allow – where the state allows the consideration of roundabouts as an alternative.

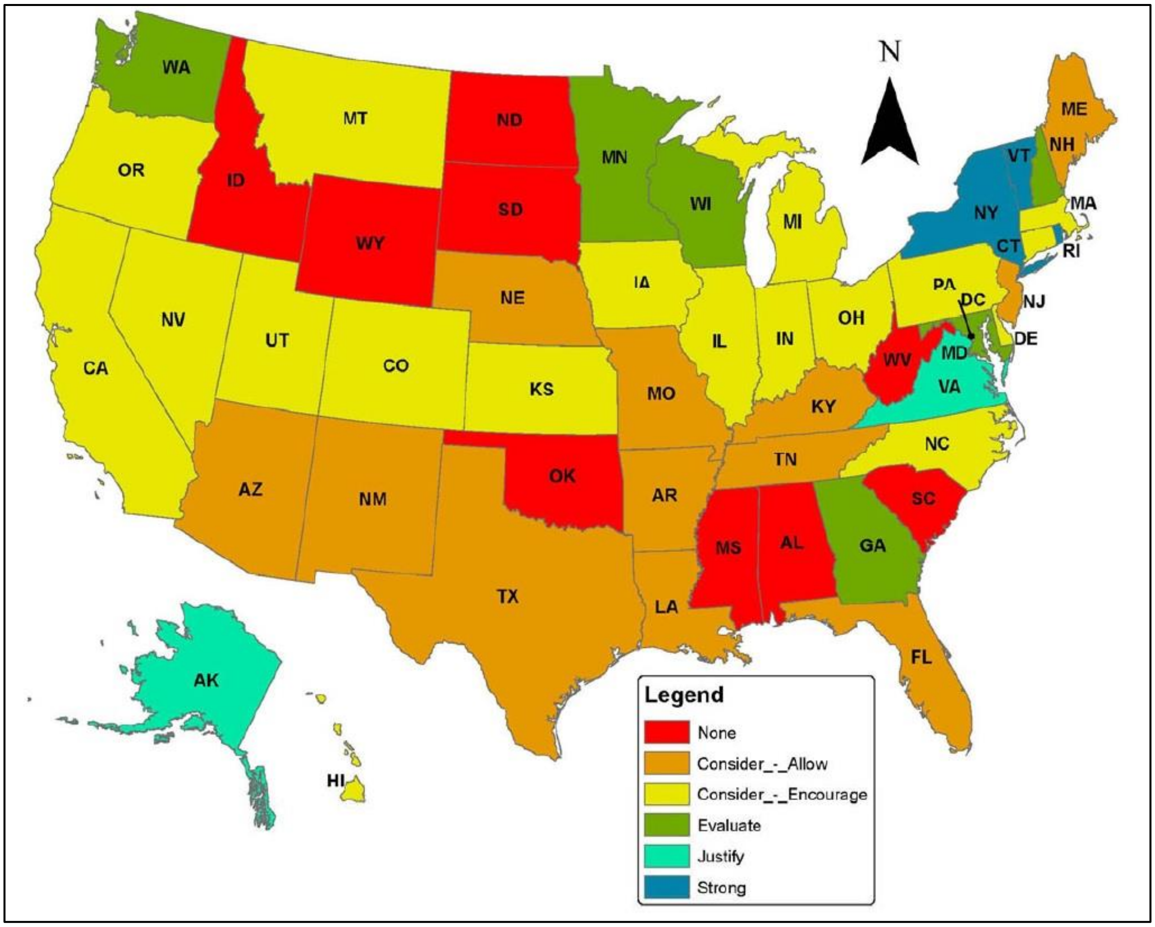
(c) Encourage – where the state encourages the consideration of roundabouts as alternatives.

(d) Evaluate – where the state requires roundabouts to be considered as alternatives.

(e) Justify – where a state requires a written justification if roundabout is not the preferred alternative.

(f) Strong – where a roundabout is the preferred alternative by default unless proven otherwise.

Figure 5 presents a map of the US showing different state roundabout policies.



(Source: Pochowski 2011)

Figure 5 Statewide Roundabout Policies in 2011

1.3.2 Types of Roundabouts

1.3.2.1 Mini-Roundabouts

These have the smallest diameters and are used in low-speed urban environments. Their central island is mountable so larger vehicles go over it when necessary. They are useful in areas where there exists a right-of-way constraint (Kansas Department of Transportation 2003). Figure 6 shows an example of a mini-roundabout.

(Source: Rodegerdts et al. 2010)

Figure 6 Example of a Mini-Roundabout

1.3.2.2 Urban Compact Roundabout

These have inscribed diameters between 100ft – 120ft, non-mountable central islands with aprons to accommodate large vehicles where needed, and an entry geometry which is nearly perpendicular. They are pedestrian and bicycle friendly because of low speeds (Kansas Department of Transportation 2003).

1.3.2.3 Urban Single-Lane Roundabout

These have larger inscribed diameters of about 120ft – 150ft and a more tangential entry and exit geometry. They also process higher entry, circulating, and exit vehicle speeds. (Kansas Department of Transportation 2003; Wisconsin Department of Transportation 2001). Figure 7 shows an example of a single-lane roundabout.

(Source: Rodegerdts et al. 2010)

Figure 7 Example of a Single-Lane Roundabout

1.3.2.4 Rural Single-Lane Roundabouts

These usually have larger diameters than their urban counterparts and can process higher entry, circulating, and exit speeds. They are usually installed in high-speed environments (Wisconsin Department of Transportation 2001) where few pedestrians are anticipated, currently or in the future.

1.3.2.5 Urban Multi-Lane Roundabouts

Compared to their rural counterparts these include at least one approach with at least two entry lanes (Kansas Department of Transportation 2003; Wisconsin Department of Transportation 2001) including flares from one to more lanes (Wisconsin Department of Transportation 2001).

1.3.2.6 Rural Multi-Lane Roundabouts

Similarly these roundabouts have at least one multi-lane approach. Vehicle speeds are in the range of 45 to 55 mph (Wisconsin Department of Transportation 2001). An example is shown in Figure 8.

(Source: Rodegerdts et al. 2010)

Figure 8 Example of a Multi-Lane Roundabout

1.3.3 Merits and Demerits of Roundabouts

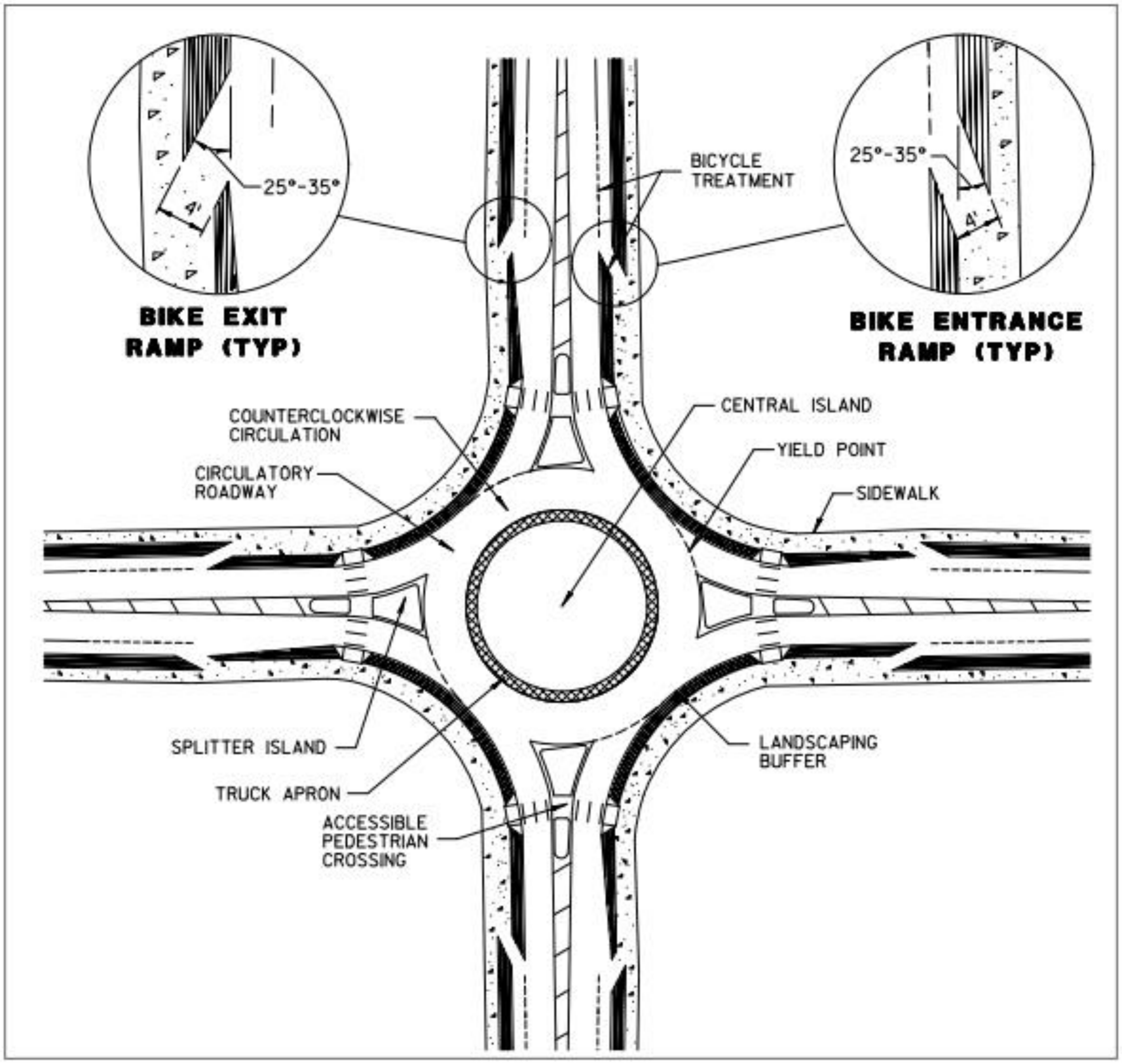
Table 1 summarizes the pros and cons of roundabouts.

Table 1 Merits and Demerits of Roundabouts

Category	**Pros**	**Cons**
Safety	• Reduced number of conflict points and less severe crashes • Reduced decision making at point of entry • Long splitter island and geometry provide advance warning to drivers	• Crashes may temporarily increase due to improper driver education • In an emergency, roundabouts can't preempt traffic like signalized intersections
Capacity	Higher capacities experienced	Coordinated signals network can provide higher capacities
Delay	Reduced delay compared to similar signalized intersection	• Equal priority may reduce progression for high volume approaches
Costs	Avoided maintenance cost for signals and reduced accident costs	Illumination costs and central island landscaping costs
Pedestrian and Bicyclists	• Splitter island provide pedestrian refuge • Improves pedestrian and bicycle safety	• Pedestrians may experience increased delay in finding acceptable gaps. • The visually impaired may have difficulty knowing when a vehicle has yielded
Environmental	Less environmental pollution	Greater spatial requirements
Space	• Often needs less storage space on approach • Reduce need for additional right-of-way between links of intersections	Often requires more space at the site than other traffic treatments

1.3.4 Physical Features of Roundabouts

A roundabout has many unique physical features which contribute to its overall safety and operational performance. Figure 9 shows some of these unique features which are also briefly discussed below.



(Source: WisDOT 2001)

Figure 9 Distinguishing Physical Features of Roundabouts

- Central Island: The raised area in the middle around which traffic circulates in a counter-clockwise direction.
- Splitter Island: The approach area with raised curb close to the point of entry. It serves to separate entry and exiting vehicles, deflect traffic, provide advance warning to drivers, and provide a refuge for pedestrians crossing the road.
- Circulatory Roadway: The circular path on which vehicles travel.
- Truck Apron: The traversable portion of the central island used to accommodate large turning trucks at small diameter roundabouts.
- Yield Point: This is the dotted line between circulatory and entering vehicles.
- Pedestrian Crossing: This is usually set back one car length from the yield line. It cuts through the splitter island at the same level as the road.
- Bicycle Treatments: This is a ramp for bicyclists to exit the roadway or shared lane and use the pedestrian crossing like a pedestrian.
- Landscaping Buffer: Separates pedestrians from vehicle traffic. Also encourages pedestrians to cross road at only designated points.
- Sidewalk: This is the pathway for pedestrians to walk and in an urban area it is common to provide a multi-use facility to be shared by pedestrians and bicyclists.

1.4 Roundabout Illumination

Roundabouts differ from conventional intersections in both traffic operations and the geometric layout. Nighttime navigation can, therefore, be challenging if adequate visibility is lacking. The FHWA states that adequate lighting must be provided at all roundabouts because drivers must be able to perceive the general layout and operation of the intersection in time to make the appropriate maneuvers (FHWA 2000). Also, the design guide for roundabout lighting identifies the two basic purposes for providing lighting at roundabouts (Illuminating Engineering Society 2008) as:.

(a) to help road users to clearly perceive the roundabout layout from a distance
(b) to enable motorized users to perceive other users in key conflict areas

The differences between traffic operations at roundabouts and other intersections can be instructive in any consideration for roundabout lighting. Some of these important differences include:

- At a roundabout, the pedestrians crossing is located at least one vehicle length before the yield line (Illuminating Engineering Society 2008). Therefore, illumination must extend beyond the intersection, especially in areas with high pedestrian activity.
- At a roundabout yield line, drivers check for conflicting traffic from only the left side and this helps to reduce delay. Adequate lighting of yield line area can help augment delay savings.
- At a roundabout, a vehicle’s headlight is tangential to the circulating roadway and so without adequate lighting drivers will be looking into darkness as they negotiate the roundabout (Illuminating Engineering Society 2008).
- The yield control means that drivers do not necessarily have to stop (Illuminating Engineering Society 2008) and this keeps capacity high. Adequate lighting can augment this benefit.

- Deflection of the travel paths by raised splitter islands and the central island implies that a driver must be able to visualize the layout well to avoid crashes and extra delays due to lack of familiarity with the site.

1.4.1 Recommended Illuminance for Roundabouts

The recommended criterion for assessing adequacy of illumination on roadways is luminance (Illuminating Engineering Society 2000; International Commission on Illumination 2010). However, in conflict areas such as intersections and pedestrian activity areas it is recommended that illuminance should rather be used. Illuminance refers to the incident light while luminance refers to reflected light from the surface.

The Illuminating Engineering Society for North America (IESNA) design guide for roundabout lighting (Illuminating Engineering Society 2008) provides recommended illuminance levels for a combination of three roadway functional classifications and three pedestrian area classifications. These illuminance levels are based on the same criteria for intersection lighting recommended in the American National Standard Practice for Roadway Lighting (Illuminating Engineering Society 2000). The three roadway classifications are as explained below.

- Major Roadway – these are the principal networks for through-traffic flow and can be important rural roadways or can be connections between two major traffic generation areas. They are also known as arterial, thoroughfares, or preferentials. The existing daily traffic volumes on these roads, for the purposes of intersection lighting only, is more than 3500 ADT (Wisconsin Department of Transportation 2001)

- Collectors – these are connections between major and local streets. They service traffic from residential, commercial, or industrial areas and can be expected to have 1500 to 3500 ADT (Wisconsin Department of Transportation 2001). These volumes are only for the purposes of intersection lighting.
- Local Streets – these streets provide direct access to residential, commercial, or industrial property. Their expected traffic volumes for the purposes of intersection lighting, is in the range of 100 to 1500 ADT (Wisconsin Department of Transportation 2001).

The three pedestrian area classifications (Illuminating Engineering Society 2008) are also explained below.

- High – significantly high number of pedestrians are expected to be on the sidewalks or crossing streets during nighttime. They are mostly located near downtown retail areas, theatres, concert halls, stadiums, and transit terminals. They could have more than 100 pedestrians during the average annual peak hour of darkness, i.e., 18:00 to 19:00 hours.
- Medium – about 11 to 100 pedestrians during 18:00 to 19:00 hours can be expected in these areas which can be found around downtown office areas, blocks with libraries, movie theaters, apartments, neighborhood shopping, industrial areas, older city areas, and streets with transit lines.
- Low – these areas have low nighttime pedestrian volumes and are on small urban streets with single-family homes, very low density residential developments, and rural or semi-rural areas. Less than 11 pedestrians can be expected during 18:00 to 19:00 hours.

The pedestrian volume includes those on both sides of the street plus those crossing the street at non-intersection locations in a typical block or 200 m (656 feet) section (Illuminating Engineering Society 2008). Table 2 presents the recommended minimum maintained horizontal illuminance for roundabouts on continuously lighted streets. For roundabouts on streets that are not continuously lighted, it is recommended that the local/local functional road classification be used.

Table 2 Recommended Horizontal Illuminance for Roundabouts

Functional Classification	**Maintained Average Horizontal Illuminance in Lux/FC for different pedestrian area classifications**			**Uniformity Level (E_{avg}/E_{min})**
	High	**Medium**	**Low**	
Major/Major	34.0/3.4	26.0/2.6	18.0/1.8	3:1
Major/Collector	29.0/2.9	22.0/2.2	15.0/1.5	3:1
Major/Local	26.0/2.6	20.0/2.0	13.0/1.3	3:1
Collector/Collector	24.0/2.4	18.0/1.8	12.0/1.2	4:1
Collector/Local	21.0/2.1	16.0/1.6	10.0/1.0	4:1
Local/Local	18.0/1.8	14.0/1.4	8.0/0.8	6:1

(Source: Illuminating Engineering Society 2008)

Next, in order for drivers to clearly see pedestrians in the crosswalks, IESNA further recommends that the average vertical illuminance for a series of points 1.5 meters (5ft) in height, along the centerline of the crosswalk and extending to the edge of the roadway, spaced at 0.5 meters (1.65ft), for each approach, should be equal to the required horizontal illuminance and uniformity level.

1.5 Research Motivations

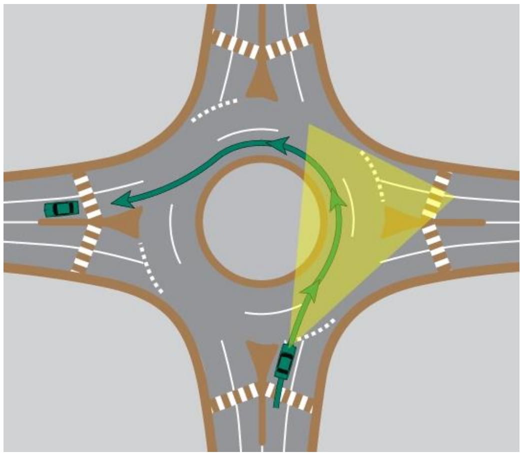
1.5.1 Good Visibility of Roundabout Layout is Critical for Nighttime Safety

As mentioned prior, traffic operations and geometry layout of roundabouts are uniquely different from other intersections. This unique speed reducing geometry incorporates raised splitter islands with flared ends at the exit and entry points to deflect the travel path of vehicles around a raised central island along a circular path. Figure 10 presents a roundabout with raised splitter island with flared ends and a raised central island. The picture credit

(Source: NYSDOT)

Figure 10 Raised Splitter Island with Flared Ends and a Raised Central Island at Roundabouts

This deflected travel path implies that roundabouts require visibility enhancing treatments to give drivers advance warning and to ensure that they can be safely negotiated, especially during nighttime conditions. Also, a vehicle’s headlight beam at a roundabout is often more tangential to the circular path and does not illuminate objects and/or conflicting movements from the left side of the vehicle. This implies that drivers will often be looking into darkness as they navigate the roundabout (Illuminating Engineering Society 2008) if illumination is absent. Consequently, the FHWA states that all roundabouts should be illuminated (FHWA 2000). Figure 11 depicts a vehicle's headlight beam at an intersection.



Original Image: WisDOT

Figure 11 Vehicle's Headlight Beam at a Roundabout

1.5.2 Current Illumination Requirements may Hinder Wider Use of Roundabouts

Perhaps as a result of the FHWA's statement, current U.S. national guidelines for roundabout illumination, *Design Guide for Roundabout Lighting IES DG-19-08* (Illuminating Engineering Society 2008), which has been adopted in both *Roadway Lighting ANSI/IES RP-8-14* (Illuminating Engineering Society 2014) and *Roundabouts: An Informational Guide NCHRP 672* (Rodegerdts et al. 2010) recommend systematic provision of illumination for roundabouts in both rural and urban areas.

However, in most countries around the world, rural roundabouts are kept unlit as indicated by a recent survey (Rodgers et al. 2014) of international roundabout illumination policies and standards from 45 countries (22 from Europe, 12 Asian countries, 2 African countries, and 9 countries from the Americas outside of the U.S.). Some of the countries that do not have a systematic requirement include countries with comparable transportation systems such as France, United Kingdom, Holland, Germany, Canada, and New Zealand. The survey highlighted a trend of leaving the decision to illuminate rural roundabouts to the discretion of local authorities, and the key factors that favor the installation of illumination were the presence of pedestrian crossings, one or more lighted approaches, presence of illumination in the immediate vicinity, and availability of power. Figure 12 shows a map of countries surveyed for roundabout illumination policies and standards.

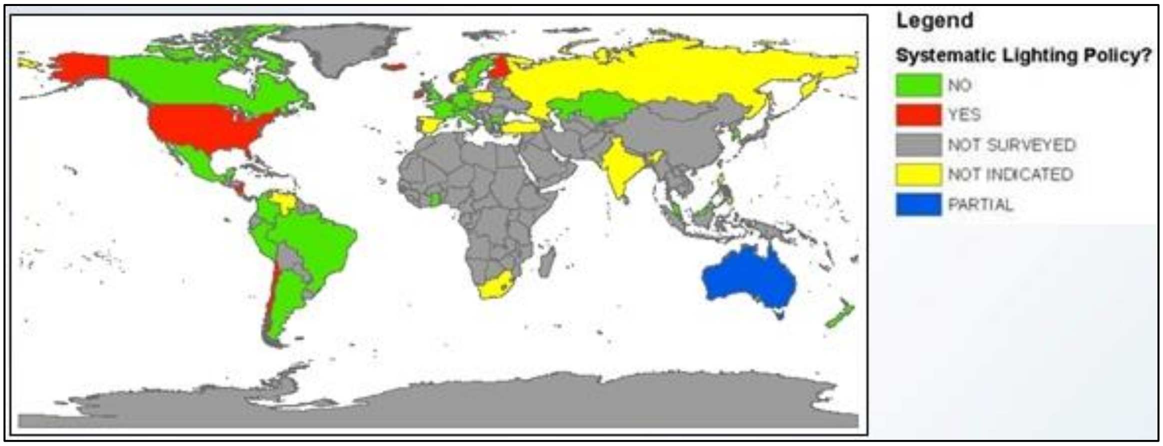


Figure 12 Map of Countries Surveyed for Roundabout Illumination Policies and Standards

Furthermore, roundabout illumination is very expensive to both install and maintain with associated maintenance and power costs representing up to 1.5 times the initial investment costs over a 15 year period (SETRA 1998). Therefore, given the fact that a lot of U.S. roundabouts are used to replace existing uncontrolled or stop-control intersections, which are normally kept unlit in rural areas, the associated costs of roundabout illumination imposed by the current guidelines could preclude the installation of a roundabout that would otherwise be safer than a conventional intersection.

1.5.3 Potential Safety Benefit from Reduced Illumination on Roadways

Recent studies (Bhagavathula et al. 2015; Bruneau and Morin 2005; Bullough et al. 2014; Gibbons et al. 2015; Oya et al. 2002) have presented findings which indicate that reduced illumination levels on road and/or intersections might be equally effective for nighttime safety. One of these studies (Gibbons et al. 2015) reports that the reduction could be as much as much as 50 percent on rural roads without compromising safety. Furthermore, a recent GDOT sponsored study (Gbologah et al. 2015; Rodgers et al. 2014) also indicated that illuminating only the roundabout circle can provide about 80 percent of the safety benefits of illuminating both the circle and transition zones on the legs.

1.5.4 No Existing U.S. Roundabout Illumination and Safety Research Available

Despite the recommendation for systematic illumination, there is no quantitative research on illumination impacts on safety at roundabouts. All previous U.S. research studies evaluating the link between illumination levels and intersection safety have been focused on conventional intersections and almost all of these studies have treated illumination as a binary (Yes/No) variable. Consequently, the current edition of the

Highway Safety Manual lacks any kind of a roundabout illumination crash modification factor (CMF). For conventional intersections, the Highway Safety Manual includes an illumination CMF for the lit/unlit condition. However, even in the absence of any purpose-built roadway lighting there may be nearby ambient light sources (e.g. gas stations, houses, or stores) that may provide significant intersections illumination relative to the truly unlit condition. These ambient light sources need to be accounted for in intersection illumination studies. Also, a CMF for a purposely built lit condition would only be viable if safety benefits are truly independent of illumination level.

1.6 Research Focus and Challenges

The focus of this dissertation is to evaluate the influence of illumination on nighttime safety at intersections with a special emphasis on roundabouts. To conduct this evaluation successfully would require the simultaneous availability of several types of data; location data, activity data, crash data, and illumination data.

Location data is not always available in a consistent format. Sometimes location is indicated as longitude/latitude or as mileposts. Location data may also lack information on important features such as the number and type of lanes, intersection control type, the adjacent land-use pattern, approach sight distance, intersection skew angle, and presence of a crosswalk with/without refuge island. Availability of activity data also varies, at times road AADTs may be missing for one or more years. This often limits the sample size available to a study.

Crash data is often incomplete and may require extensive man-hours to QAQC it and make it more useful. Also, crash data is usually sourced from accident reports filed by the investigating police officer on standardized forms. This information is often manually entered later by data entry clerks into an electronic database. The process can introduce a lot of human error, making the data unreliable and further increasing the man-hours required to sanitize the data.

There is currently no repository of quantitative intersection illumination data which can be used to successfully evaluate the impact of illumination levels on safety at intersections. Further compounding this problem is the fact that existing protocols (Illuminating Engineering Society 1999; International Commission on Illumination 2000) for measuring roadway illumination require the use of expensive high-precision luminance meters and are overly time consuming to follow. Consequently, almost every previous study has been forced to rely on the less informative binary (Lit/Unlit) illumination data. The few exceptions which used actual illumination data (Bhagavathula et al. 2015; Gibbons et al. 2015) were published as recent as 2015 with data obtained with the aid of an even more expensive instrumented data collection vehicle which is owned by Virginia Tech.

Out of all these datasets, the lack of quantitative illumination data is the biggest impediment. Therefore, from the onset the most relevant data needed for the study did not exist. This afforded a unique opportunity to pioneer studies in roundabout illumination and safety as well as to develop a cost-effective process which can be used to collect illumination level data from both conventional intersections and roundabouts.

1.7 Research Objectives

Based on the existing data challenges and research motivations, this dissertation has the following objectives;

1.7.1 Evaluate the Impact of Illumination on Nighttime Safety at Roundabouts using the Best Available Data

This study will conduct a thorough search of all available national and state highway data repositories to identify the best available data in the absence of quantitative illumination data.

1.7.2 Develop a Cost-Effective, Accurate, and Rapid Measurement Protocol for Intersection Illumination

The dissertation will also develop a cost-effective, accurate, and rapid measurement protocol for intersection illumination. In pursuance of this second objective, a photographic method utilizing a calibrated digital single lens reflex (DSLR) camera for measuring intersection luminance from both conventional and roundabouts will be developed and field tested.

1.7.3 Apply the Developed Protocols in a Case Study of Roundabouts in Georgia

The final objective is to apply the developed illumination measurement protocol to a case study in Georgia. This will require the development of additional procedures to maximize the use of existing location, activity, and crash data. Actual intersection illumination data will be collected from more than one hundred roundabouts and conventional intersections across Georgia. Crash data and traffic volume information will be obtained from GDOT’s crash database and RC-Link database respectively. A civil survey will also be conducted at each intersection to collect additional data intersection characteristics.

This analysis will highlight the current deficiency in existing highway safety knowledge and potentially serve as the initial basis for the development of an illumination level intersection crash modification factor for the highway safety manual.

CHAPTER 2: REVIEW OF ROUNDABOUT SAFETY, ILLUMINATION IMPACTS, AND INFLUENCE OF PAVEMENT REFLECTIVITY ON LUMINANCE

2.1 Roundabout Impact on Safety

Roundabouts significantly reduce the number of conflict points in a conventional stop-control or signalized intersection (Flannery 2001; Lenters 2005) and also offer significant reduction in injury severity. Their design and operational features force drivers to reduce speed regardless of posted speed limits and promote better driver behavior (Isebrands et al. 2014). Their overall safety advantages has made them preferred to other alternatives, for example, in Sweden major road intersections with high pedestrian and/or cyclist volume are being converted to roundabouts (Azhar and Svante 2011).

2.1.1 Impact on Vehicle Crashes

The conversion of stop-control or signalized intersections to roundabouts have been found to offer substantial reductions in crash frequency and crash rates (Retting et al. 2001). One of the earliest studies (Troutbeck 1993) indicated a 74 percent reduction in injury crash rates after conversion of 73 conventional intersections in Australia. Similarly, an analysis of 181 converted intersections in the Netherlands (Schoon and van Minnen 1994) reported 47 percent and 71 percent reductions in total crashes and total injuries respectively. Severe crashes were also found to have reduced by 81 percent. (Hydén and Várhelyi 2000) investigated the safety, time, and environmental effects of large scale use of roundabouts in a Swedish urban area by analyzing 21 high-risk signalized and un-signalized intersections which were replaced with small roundabouts. The results show a statistically significant reduction in speeds at the intersections and on road segments between roundabouts, however, there was no change in speeds on the segments not bounded by roundabouts.

Also, a highly significant reduction of 38 percent in total crashes, 76 percent in injury crashes, and 90 percent in fatal and severe injury crashes were estimated in a study (Retting et al. 2001) that used the empirical Bayes (EB) procedure to estimate changes in crashes from the conversion of 24 stop-control and signalized intersections. Similarly, Persaud et al. (2001) used EB procedure to analyze the conversion of 19 stop-control and 4 signalized intersections. The authors estimated about 40 percent reductions in total crashes, 80 percent reductions in injury crashes, and 90 percent reductions in fatal and incapacitating injury crashes. Further sub-grouping analysis of converted single lane urban stop-control intersections indicated 72 percent reduction in total crashes and 88 percent reduction in injury crashes. Similar analysis for the rural counterparts showed 58 percent reduction in total crashes and 82 percent reduction in injury crashes while converted signalized intersections showed 35 percent reduction in total crashes and 74 percent reduction in injury crashes.

Next, De Brabander and Vereeck (2007) evaluated safety at 95 roundabouts and 230 conventional intersections in Belgium. Their results showed that roundabouts reduce injury accidents by 39 percent, severe injury accidents by 17 percent and light injury accidents by 38 percent. Another study (Rodegerdts et al. 2007b) reports the results of a before and after safety analysis of converted intersections in three countries; 41 percent reduction in total crashes, 45 percent reduction in injury crashes, and 63 percent reduction in fatal crashes after the conversion of 230 Australian intersections; similarly 83 converted intersections in France showed a 78 percent reduction in injury crashes and 82 percent reduction in fatal crashes; also crash data from converted U.S. intersections showed 45 percent reduction in total crashes and 81 percent reduction in injury crashes.

Similarly, *NCHRP Report 572* (Rodegerdts et al. 2007a) presents the results of an EB analysis of crash data from 55 roundabouts indicating 35 percent and 76 percent reduction in a total crash and injury crashes respectively. However, a separate analysis of nine high-speed locations indicated larger safety benefits of 71 percent reduction in total crashes and 87 percent reduction in injury crashes. Following this, Isebrands (2009) analyzed 17 high-speed rural intersections that were converted to roundabouts from predominantly two-way stop-controls. Using data with an average of 4.6 years of before crashes and an average of 5.5 years of after crashes, the author found a reduction of 84 percent and 89 percent for injury crash frequency and crash rate respectively. Also, angle crashes reduced by 86 percent while fatal crashes reduced by 100 percent. In another study (Isebrands and Hallmark 2012) the authors developed a crash prediction model for 19 converted high-speed rural roundabouts from six US states. The before and after data both averaged 5.2 years. First, using a negative binomial regression model the results showed statistically significant reductions of 63 percent for total crashes and 88 percent for injury crashes. A separate EB analysis yielded consistent results of 62 – 67 percent reduction for total crashes and 85 – 87 percent reduction for injury crashes.

Uddin et al. (2012) used the EB procedure with 2.5 years of both before and after data to analyze safety at two previously stop-control interchange-terminals roundabouts

The results indicated a 38 percent and 60 percent reduction in total and injury crash frequency respectively. Also, Jensen (2013) evaluated crashes at 332 converted roundabouts in Demark. After correcting for general crash trends and regression-to-the-mean effects the author estimated overall safety benefit of 27 percent and 60 percent for total and injury crashes respectively. Also, fatalities reduced by 87 percent and PDO reduced by 16 percent.

Next, Gross et al. (2013) analyzed 28 converted signalized intersections using the EB method as well as the negative binomial regression. The results of the EB analysis showed 21 percent and 66 percent reduction in total crashes and injury crashes respectively. Furthermore, it was seen that safety benefit decreased with increasing entering AADT. The results of the cross-sectional analysis also corroborated the findings of decreasing safety benefit with increasing entering AADT. Also, Qin et al. (2013) used the EB procedure to analyze the safety performance of 24 converted intersections from Wisconsin. Both before and after data averaged 3 years and the results showed an unbiased estimate of 9.2 percent reduction in total crashes as well as a significant 52 percent reduction in injury crashes.

It is a known and well established characteristic that roundabouts force drivers to reduce speeds. Isebrands et al. (2014) undertook a study to verify this phenomenon at high speed rural locations by evaluating the change in average approach speeds between roundabouts and two-way-stop-control intersections and also between roundabouts with rumble strips and those without rumble strips on their approaches. The study included four roundabouts and two two-way-stop-control intersections and the findings indicate that the mean speed 100 feet from the yield line at roundabouts was about 2.5 mph lower than the mean speed 100 feet from the stop bar at stop-control intersections. Also, mean speeds at locations with rumble strips were 4.3 and 3.3 mph lower at 100 feet and 250 feet from the yield line respectively.

2.1.2 Impact on Other Road Users

De Brabander and Vereeck (2007) argue that roundabout injury reductions could vary greatly among various subgroups in crash data because although, the total number of accidents involving vulnerable road users reduced by 14 percent, the same statistic went up by 28 percent at previously signalized intersections. Also, Daniels et al. (2008) evaluated bicyclist safety at 91 roundabouts in Belgium using before-and-after methodology and the results show that injuries increased by 27 percent while fatal or serious injuries increased by 41- 46 percent after conversions. Furthermore, in built-up areas there was a 48 percent and 77 percent increase in injury crashes and fatal or serious crashes respectively. Outside built-up areas the results were not statistically significant.

In order to understand why roundabouts pose a proportionately higher risks to bicyclists, Møller and Hels (2008) surveyed 1019 bicyclists at 5 roundabouts in Denmark seeking their perception of risk in roundabouts. The survey respondents were between the ages of 18 – 85 and surveys were administered Tuesdays through Thursdays between 7:30 AM and 4:30 PM. The authors measured perceived risk in two dimensions; (a) risk of being involved in an accident and (b) perceived danger. These dimensions require cognitive judgment and an emotional response respectively. The results show that underestimating of risk and lack of knowledge about traffic rules may be the contributing factors in vehicle-bicycle crashes at roundabouts. Also, the study found that perceived risk is influenced by factors regarding the individual cyclist (age and gender), design features that govern the interaction between road users, and traffic volume. Next, the results show that roundabouts with a cycle facility are perceived as safer than those without it. The authors also note that the possible effect of bicycle facilities may be reduced because cyclists are likely to compensate their decreased perception of risk by a risk taking behavior.

In a subsequent study, Daniels et al. (2010a) attempted to shed light on the variation in safety performance of roundabouts by analyzing 90 roundabouts in Flanders, Belgium. The authors used state-of-the-art cross-sectional risk models based on crash data, geometric data, and traffic data in this study. During the analyses, the authors detected under-dispersion in the data so gamma modeling techniques in addition to Poisson modelling were used. The study results however indicate that roundabouts with cycle lanes performed worse than those with cycle paths (dedicated paths for bicyclists at a distance of more than 1 m from the roadway).

2.1.3 Safety Influencing Features of Roundabout

The safety and operational performance of roundabouts can be negatively impacted by inadequate geometric design and site characteristics. Flannery (2001) used case studies to review the geometric characteristics and safety of roundabouts from Maryland, Florida, and Nevada and found that (a) inadequate sight distances hinder the free flow of vehicles into the roundabout, forcing drivers to reduce speeds considerably, (b) lack of adequate deflection encourages drives not to slow down, with some of them driving over the island apron, and (c) operating roundabouts with low volume/capacity ratio, especially in multilane roundabouts, can encourage high speeds through the roundabout and lane crossings.

Next, Lenters (2005) explains some geometric design features of roundabouts which have an influence of safety;

- Sharply increasing the angle between arms reduces accident frequency and so roundabouts with equally spaced arms may be safer.
- Increasing entry width produces significant increases in accident frequency. A roundabout design that applies entry flaring in combination with moderate entry path curvature can offer improved capacity and balanced safety performance
- Increasing circulating width increases accident frequency.
- Very small values of entry path radius must be avoided. However, these values are usually large and need to be reduced. Optimum values will depend on entry and circulating flows.
- Increasing the half width provides very small reduction in accidents.

The geometry of roundabouts is such that making a change in one geometric element can reduce the probability of one crash type but it can also increase the odds for other types of crash. Lenters (2005) also performed a safety auditing of roundabouts in Canada and made the following additional findings about the effect of roundabout geometric elements on crashes.

- Even though a good deflection is desirable for safety, designs with entry path curvatures that are too tight as with perpendicular or sharply curved entries, can increase crashes resulting from loss of control on the roundabout approaches.

- Inconspicuous central island and/or splitter islands are the primary contributing factors to loss of control crashes because drivers that are unfamiliar with the layout often do not get sufficient visual information to adjust speed and path.
- Inadequate stopping sight distance limits vertical sight and makes it difficult for drivers to see the yield line as well as the center and splitter islands. This results in drivers overshooting the entry or failing to brake in time. Also, insufficient sight distance to the left near the entry can result in entry-circulating crashes while providing visibility that is beyond 15 m from the yield line, to the right of the entry can encourage drivers to compete for gaps.
- Increasing the deflection with small inscribed circles provides better safety for bicycles.
- Improper lane designation contributes to exit crashes
- Positive contrast lighting and vertical luminance are essential for pedestrian and signage visibility.

In a similar study, Montella (2011) investigated crash contributory factors and their interdependencies at 15 urban roundabouts located in Naples, Italy, using crash data from 2003 to 2008. The study analyzed only 274 crashes but the findings showed that the most common crash contributory factor was geometric design; (a) an excessive radius of deflection associated with rear-end and angle crashes at entry, (b) an excessively low angle of deviation associated with angle crashes at entry, and (c) an excessive radius of deflection of the left approach associated with angle crashes. Next, it was found that poor markings contributed to more than half of the crashes, with missing yield lines or symbols being associated with angle crashes at entry, and missing, faded, or poorly located pedestrian crossing being associated with pedestrian crashes at exit. Next, inadequate pavement friction was found to be the most common pavement contributory factor being associated with a third of all crashes.

Zirkel et al. (2013) evaluated the influence of sight distance on safety at low-volume single-lane roundabouts by analyzing 72 roundabout approaches from 19 single-lane roundabouts. Their findings showed that increasing sight distance increases the risk of crash occurrence as well as the speed differential between the approach and entry to the roundabout. However, the authors acknowledged that other parameters not included in the study could also contribute to the variability in crashes and crash rates.

Hammond et al. (2014) also investigated the effect of additional lane lengths on roundabout operational characteristics using delay as the performance measure. Delay was measured within 250 feet of the yield line. The authors analyzed a hypothetical four-leg, double-lane roundabout with additional lanes at both entry and exit. They varied the lengths of these additional lanes to study their effect on operations. Based on the findings from the hypothetical roundabout, similar additional lane lengths were applied to a calibrated and validated model of an existing roundabout. The findings indicate that shorter lengths of additional lanes (and flares) between 50 - 150 feet provided the best operational performance.

2.2 Illumination Impact on Intersection Safety

Review of the literature on illumination and intersection safety shows that most of these studies were conducted using either a before and after analysis method or a cross-sectional method comparing roundabouts with lighting to those without lighting. A few of studies have been compelled to use methods other than these two because of their inherent limitations.

2.2.1 Before-and-After Studies

Walker and Roberts (1976) analyzed crash data from 47 rural at-grade intersections in Iowa using crash data which spanned 3 years before and after lighting was installed. The study assumed that nighttime traffic volume was 0.27 times the existing daily traffic volume. The results showed a reduced crash rate of 0.91 per million entering vehicles (MEV) in the after period compared 1.89 per MEV in the before period. Also, it was generally found that the impact of lighting was less for low volume roads with daily traffic volumes less than 3500 vehicles per day. After this study ended and in the wake of the 1973 energy crisis, the Iowa Department of Transportation commissioned another study (Marks 1977) to investigate the *Effects of Reduced Intersection Lighting on Nighttime Accident Frequency.* The study analyzed crash data from 19 pairs of intersections with similar geometrics and one intersection out of each pair had some lights turned off to produce a lighting differential. The results showed that the nighttime crash rate at the rural intersections with full lighting was 1.06 while the nighttime accident rate at the rural intersections with reduced lighting was 1.01. Based on the results, it was concluded that the lighting level of lighted rural at-grade intersections does not have a significant effect on the accident frequency as long as the conflict area is sufficiently illuminated.

In 1999, Preston and Schoenecker (1999) undertook a study of 12 rural Minnesota intersections associated with installation of lighting to determine the relative changes in crash frequencies and other crash characteristics. They reported findings of about 40 percent reduction in nighttime crash rates at the 5% significance level and also indicated a 20 percent crash severity reduction at the 10% significance level. Also, Green et al. (2003) investigated the effect of roadway lighting on driver safety using crash data from nine Kentucky intersections. This study was severely limited by sample size and no statistical tests were reported but the results indicated a 45 percent reduction in nighttime crash frequency after installing lights.

Next, Isebrands et al. (2010) also used a Poisson regression model to evaluate the change in expected crash frequencies after installation of lighting at 33 rural intersections where rural intersection is defined as an intersection that is at least 1 mile away from any development or 1 mile away from signalized intersection on the same roadway. Both the before and after data had at least 3 years of information and the Poisson model included intersection related variables such as a night/day variable, before/after variable, number of intersection legs variable, posted speed limits variable, intersection control variable, presence of turn lanes variable, and presence of horizontal or vertical curve. Using a significant threshold of 10%, the Poisson regression model revealed a statistically significant reduction in nighttime crash rate of 37 percent after lighting was installed. There was also a reduction in daytime crash rate of 4 percent but this was not found to be statistically significant.

2.2.2 Cross-sectional Studies

Sometimes it is difficult to identify intersection locations with enough samples of before-and-after crash data where illumination was the only safety treatment applied during the study period. In such instances a cross-section study can be used. Cross-sectional studies compare an intersection with a particular attribute, in this case lighting, to a site without it.

Wortman and Lipinski (1974) evaluated the impacts of intersection lighting on crashes at rural highway intersections by analyzing 263 lighted intersection-data-years and 182 unlighted intersection data years. Their findings indicate an average night/total crash ratio of 0.25 for lighted intersections and average night/total crash ratio of 0.33 for unlighted intersections. This corresponds to a 24 percent reduction in night accidents. Later on Lipinski and Wortman (1978) analyzed 445 intersection-data-years and their results show a 22 percent reduction in night/day crash ratio, 45 percent reduction in nighttime crash rate, and 35 percent reduction in total crash rate at all intersections.

Also, Preston and Schoenecker (1999) performed a cross-sectional study of over 3400 intersections in Minnesota with crash data from 1995 to 1997 and their results indicate a 25 percent reduction in nighttime crash rate (0.63 to 0.47 per million entering vehicles) and 8 percent reduction in injury severity. Similarly, Bruneau and Morin (2005) also evaluated the safety aspects of roadway lighting at rural and near-urban intersections in Quebec, Canada, by comparing unlit intersections with lit intersections. The lit intersections were made of those with standard lighting and non-standard lighting and there were both 3-legged and 4-legged intersections included. The study analyzed a total of 376 sites and the results which were statistically significant at the 5% level showed that rural intersection lighting can reduce night accident rate by 29% for non-standard lighting and by 39% for standard lighting.

Next, Isebrands et al. (2006) evaluated 3622 rural illuminated and unilluminated intersections in Minnesota. Their linear regression model indicated that the relevant variables that affect the ratio of nighttime accidents to total accidents were presence of lighting, volume, and number of intersection legs. Furthermore, the model showed that the expected ratio of nighttime to total crashes was 7 percent higher for unilluminated intersections than for illuminated intersections. Also, Hallmark et al. (2008) conducted a cross-sectional study of 223 rural intersections using a hierarchical Bayesian model with Poisson distribution. The authors found that the expected mean of nighttime accidents was 2.01 times higher for unlit intersections than for illuminated intersections.

Also, Donnell et al. (2011) estimated the safety effects of roadway lighting at intersections from Minnesota and California using a cross-sectional approach with four years of intersection data They computed expected night-to-day crash ratios at intersections with and without roadway lighting and their results indicate 12 and 23 percent reductions in expected night-to-day accident ratios between intersections with and without lighting in Minnesota and California respectively.

More, recently Donnell (2015) undertook a study exploring statistical issues in relating lighting to safety. As part of the study he compared two cross-sectional studies. Each analysis was undertaken with a negative binomial regression but the input data was treated differently. One analysis incorporated observed crash data while the other analysis used a propensity score – potential outcome framework. Propensity scores are estimated using binary logit regression to determine probability that an entity contains intersection lighting based on site-specific conditions in order to identify lighted and unlighted sites based on covariates. The results indicate a lighting safety benefit of 11.9 percent and 9.5 percent for the analysis based on observed data and propensity scores respectively.

2.2.3 Issues with Before-and-After and Cross-sectional Studies

Before-and-after studies are faced with issues that can affect the statistical validity of results. First, such studies can give biased results due to the phenomenon called regression to the mean (Per Ole 2009; Retting et al. 2001). Usually, it is difficult to find a large sample of data for the before case and the after case. Therefore, these datasets usually cover a few years on either side of light installation. The mean of such data is easily affected by temporary events and this can bias the results from a before-and-after case study. On the other hand if the duration of the before and after samples are increased too much the study can be influence by long-term trends which might not be true any longer. Furthermore, a before-and-after study can also be faced with selection bias (Donnell et al. 2010) or endogeneity bias as referred to in other studies (Per Ole 2009). This bias arises due to the fact that a traffic safety countermeasure such as lighting is normally applied to a site with a recent or proportionately higher nighttime number of crashes. However, warrants for lighting are usually applied with other operational considerations so other safety influences may be influencing the results.

On the other hand, cross-sectional studies mainly attempt to address the regression to the mean bias faced in before-and-after studies. In cross-sectional studies no treatment is applied to a site but rather sites with particular attributes are compared to those without. However, these studies also face a selection bias issue and so it is difficult to categorically make a case for causation (Donnell et al. 2010).

In order to address these challenges, different approaches have been adopted in some previous studies. Hauer (2005) proposed a before-and-after study in which the observed effect of a treatment is compared to an estimate of the expected number of crashes that would have occurred if the treatment had not been applied. Also, Donnell et al. (2010) points out that the empirical Bayes method has been advocated by (Hauer 1997) and (Persaud and Lyon 2007) as a way to address issues of selection bias. Bo et al. (2009) also developed a Full Bayesian Empirical approach that addresses issues of selection bias as well as the Empirical Bayes method.

The Empirical Bayes method provides several advantages such as (Gross et al. 2013):

- Properly accounting for regression to the mean effects.
- Overcoming difficulties in the use of crash rates to normalize for changes in before and after period traffic volumes.
- Reducing the level of uncertainty in the estimate of the safety benefit.
- Properly accounting for differences in crash experience and crash reporting practice when combining data and results from different jurisdictions.

However, the Empirical Bayes method also has some draw backs such as (Donnell 2015):

- Requires installation dates and time-sequence.
- Possible confounding with other “treatments”.
- Adequate reference and treatment sites needed for evaluation.

Therefore, other researchers such as Donnell et al. (2010) have used cross-sectional studies with application of multivariate regression models that permit the controlling of other safety influences.

2.2.4 Other Studies Using Different Analysis Methods

Other previous studies have also used different approaches to study the impact of intersection illumination on accident reduction. In 1992 the International Commission on Illumination (CIE) published the results of a meta-analysis of 62 studies from 15 countries (International Commission on Illumination 1992). According to the study, 85 percent of the results showed lighting to be beneficial with about 30 percent of these results being statistically significant. Furthermore, this meta-analysis study observed accident reductions in the range of 13 percent to 75 percent. For rural intersections the reductions were in the range of 26 percent to 44 percent. Also, an economic analysis which was performed as part of the study showed that the benefits of illumination far outweighed the cost of illumination. Next, Elvik (1995) also carried out a meta-analysis of 37 published studies from 11 countries. The studies were published from 1948 to 1989. The results showed a 65 percent reduction in nighttime fatal crashes, 30 percent reduction in nighttime injury accidents, and a 15 percent reduction in nighttime property-damage-only crashes at intersections and on road segments.

Per Ole (2009) estimated the safety effect of lighting on nighttime accidents on roads in Holland. He used the odds ratio estimator effect and the ratio of odds ratio estimator effect to evaluate the safety impact. His results show that lighting can reduce the frequency of nighttime crashes by 50 percent on all roads and by 54 percent on rural roads. Also, the results show that adverse weather reduces the benefit of lighting on roads; 26 percent during precipitation with snow and 22 percent when snow or ice covers the surface. He also measured the risk of injury accidents under various conditions; on lit rural roads the risk is 17 percent while on unlit roads the risk is 145 percent; during rainy conditions the risk on lit roads is 53 percent while on unlit roads it is 192 percent.

Donnell et al. (2010) notes that most published lighting-safety research have been focused on rural, stop-control intersections. The authors further stresses that given the advancement in highway safety research over the past 15 – 20 years there is a need to identity new and improved ways to estimate safety effects of intersection lighting. To this end, the authors developed a comprehensive framework using a negative binomial model. Their results indicate a much lower reduction in nighttime crash frequency, 7.6 percent, than what has been reported in previous published studies. However, when the authors analyzed the data without controlling for other safety influencing features a reduction of 28 percent in night crash frequency was observed. This is similar to previous studies and an indication that published benefits in previous studies which did not control for safety contributing features may have been over estimated. Also, the authors make a case for a complete lighting management system or database (to include variables such as luminance, illuminance, pole height, etc.) which is linkable to roadway inventory and crash records to help researchers to develop a complete understanding of safety impacts of fixed roadway lighting.

Bassani and Mutani (2012) investigated the effect of environmental lighting on driver behavior in terms of vehicle speeds. This investigation was carried out on six (2 and 3 lane) arterial roads, with posted speeds in the range of 31 to 43.5 mph, in the city of Turin, Italy. The results indicate that at daytime, operating speeds increases with illuminance and speeds are generally higher on sunny days than on cloudy days. In addition, the results show that nighttime speeds were higher than daytime speeds even though illuminance levels at night were lower than during the day. The authors explained this phenomenon as being due to the increased proportion of younger drivers during the nighttime compared to during the day. One limitation with the study was that the authors did not control for other speed influencing factors such as luminance uniformity from driver’s perspective, driver alcohol level, and traffic volume.

2.3 Approaches for Quantifying Illumination’s Impact

Many methods have been used to quantify the impact of roadway illumination on crashes. These methods range from naive techniques which are often faced with statistical soundness to very sophisticated approaches designed to overcome specific issues with other techniques.

2.3.1 Night-to-Day Ratios

Some studies quantified the impact of illumination by comparing night/day crash frequency ratios for lighted and unlighted conditions. This approach can be applied to both before/after studies and with/without studies. One of the main draw backs of this frequency ratio is that it is unable to account for different traffic volumes between day and night. Therefore, other studies used night/day crash rate ratios instead. For example, Box (1970) estimates that if 25 percent of driving occurs at night then a single nighttime crash is equivalent to three daytime crashes. In either case effectiveness of illumination is presumed if the night/day ratio is lower for illuminated condition than in the unilluminated condition (Rea et al. 2009). Lighting installation is hardly random because it is usually linked to expected high crash frequencies and this lack of randomness can often confound statistical results from the night/day ratio method. Also, lighting is often installed with other nighttime safety improvement features which are difficult to account for with this approach (Rea et al. 2009).

2.3.2 Odds Ratio

The odds ratio (Elvik 1995; International Commission on Illumination 1992) is a safety criterion which can be applied to both with/without or before/after (Rea et al. 2009). The ratio can be calculated as shown in Equation 1.

$$\frac{N_{lighted}}{N_{unlighted}} \bigg/ \frac{D_{lighted}}{D_{unlighted}} \ldots\ldots\ldots (1)$$

where N is the number of nighttime crashes and D is the number of daytime crashes. Although, not necessarily valid, the odds ratio is assumed to control for other nighttime safety improvement features because it separates the lighted sites from the unlighted sites (Rea et al. 2009). An odds ratio of one indicates no effect of lighting, a value less than one indicates effectiveness with a corresponding reduction in nighttime crash risk equal to difference between the ratio and one (Rea et al. 2009).

2.3.3 Empirical Bayes Method

The empirical Bayes method (EB) offers a way to address selection bias (Donnell et al. 2010) due to fact the lack of randomness in road lighting installation. Also, EB is able to account for regression to the mean while normalizing for the difference in traffic volume in the before and after periods (Hauer 1997; Persaud et al. 2001).

This method compares the change in crashes at a site in response to a specific treatment to the expected number of crashes that would have occurred in the absence of the treatment. The change in the number of crashes can be expressed as shown in Equation 2:

$$\beta - \lambda \ldots \ldots \ldots (2)$$

β = expected number of crashes that would have occurred without the treatment

λ = actual number of crashes that occurred in with the treatment.

β can be estimated by first using a regression model (safety performance function (SPF)) to estimate the annual number crashes (P) that would be expected in the before period at other locations with similar geometrics, traffic volume, and other characteristics. This regression estimate is then combined with the crash count (χ) in the periods (η) before the treatment at a study site to estimate the expected annual number of crashes (m_b) at a site before the treatment was installed (Persaud et al. 2001). This is an important step because the crash count in the before period in itself is not a good estimate due to traffic volume changes, regression to the mean effects, and trends in crash reporting (Hauer 1997; Persaud and Lyon 2007).The expected annual number of crashes before treatment, m_b, is estimated as shown in Equation 3:

$$m_b = w_1 (x) + w_2 (P) \ldots \ldots \ldots (3)$$

W_1 and W_2 are weights estimated from the mean and variance of the regression estimate as shown in Equation 4 and Equation 5 respectively (Persaud et al. 2001):

$$w_1 = \frac{P}{k + \eta_b P} \dots\dots\dots (4)$$

$$w_2 = \frac{k}{k + \eta_b P} \dots\dots\dots (5)$$

k is a model specific constant which can be estimated from the regression as shown in Equation 6:

$$k = \frac{P^2}{Var(P)} \dots\dots\dots (6)$$

Next, the difference in traffic volume between the before period and the after period as well as the length of the after period need to be considered. First, the regression model must be used to estimate the annual number of crashes (Q) that would be expected at the other similar intersections in the after period. Next, the expected annual number of crashes at a study site in the after period must be estimated by multiplying the ratio (R) of the annual regression predictions for the after and before period to the estimated expected annual crashes at a study site in the before period (Persaud et al. 2001).

$$R = \frac{Q}{P} \dots\dots\dots (7)$$

$$m_a = R * m_b \dots\dots\dots (8)$$

β can then be estimated by multiplying m_a with the length of the after period as shown in Equation 9.

$$\beta = m_a * \eta_a \dots\dots\dots (9)$$

The variances of the expected number of crashes in the after period and the actual crashes can be estimated as shown below in Equation 10 and Equation 11 respectively:

$$Var(\lambda) = \lambda \dots\dots\dots (10)$$

$$Var\ (\beta) = \frac{m_b * (R * \eta_a)^2}{\frac{k}{P} + \eta_b} \dots\dots\dots (11)$$

The safety effect of the treatment can be estimated as (a) reduction in expected number of crashes or (b) as a crash modification (Persaud et al. 2001). The reduction in expected number of crashes (δ) can be estimated from Equation 12.

$$\delta = \sum \beta - \sum \lambda \dots\dots\dots (12)$$

Also, the variance can be estimated as shown in Equation 13.

$$Var(\delta) = \sum Var(\beta) + \sum Var(\lambda) \ldots\ldots\ldots (13)$$

The crash modification factor (θ) based on the Empirical Bayes method can also be calculated from Equation 14 and the variance can also be estimated from Equation 15.

$$\theta = \frac{\sum \lambda / \sum \beta}{1 + \frac{\sum Var(\beta)}{\left(\sum \beta\right)^2}} \ldots\ldots\ldots (14)$$

$$Var(\theta) = \theta^2 \left[\frac{\frac{\sum Var(\lambda)}{\left(\sum \lambda\right)^2} + \frac{\sum Var(\beta)}{\left(\sum \beta\right)^2}}{\left(1 + \frac{\sum Var(\beta)}{\left(\sum \beta\right)^2}\right)^2} \right] \ldots\ldots\ldots (15)$$

Values of θ less than 1.0 indicate a crash reduction effect while values greater than one indicate adverse effect from lighting. Also, the percentage reduction or increase in the effect is given as 100 (1- θ) (Monsere and Fischer 2008).

The empirical Bayes method is the state-of-the-art in assessing the effect of road safety improvement programs. However, in order to apply it to study the impact of illumination it will require separation of crash data into before-after samples based on the illumination installation date. Most often this information is not available; therefore, the method has been rarely used in the studies of illumination impacts.

2.3.4 Negative Binomial Regression

Due to the general inability to separate crash data into before and after sets based on lighting installation date, the Negative binomial regression has been the status-quo for safety studies assessing the impact of illumination because it only requires crash data to be separated into illuminated or unilluminated sets. The negative binomial regression is able to account for over-dispersion which is prevalent in crash data (Bhagavathula et al. 2015; Donnell et al. 2010) but can't be captured by other regression models including the Poisson regression model (Scott 1980). It has a functional form as shown in Equation 16:

$$lnY_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots .. + \beta_n X_n \dots \dots \dots (16)$$

Y_i = expected number of crashes at intersection i

$X_1, X_2, \ldots X_n$ = represent the explanatory variables

$\beta_1, \beta_2, \ldots \beta_n$ = the coefficients of the explanatory variables.

Bhagavathula et al. (2015) argue that if only the nighttime crashes are used as a dependent measure then the model discounts the number of day crashes and will result in either overestimation or underestimation of the other explanatory variables. Therefore, they propose using the number of day crashes (DC) as an offset variable in the model since it won't change the underlying distribution. The functional form of the modified model is shown in Equation 17.

$$lnY_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots .. + \beta_n X_n + \ln(DC_i) \dots \dots \dots (17)$$

The variance of observed crashes λ at intersection i, can be estimated from Equation 18 (Donnell et al. 2010):

$$Var(\lambda_i) = E(\lambda_i)[1 + \alpha E(\lambda_i)] \ldots \ldots \ldots (18)$$

α = over-dispersion parameter from the model

$E\ (\lambda_i)$ = expected crash frequency at intersection i.

The percent change in the number of night crashes for a one-unit increase in a continuous independent variable or when a categorical independent variable changes from one level to the next is expressed as the risk ratio (RR) and it can be estimated from Equation 19 (Bhagavathula et al. 2015).

$$RR = \exp(\beta_n) - 1 \ldots \ldots \ldots (19)$$

If RR < 1, then the expected number of nighttime crashes decreases if the independent variable is increased by one-unit while other independent variables are held constant. If RR > 1, the effect of increasing the independent variable while holding other independent variables is to increase the expected number of nighttime crashes.

According to Donnell et al. (2010) if the crash database is structured such that there is only one row per intersection (i.e., individual intersection crash counts are summed over the entire analysis period), temporal correlation among crash counts will not be an issue. Conversely, if the crash database is structured as a panel (i.e., individual intersection counts for each year in the analysis period are entered as rows) then temporal correlation may be an issue. This temporal correlation will likely result in underestimating the standard errors of the model parameters (Green 2003). Therefore, the propose that panel structured data can be analyzed with the random effects negative binomial regression model (RENB) (Chin and Quddus 2003; Shankar et al. 1998), the generalized estimating equation (GEE) (Lord and Persaud 2000; Wang et al. 2006), or the negative multinomial (NM) (Ulfarsson and Shankar 2003) regression model.

The NB, RENB, and NM were compared by Ulfarsson and Shankar (2003) and the authors found that the NB outperformed the RENB while the NM outperformed the NB. The main differences between these two top models is that (a) standard errors were generally underestimated in the NB model and (b) the error term in the NM is section-specific rather than observation specific.

The negative binomial regression model is usually applied in cross-sectional studies to work around the limitations of the empirical Bayes method. However, applying the negative binomial in a cross-sectional study has its own strengths and limitations which have been summarized by Donnell (2015) and presented in Table 3 below.

Table 3 Merits and Demerits of Negative Binomial Regression Models

Strength	Limitation
• Large number of sites with and without lighting can be identified • No time-sequence necessary	• No “change” to sites so causal effect is not possible to establish • Omitted variable bias possible • Possible site selection bias issues

2.4 Evaluating Roadway Illumination

The performance of roadway illumination can be evaluated by illuminance, luminance, or small target visibility (STV) methods (Zhou et al. 2009). Luminance is a measure of the quantity of light reflected from a surface (Illuminating Engineering Society 2000; Illuminating Engineering Society 2008; International Commission on Illumination 2010) and it is measured in candela per square meter (cd/m^2). It is what is perceived by the human eye as brightness of the road surface. Illuminance measures the quantity of light falling on the road surface (Illuminating Engineering Society 2000; Illuminating Engineering Society 2008; International Commission on Illumination 2010) and it is measured in lux or foot candles. STV is a metric used to determine the visibility of an array of targets on the roadway (Illuminating Engineering Society 2000). The recommended method for conflict points including intersections is surface or horizontal illuminance (CEN 2008c; Illuminating Engineering Society 2000) Also, vertical illuminance which helps drivers to see pedestrians and objects in the crosswalk should be measured at a height of 1.5 meters above the roadway in the crosswalk.

2.4.1 Quantity and Quality of Roadway Illumination

Four different studies (Cobb et al. 1979; Green and Hargroves 1979; Hargroves and Scott 1979; Scott 1980) that evaluated the relationship between illumination parameters (illuminance, luminance, uniformity, and glare) on crashes all concluded that luminance was statistically related to night/day crash frequency ratio. One of these four studies (Scott 1980) further estimated that within the luminance range of 0.5 – 2.0 cd/m2, an increase in average surface luminance of 1.0 cd/m2 results in a 35 percent reduction in nighttime crash frequency ratio. Similarly, in a review of 62 studies (International Commission on Illumination 1992) from 15 nations the CIE noted that crashes might increase as uniformity of lighting increases beyond a certain level due to reduction in contrast between an object and its surrounding visual environment.

Next, .Oya et al. (2002) also evaluated illuminance at 18 trunk road intersections, each with at least 10000 AADT using one year of before data and 4 years of after data. Illuminance data was calculated for each intersection and the results show that illuminance levels of 30 lux or more can positively help to reduce nighttime crashes. This was found to be significant at the one percent level. Also, the study found that illuminance levels between 20 to 30 lux can reduce nighttime crashes even though the study could not find any statistical significance for this category of lighting level. Next, a Japanese study (Minoshima et al. 2006) found that an illuminance of 10 lux or more is needed for drivers to have good visibility of pedestrians at an intersection and an illuminance uniformity ratio of 0.4 will make an intersection safer.

Medina et al. (2013) measured illuminance from three different sets of LEDs and one set of HPS luminaires and compared the measured values to estimates derived from computer analysis with AGi32® lighting software. The measurements were done on dry days and under skies with no full moon and the results show both close agreement and significant differences between measured values and software estimates. The authors attribute this to luminaire specific differences, underscoring the need to perform periodic audits to verify if in-situ lighting levels meet the design specifications.

Performing street lighting audits with hand held meters over large sections of the roadway system can pose both a data collection and safety challenge for the data collection personnel. Efforts to overcome this challenge has resulted in the development of automatic mobile reading systems and also the use of photography methods that enable quicker data collection from either intersections or road segments. Zhou et al. (2009) developed a new measurement system for collecting illuminance data for Florida DOT. The system collects data every 17.5 feet from a vehicle moving at 30 mph through a computer linked to a lighting meter and a distance measuring instrument. An inverse square method is used to transform measurements made at the top of the moving vehicle to the equivalent measurements at six inches above the pavement and a Wilcoxon test was used to compare the measurements. The results showed that the median of differences between the two is not significantly different from zero.

Schmidt et al. (2014) also explored the feasibility of LED roadway luminaires by analyzing 8 different LED luminaires produced by different manufactures and three HPS luminaires with power ratings of 150 W, 250 W, and 400 W. Annualized life cycle costs were used for economic analysis while the technical feasibility was determined by comparing in-situ measurements to recommended IES standards. The study results showed that only one LED luminaire conformed to the IES standard for moderately busy, medium pedestrian conflict road with R3 pavement. Also, only one of the eight studied LED luminaires economically outperformed the existing HPS in life cycle costs. Therefore, the study concluded that LED luminaires are a promising technology but more technological advancement would be needed to accurately confirm their in roadway illumination.

Bullough et al. (2014) argue that existing installation methods for roundabout illumination, luminaires handing from fixed heights on poles, don’t necessarily provide the best visibility for drivers and they can also be energy/cost intensive. Therefore, they evaluated a new lighting approach called ecoluminance which relies on both *illuminance* and *luminance* using a combination of roadside vegetation to provide visual delineation, lower-level lighting such as landscape lighting to reinforce delineation, pedestrian level lighting to provide illumination for important safety hazards, and retroreflective elements to provide cues about road geometry. Ecoluminance was tested in New York and the results show comparable approach speeds and initial costs for ecoluminance and conventional lighting; however, ecoluminance used only a quarter of the energy required by the conventional illumination method.

Niaki et al. (2014) developed a method for performing illumination audits for intersections using light sensors attached to a handle and a data logger for recording both illumination and position via GPS coordinates. The method simplifies the time-consuming spot measurements of illuminance required at intersections by the existing measurement protocols. Measurement can be made by walking across the exit/entrance line of each intersection leg and then averaging to obtain the mean intersection illuminance. The results from a case study of 85 intersections in Montreal indicate that about 59 percent had sub-standard lighting level. All though this method can simplify the measurements compared to existing protocols, it increases the safety risk for both personal and equipment since they must be in the active travel lane to collect data. Also, measurements with this method may lack luminance constancy since onsite voltage can fluctuate before all the intersections are walked across.

Jackett and Frith (2013) studied the relationship between road lighting levels and safety using 5 years of crash data and road lighting measurements from mid-block road sections in New Zealand. The lighting levels were obtained by the photographic method and 6th order polynomials were calibrated for pixel to luminance conversions at specific settings of camera exposure. The study included 152 mid-block road sections and the results showed that the most important performance measure in predicting expected crashes on road sections is average luminance and also uniformity is insignificant to predicting expected crashes on road sections. The authors note that a similar result was established in an earlier study. Next, the authors tried to apply the lighting data to intersections but the results were not very strong compared to road sections. Although, the authors used the photographic method their study is fundamentally different from the photographic method applied in this dissertation. First, their pixel to luminance conversion approach is not linked to the camera's own calibration constant and therefore it is only applicable to the specific exposure conditions (Shutter Speed, F-Number, and ISO Sensitivity) used in the calibration. However, the approach used in this dissertation work is linked to the camera's calibration constant; therefore, it is applicable for all exposure conditions as long as the same camera is used. This is very important because light conditions can vary much in the field and the exposure conditions may need to be modified to get the best measurement. Second, the photographic method has not been applied to roundabouts yet. Applying the method to roundabouts requires a different approach because roundabouts, unlike conventional intersections, have a visual obstruction at the center making it impossible to see the entire travel path in one view.

Bhagavathula et al. (2015) investigated the effect of lighting quality and quantity on the night/day (ND) crash frequency ratios at rural intersections using negative binomial regression to model illuminance, luminance, and crash data from 99 lighted and unlighted intersections. The results indicate that a one lux increase in the average horizontal illuminance at all rural intersections corresponded to a seven percent reduction in the ND crash ratio. Also, for the lighted intersections, a one lux increase in average horizontal illuminance corresponded to a nine percent decrease in the ND crash ratio while for unlighted intersections a one lux increase in average horizontal illuminance corresponded to a 21 percent reduction in the ND crash ratio. The findings also showed that stop-control intersections experience small ND crash ratios than signalized intersections while intersections with posted speed limit less than or equal to 40 mph also experienced lower ND crash ratios than those with posted speed limit greater than 40 mph.

In another study by Gibbons et al. (2015) the authors investigated the relationship between lighting level and crashes on roadways. Crash data were obtained from select states and the Highway Safety Information System while lighting measurements were collected in-situ with a mobile road lighting measurement system. The results showed that there was no benefit to illumination beyond a certain level on an urban interstate, which in the case of the study this level was about 5 lux. Therefore, the authors concluded that there is a potential to reduce lighting requirements on highways and freeways by as much as 50% while maintaining traffic safety. Also, the results indicate that the relationship between lighting level and safety was not as strong as that of lighting presence (lit or unlit) and safety.

2.4.2 Light Pollution

Roadway lighting can often result in light pollution through sky glow, light trespass, and glare (Brons et al. 2008). Sky glow refers to the inability to appreciate and see stars in a dark sky as a result of brightening of the sky from outdoor lighting. Glare can be described as discomfort and visual disability due to excessive brightness of roadway lightening. Light trespass simply refers to roadway lighting that falls where it is not needed or intended.

Aside these three effects, light pollution can also have environmental consequences for areas where the natural ecosystem of flora and fauna requires no light or minimal ambient lighting to thrive. Bertolotti and Salmon (2005) investigated the impact of coastal street lights on the orientation of turtle hatchlings using both regular pole mounted street lighting and embedded street lighting. The results showed that when the pole mounted street lights were turned on the orientation of hatchlings toward the sea was poor. However, orientation improved when the embedded street lights were used. Also, the study showed that the pole mounted lighting was visible from the turtle hatching nests on the beach while the embedded street lights were not. Therefore, the authors concluded that coastal street lighting can have a negative impact on the orientation of turtle hatchlings on the beach.

There are many publications (Illuminating Engineering Society 2000; Institute of Lighting Engineers 2000; International Commission on Illumination 2003) with recommendations to mitigate light roadway lighting pollution. Some of the recommendations include:

- Avoid lighting in excess of minimum required levels.
- Using efficient lamp technologies.
- Using lighting that improves peripheral vision such as white color light rather than yellowish/orange high pressure sodium lights.

- Using cut of luminaires to stop upward emission of light into the sky.
- Design for lighting zones.

Although, these recommendations are helpful it has been noted that none of them is entirely successful in limiting light pollution (Brons et al. 2007). IESNA has developed new luminaire classifications that give a more accurate description of light emission from a luminaire. However, recent studies have shown that the luminaire classification information might not successfully predict light pollution (Bullough 2002; Keith 2000; Keith 2003). Many US states are at various stages of adopting legislation on light pollution (Rea et al. 2009) and most existing lighting pollution ordinances have jurisdiction at the city, town, and county level. However, some states such as California have adopted environmental legislation that includes the designation of lighting zones (California Energy Commision 2005). Lighting zones help ensure that the roadway lighting does not exceed the lighting goals of the surroundings. The design guide for roundabout lighting (Illuminating Engineering Society 2008) have adopted the five different lighting zones below.

- LZ0: No Ambient Lighting – These are areas where the natural environment will be seriously and adversely affected by lighting through disturbance to the biological cycles of flora and fauna. In such areas human activity is subordinate in importance to nature and the vision of residents must be adapted to total darkness.
- LZ1: Low Ambient Lighting – These are areas where lighting might adversely affect flora and fauna. Human vision must be adapted to low light levels and lighting can only be used for safety and convenience but it is not necessarily uniform or continuous.

- LZ2: Moderate Ambient Lighting – These are areas where human vision can be adapted to moderate light levels. Lighting can be used for safety and convenience but it is not necessarily uniform or continuous.
- LZ3: Moderately High Ambient Lighting – These are areas where lighting is desired for safety, security, and/or convenience. Lighting in these areas in usually uniform and continuous.
- LZ4: High Ambient Lighting – In these area lighting is considered necessary for safety, security, and/or convenience and is mostly uniform and/or continuous.

2.4.3 Roadway Lighting Benefits and Costs

Previous research on the benefits and costs of roadway illumination are few, mostly dated, and have been focused on either intersections or urban freeway systems. A benefit/cost analysis helps to compare the tradeoff between the costs of a project and its benefits. Benefits are usually estimated as the avoided costs due to reduction in crash occurrence. The costs of implementing road lighting is often estimated as the direct initial costs of installation, maintenance, and repair costs (Rea et al. 2009). The incremental benefit/cost ratio of one lighting alternative, j, to another lighting alternative, *i*, can be estimated as shown in Equation 20.

$$BC_{j-i} = \frac{AC_j - AC_i}{DC_j - DC_i} \qquad \dots\dots\dots\dots(20)$$

Where:

BC_{j-i} = the incremental benefit/cost ratio of alternative j to alternative i

AC = the annualized avoided costs due to the crash reduction

DC = the annualized direct costs of the alternatives

Box (1970) analyzed benefit-to-cost ratios for illuminating different multilane urban freeways and his results indicate benefit-to-cost ratios of 2.3, 1.4, and 1.7 for lighting 4-lane, 6-lane, and 8-10 lane urban freeways respectively . In another study on urban freeway systems, Griffith (1994) evaluated the benefits and cost of lighting. Based on an analysis of 22 miles of urban freeway segments in Minnesota, he identified benefits and costs which yield a ratio of 1.2:1. Notably the ratios for urban freeway systems appear to very small.

The Federal Highway Administration (FHWA) produces an annual report to congress on the Highway Safety Improvement Programs (HSIP) in the US. One of the key components of the earlier reports is a benefit/cost ranking of different highway safety improvement programs. The findings in the 1994 report indicated that illumination offered the highest benefit/cost ratio of 21.0 (FHWA 1994). Also, a subsequent report to congress in 1996 again ranked illumination as the highest out 20 highway improvements, with a benefit-to-cost ratio of 26.8 (FHWA 1996; Rea et al. 2009). Table 4 presents the benefit-cost ranking of highway safety improvement programs from 1974 to 1995.

Table 4 Highway Safety Improvements with the Highest Cost-Benefit Ratios, 1974 – 1995

Rank	Improvement Description	Benefit-Cost Ratio
1	Illumination	26.8
2	Upgrade Median Barrier	22.6
3	Traffic Signs	22.4
4	Relocated/Breakaway Utility Poles	17.7
5	Remove Obstacles	10.7
6	New Traffic Signals	8.5
7	Impact Attenuators	8
8	New Median Barrier	7.6
9	Upgrade Guardrail	7.5
10	Upgrade Traffic Signal	7.4
11	Upgrade Rail Bridge	6.9
12	Improve Sight Distance	6.1
13	Median for Traffic Separation	6.1
14	Groove Pavement for Skid	5.8
15	Improve Minor Stricture	5.3
16	Turning Lanes and Channelization	4.5
17	New RR Crossing Gates	3.4
18	New RR Crossing Flashing Lights	3.1
19	Pavement Marking and Delineation	3.1
20	New RR Crossing Lights & Gates	2.9

(Source: Rea et al. 2009)

Preston and Schoenecker (1999) also evaluated the impacts of street lighting at isolated rural intersections in Minnesota. As part of their evaluation they also estimated the avoided costs of crashes and the direct costs of illumination. Their findings show that the benefits outweighed the costs by a ratio of 15.0. The analysis annualized costs and benefits over 10 years and also adopted a 5 percent discount rate.

Other studies also evaluated the benefit and costs of road lighting in terms of its societal benefit from crime reduction. Painter and Farrington (2001) used official crime valuation data in the UK to evaluate the benefits and cost of lighting installation in Dudley and Stoke-on Trent in the UK. The results for Dudley showed that one year after installation of lighting the benefit/cost ratio was approximately 10:1 and increases to about 121:1 if a 20-year payback is assumed. Similarly, the results for Stokes-on Trent showed that the benefit/cost ratio after one year of lighting installation was 2.4:1 or 24:1 if a 20-year payback is assumed.

2.5 Reflection of Light (Luminance) from Pavement Surface

Luminance measures reflected light from a surface and so it can be affected by the reflective properties of pavement materials. The same amount of incident illumination on different road pavements can show different luminance levels.

2.5.1 Surface Reflection Types

Incident light on any surface may be reflected as specular, spread, diffuse, or compound reflection (Gibbons 1997).

2.5.1.1 Specular Reflection

Specular reflection is usually evident on polished surfaces where the angle of incidence is usually equal to the angle of reflection. Under perfect conditions, the intensity of the reflected beam is equal to the intensity of the incident beam.

2.5.1.2 Spread Reflection

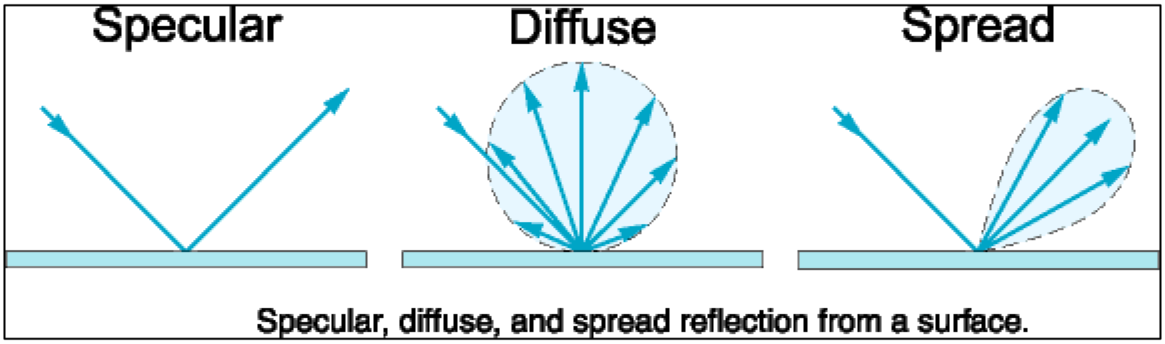
Spread reflection of incident light from a surface such as a pavement is similar to specular reflection. However, instead of a single reflected ray of light, there is a cone of reflected rays such that the reflected angle of the central ray is equal to the incidence angle. The intensity of the reflected ray depends on the angle of observation.

2.5.1.3 Diffuse Reflection

Diffuse reflection can generally be observed on rough surfaces. Incident light on a perfectly diffuse surface is reflected with equal brightness in all directions irrespective of the observation angle.

2.5.1.4 Compound Reflection

Compound reflection is a mixture of specular, spread, or diffuse reflections. Most surfaces, including pavements exhibit compound reflection. On such surfaces, the incidence angle and the observation angle determines what is observed by the eye. Figure 13 shows examples of specular, diffuse, and spread reflections.



(Source: www.kmdlightingdesign.com)

Figure 13 Basic Types of Surface Reflections

2.5.2 Nature of Pavement Surface

The reflection property of pavement surfaces is influenced by pavement material and surface wear (Gibbons 1997). A pavement is usually a mixture of aggregates and a binder material. The different sizes, shapes, and face angles of aggregates showing on a pavement surface, as well as surface wear on the pavement surface result in compound reflection. Also, it has been shown that a pavement that uses a concrete binder can have a reflectance of about 10 percent. On the other hand, a pavement that uses an asphalt binder can have a reflectance of about 5 percent and 15 percent respectively if dark color aggregates or light color aggregates are used (Gibbons 1997).

2.5.3 Pavement Reflectivity and Observational Angle

The reflection properties of pavement surfaces cause a compound reflection of any incident light. Therefore, the brightness or intensity of the reflected light is dependent on the incidence angle and the observation angle of the eye. Consequently, available luminance standards for street lighting design are tied to fixed observational angle. Both the CIE and IES luminance standards are based on an assumed 1^{o} observational angle. The IES standard further assumes an observer eye level of 1.47 meters above the pavement and consequently an observer at a distance of 84.7 meters. Also, the CIE standard assumes that the observer is at a distance of 60 meters from the first luminaire (Nicholas 1991).

2.5.4 Relationship between Luminance and Illuminance

Luminance (L) is a measure of the amount (quantity and quality) of light reflected of the pavement surface that is helpful for the driver to see the surface clearly. It is an indication of the brightness of the pavement surface. On the other hand illuminance (E) is a measure of the amount of incident light (luminous flux) on the pavement surface. It is an indication of how well objects above the pavement surface can be seen. These two road illumination properties are related as shown in Equation 21 (Bassani and Mutani 2012);

$$L = q * E \cong \frac{\rho}{\pi} * E \dots\dots\dots (21)$$

L = the luminance in cd/m2

q = the luminance coefficient in cd/m2/lux

E = the illuminance in lux

ρ = the reflection coefficient.

The luminance coefficient varies across different points of the pavement surface (Fotios et al. 2005) because it depends on the pavement material, observer position, and the luminaire position relative to the point of interest. The reflection property of a road pavement surface is often summarized into the r-table which is based on two surface reflection metrics; the diffuse reflection, Q_0, and the specular reflection, S_1 (International Commission on Illumination 1982; International Commission on Illumination 1984). It has been found (Fotios et al. 2005) that the average reduced reflection coefficient is 0.05 and 0.085 for asphalt pavements and concrete pavements respectively.

Casol et al. (2008) have shown that for the purposes of simplifying road lighting analysis a road surface can be assumed to be perfectly diffused with a reflection coefficient equal to πQ_0. Many values of this modified reflection coefficient have been indicated in published studies; Uncu and Kayaku (2010) found an average value of 0.13 for asphalt roads while Fotios et al. (2005) also found an average value of 0.16 and 0.27 for asphalt and concrete road surface's respectively.

2.6 Safety Analysis

2.6.1 Identifying Intersection Related Crashes

The selection of intersection related crashes for analysis requires a systematic way to determine an intersection’s safety influence area. The length of this influence area depends on the geometry, traffic control, and operating features (Abdel-Aty et al. 2009; North Carolina Department of Transportation 1999). Some states use a distance of 250 feet from the center of the intersection as the influence area (Abdel-Aty et al. 2009). Others also determine this area by considering the effect of left turning lanes (Abdel-Aty et al. 2009). Crashes that occur within the safety influence area but outside the physical limits of the intersection are often called “intersection related”. Table 5 shows the distances used by different states.

In terms of previous studies there have been a lot of inconsistencies in the length of the safety influence area. Lyon et al. (2005) used a distance of 65.6ft from the center of the intersection to identify intersection related crashes for their study in Toronto. A distance of 150ft has also been used by Persaud et al. (2005) to identify rear-end collisions related to intersections. Next, Hardwood et al. (2003), Mittra et al. (2007), Donnell et al. (2010) all used a safety influence distance of 250ft to identify intersection related crashes. Cottrell and Mu (2005) also identified intersection related crashes in Utah based on stopping sight distance. Initially they applied a distance of 500ft for an average approach speed of 40 mph. However, they realized that a 100ft distance was applicable to most of their intersections and only two intersections needed the 500ft distance as influence area. Another study (Joksch and Kostyniuk 1998) of intersections from three different states applied varying influence area distances up to 350ft. Gbologah et al.

(2015) also used a distance of 325 feet for from the center of the central island to identifying the intersection related crashes for roundabouts.

Abdel-Aty et al. (2009) argue that the main challenge in determining intersection related crashes is deciding the safety influence area upstream of the approach. Therefore, they undertook a study to investigate how the size of the intersection, left-turn lane length, through and left turning traffic volumes, skewness, and other intersection features affect the safety influence area upstream of approach. The study analyzed crash data from 177 regular four-legged intersections in Florida from 2000 to 2005. The results show that the approach upstream safety influence area is influenced by the through volume, approach speed, number of right lanes, and left-turn protection. The authors concluded that since the approaches to an intersection can have varied attributes, it may be better to define the safety influence area of each approach separately.

Table 5 Default Distances Used by States to Identify Intersection Safety Area

State	Length of Intersection Influence area from center of Intersection
Alaska	200 feet
California	250 feet
Colorado	264 feet upstream of approach
Connecticut	50 feet from stop bar
Delaware	528 feet
Florida [a]	At Intersection: less than 50 feet Intersection related: 50 to 250 feet
Hawaii [b]	75 feet, more if crash occurred in left turn lane
Iowa	Urban: 75 feet Rural: 150 feet Expressways: 300 feet High speed road: up to 1320 feet
Kansas	150 feet, more if intersection is large
Maryland	250 feet
Mississippi	500 feet of upstream only
Missouri	132 feet
Utah	138 feet, more if intersection is large
Vermont	Determined by stopping sight distance, e.g. 275 feet for 40 mph
Virgin Islands	100 feet

Note: [a] Crash reports show that police officers usually measure from stop bar and not center of intersection
[b] Not stated in report if distance is from the center or edge

(Source: Abdel-Aty et al. 2009)

2.6.2 Sources of Bias in Crash Data Analysis

The following section highlights the various source of bias that can affect the quality of crash data. These are very important issues that must be identified and corrected or considered when inferences from crash analysis are drawn.

2.6.2.1 Data Quality and Accuracy

The main source of crash data is the accident reports filed by police personnel on standardized forms (AASHTO 2010). For most property damage only (PDO) crashes the data comes from information provided by self-reporting citizens. Sources of error in the data may be due to typographic mistakes, terms used to describe a location, and subjectivity issues such as estimating property damage or excessive speed.

2.6.2.2 Crash Reporting Thresholds

Sometimes not all crashes are reported. This may be due to the minimum dollar value threshold used by states. Often states have to change this threshold to compensate for the effect of inflation. Such changes can make it impossible to make comparisons between different years. Also, a change in the minimum threshold is usually followed by a drop in the number of reported crashes. It is important to ensure that there was no change in the minimum threshold during the study period otherwise the drop could be misconstrued as an improvement in safety (AASHTO 2010).

2.6.2.3 Crash Frequency-Severity Indeterminacy

It has been found that crashes with higher severity are reported more reliably to police than crashes with lower severity. This often leads to a situation where it is difficult to determine if a change in number of reported crashes is caused by an actual change in crashes, a shift in severity proportions, or a mix of the two (AASHTO 2010).

2.6.2.4 Different Crash Reporting Criteria for Jurisdictions

Different jurisdictions can have different requirements for reporting and recording crashes. This makes it difficult to develop statistical models to compare facilities from different jurisdictions. For example, differences in definition of crash severity terms and the use of AADT as opposed to ADT to indicate annual traffic volume can lead to inconsistencies in reported crash data across different jurisdictions (AASHTO 2010).

2.6.2.5 Natural Variability in Crash Frequency

Crashes are by nature random events. Therefore, expected crash frequency estimates based on analysis over a short-term can be significantly different from estimates based on long-term data. Short-term data may represent a typically high, medium, or low crash frequency and this fact may be difficult to determine (AASHTO 2010).

2.6.2.6 Regression to the Mean

Due to the natural variation in crash frequency it is at times difficult to know if observed changes in crash frequencies are due to changes in site conditions or are due to natural fluctuations. Hauer (Hauer 1996) explains that it is statistically probable for a comparatively high observed frequency to be followed by a comparatively low frequency and vice-versa. This is known as regressing to the mean (AASHTO 2010). This implies that it is possible for any observed short-term trends (increasing or decreasing) at a site to change direction and regress towards the average frequency without any improvement or deterioration of safety. Therefore, safety analysis to evaluate the effectiveness of treatments must consider this phenomenon otherwise the results may overestimate or underestimate the benefits.

2.6.2.7 Variation in Roadway Characteristics and Environment

A roadway or an intersection's characteristics change overtime. Changes in characteristics such as weather, traffic volume, and road alignment can make it difficult to attribute changes in expected crash frequencies to specific safety measures (AASHTO 2010). This problem is particularly important when long-term data is used in an effort to avoid the biases introduced by regression to the mean and natural variability in crash frequencies. It often limits the number of years of observed crash frequency data which can be included in a study (AASHTO 2010). Also, limitations due to roadway or intersection characteristics and environment needs to be addressed in studies that adopt a "before" and "after" methodology because the effectiveness of treatment can be overestimated or underestimated (AASHTO 2010).

2.6.3 Crash Modification Factors for Intersections

Crash modification factors (CMFs) are estimates of expected changes in crash frequency and/or crash severity at a site due to implementing a particular safety countermeasure, design modification, or change in operations (AASHTO 2010). Usually, crash modification factors are estimated for three crash severities namely fatal, injury, and non-injury. However, it is not uncommon for fatal and injury to be generally combined as injury such as is done in the Highway Safety Manual. Also, crash modification factor estimates can be influenced by the definition of an intersection crash. Whereas some agencies define an intersection crash as a crash falling within the crosswalk limits or physical intersection area, others also define an intersection as a crash that falls within a specific distance, say 250ft, from the center of an intersections (AASHTO 2010; Box 1970).

The Highway Safety Manual provides four main groupings of crash modification factors that relate to at-grade intersections. In the sections which follow, the availability of CMFs within each of these groupings is presented and areas where more research is needed to evaluate statistically sound CMFs are indicated.

2.6.3.1 CMFs Relating to Intersection Types

Intersection types (signalized, stop-control, and roundabout) are defined by their basic geometric design characteristics and traffic control mechanisms. The intersection types are further broken down into urban, suburban, and rural settings. Table 6 shows the availability of CMFs for intersection types. It should be noted that this is the only group, out of the four groups of crash modification factors, which includes CMFs relating to roundabouts. The actual values of the roundabout CMFs are presented in Table 7 and Table 8.

Table 6: Availability of Crash Modification Factors Relating to Intersection Types

	Urban				**Suburban**				**Rural**			
	Stop		**Signal**		**Stop**		**Signal**		**Stop**		**Signal**	
Treatment	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**
Convert 4-Leg Int. to two 3-Leg Int.	Yes	--	--	--	--	--	--	--	--	--	--	--
Convert signalized Int. to a modern roundabout	n/a	n/a	Yes	Yes	n/a	n/a	Yes	Yes	n/a	n/a	Yes	Yes
Convert stop-control Int. to a modern roundabout	Yes	Yes	n/a	n/a	Yes	Yes	n/a	n/a	Yes	Yes	n/a	n/a
Convert minor-road stop control to all-way stop control	Yes	--	--	--	--	--	--	--	Yes	--	--	--
Remove unwarranted signal on one-way streets	--	--	Yes	Yes	--	--	--	--	--	--	--	--
Convert stop control to signal control	Yes	--	n/a	n/a	--	--	n/a	n/a	Yes	--	n/a	n/a

Notes:
Yes = CMF is currently (HSM 2010) available
n/a = treatment is not applicable
-- = CMF is currently (HSM 2010) not known and more research is needed

Table 7: Applicable CMFs for Converting Signalized Intersection into Modern Roundabout

Treatment	Setting (Intersection Type)	Crash Severity	CMF	Std. Error
Convert signalized intersection to modern roundabout	Urban (one or two lanes)	All severities	0.99	0.1
		Injury	0.40	0.1
	Suburban (two lanes)	All severities	0.33	0.05
	All settings (one or two lanes)	All severities	0.52	0.06
		Injury	0.22	0.07
Notes: CMFs with Std. Error greater than 0.1 are deemed less reliable				

Table 8: Applicable CMFs for Converting Stop-Controlled Intersections into Modern Roundabout

Treatment	Setting (Intersection Type)	Crash Severity	CMF	Std. Error
Convert intersection with minor-road stop control to modern roundabout	All settings (one or two lanes)	All severities	0.56	0.05
		Injury	0.18	0.04
	Rural (one lane)	All severities	0.29	0.04
		Injury	0.13	0.04
	Urban (one or two lanes)	All severities	0.71	0.1
		Injury	0.19	0.1
	Urban (one lane)	All severities	0.61	0.1
		Injury	0.22	0.1
	Urban (two lanes)	All severities	0.88	0.2
	Suburban (one or two lanes)	All severities	0.68	0.08
		Injury	0.29	0.1
	Suburban (one lane)	All severities	0.22	0.07
		Injury	0.22	0.1
	Suburban (two lanes)	All severities	0.81	0.1
		Injury	0.32	0.1
Convert all-way, stop-control intersection to roundabout	All settings (one or two lanes)	All severities	1.03	0.2
Notes: CMFs with Std. Error greater than 0.1 are deemed less reliable				

2.6.3.2 CMFs Relating to Access Management

These CMFs relate to treatments or actions that can be taken to manage the frequency and type of conflict points at public intersections and at residential and commercial access points (AASHTO 2010). Currently, these CMFs have not been quantified because the effects of access management techniques on crash frequency or crash severity at or near at-grade intersections are not well known. More research will be needed before any of these CMFs can be quantified with adequate statistical soundness.

2.6.3.3 CMFS Relating To Intersection Design Elements

These CMFs estimate the potential changes in crash frequency and/or crash severity due to specific treatments to intersection design elements. Table 9 shows the currently available CMFs in this group. Please note that there is a CMF for lighting intersections but the list of intersections does not include roundabouts.

2.6.3.4 CMFs Relating to Intersection Traffic Control and Operational Elements

CMFs in this group relate to intersection traffic control and operational elements. Some common traffic control devices for intersections include signs, signals, warning beacons, and pavement markings. Also, operational elements for intersections include the type of traffic control type, traffic signal operations, speed limits, traffic calming, and on-street parking. Table 10 presents the currently available CMFs for intersection traffic control and operational elements.

Table 9: Availability of Crash Modification Factors Relating to Intersection Design Elements

	Urban				**Suburban**				**Rural**			
	Stop		**Signal**		**Stop**		**Signal**		**Stop**		**Signal**	
Treatment	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**
Reduce Int. skew angle	--	--	--	--	--	--	--	--	Yes	--	--	--
Provide a left-turn lane on approach to 3-Leg Int.	Yes	--	Yes	n/a	--	--	--	--	Yes	--	Yes	n/a
Provide a left-turn lane on approach to 4-Leg Int.	Yes	--	n/a	Yes	--	--	--	--	Yes	--	n/a	Yes
Provide a channelized left-turn lane on approach to 4-Leg Int.	--	--	n/a	--	--	--	n/a	--	Yes	Yes	n/a	Yes
Provide a channelized left-turn lane on approach to 3-Leg Int.	--	--	--	n/a	--	--	--	n/a	Yes	Yes	Yes	n/a
Provide a right-turn lane on approaches to intersection	Yes	--	Yes	Yes	--	--	--	--	Yes	--	Yes	Yes
Increase Int. median width	Yes	Yes	--	Yes	Yes	Yes	--	Yes	Yes	Yes	--	--
Provide Int. Lighting	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Provide bicycle lanes or wide curb lanes at Int.	--	--	--	--	--	--	--	--	--	--	--	--
Narrow roadway at pedestrian crossing	--	--	--	--	--	--	--	--	--	--	--	--
Install raised pedestrian crosswalk	--	--	--	--	--	--	--	--	--	--	--	--
Install raised bicycle crossing	--	--	--	--	--	--	--	--	--	--	--	--
Mark crosswalks at uncontrolled locations, intersection, or mid-block	--	--	--	--	--	--	--	--	--	--	--	--
Provide a raised median or refuge island at marked and unmarked	--	--	--	--	--	--	--	--	--	--	--	--

	Urban				**Suburban**				**Rural**			
	Stop		**Signal**		**Stop**		**Signal**		**Stop**		**Signal**	
Treatment	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**
crosswalks												

Notes:
Yes = CMF is currently (HSM 2010) available
n/a = treatment is not applicable
-- = CMF is currently (HSM 2010) not known and more research is needed

Table 10 Availability of CMFs for Intersection Traffic Control and Operational Elements

	Urban				**Suburban**				**Rural**			
	Stop		**Signal**		**Stop**		**Signal**		**Stop**		**Signal**	
Treatment	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**
Prohibit left-turns and U-turns with “No left Turn”, “No U-Turn” signs	Yes	--	Yes	Yes	Yes	--	Yes	Yes	--	--	--	--
Provide “Stop Ahead” pavement markings	--	--	--	--	--	--	--	--	Yes	Yes	--	--
Provide flashing beacons at stop-control intersections	Yes	Yes	n/a	n/a	Yes	Yes	n/a	n/a	Yes	Yes	--	--
Modify left-turn phase	--	--	--	Yes	--	--	--	--	--	--	--	--
Replace direct left-turns with right-turn/U-turn combination	Yes	--	--	--	Yes	--	--	--	Yes	--	--	--
Permit right-turn on Red	--	--	Yes	Yes	--	--	Yes	Yes	--	--	Yes	Yes
Modify change and clearance interval	--	--	--	Yes	--	--	--	Yes	--	--	--	Yes
Install red-light cameras	--	--	Yes	Yes	--	--	--	--	--	--	--	--

Notes:
Yes = CMF is currently (HSM 2010) available
n/a = treatment is not applicable
-- = CMF is currently (HSM 2010) not known and more research is needed

CHAPTER 3: EXISTING DATA STUDY

This chapter presents the methodology and results of analysis performed on the best available roundabout crash and illumination data. A discussion on the data and its inherent issues is followed by a description of the analysis methodology and discussion of the results before finally summarizing the key findings on the impacts of illumination on roundabout nighttime safety. The results from this existing data study have been submitted for publication (Gbologah et al. 2015) in the Journal of Accident Analysis and Prevention.

This existing data study was undertaken as part of a research program sponsored by the Georgia Department of Transportation (GDOT) to evaluate the safety impacts of illumination at roundabouts (Phase 1) and also to evaluate the cost-effectiveness of illumination as a safety treatment at rural intersections (Phase 2). The GDOT research program also included a parallel study which reviewed international roundabout illumination policies and standards. The report on this parallel study can be found in Appendix A.

3.1 Data

3.1.1 Minimum Data Requirements

A successful evaluation of the impacts of illumination on roundabout safety requires the simultaneous availability of several types of data; crash data, roadway characteristics, intersection characteristics (including intersection type and presence/absence of purpose-built lighting and illumination levels), and traffic data. At the start of this dissertation, the Highway Safety Information System (HSIS) was the only publicly available data repository providing all these datasets, although, the availability of attributes within each dataset vary between the participating states. Additionally, the analysis requires historical sunrise and sunset data which could be used together with information on time of crash to distinguish nighttime crashes from daytime crashes.

The crash data must provide case-by-case information on accidents within the study period. At a minimum it must include information such as:

- Date of accident.
- Accident or case ID.
- Time of accident.
- Location of accident (roadway and milepost or latitude/longitude, rural/urban designation, road segment or intersection).
- Crash severity (fatal, serious, injury, possible injury, and PDO).

The roadway data must also include, at the least, information that allows the identification of different homogenous segments. For example, county route name, number of lanes, width of lanes, posted speed limits, beginning milepost, and ending milepost. It must also distinguish between one-way and two-way segments for accurate computation of intersection entering volumes.

Also, there must be information on the intersections of interest within the study area. Essentially, information must be available on

- Intersection type
- Traffic control mechanism

- Illumination levels
- Location (rural/urban designation, route and milepost).

Next, there must be reliable traffic volume data on the annual average daily traffic (AADT) for every intersection leg for all the years in the analysis period. Last, historical sunrise and sunset data with adjustments for daylight savings would be needed to distinguish nighttime crashes from daytime crashes.

3.1.2 Best Available Data Source

A rigorous search of both federal and state level highway data repositories identified the Highway Safety Information system (HSIS) as the best available data source. The HSIS provides access to relatively high quality data from selected states that have been selected based on the (a) range of data variables collected, (b) the quality of the data, (c) the quantity of the data, and (d) the ability to merge electronically coded data from different files (Forrest and Yussuf 2007). It includes the potential crash, roadway, intersection, and traffic data required for this existing data study.

There are seven U.S. states (Washington State, California, Minnesota, Illinois, North Carolina, Ohio, and Maine) included in the HSIS. However, most jurisdictions do not archive illumination data and only few jurisdictions have had a significant number of roundabouts for a sufficiently long time. An extensive search of the HSIS based on the data requirements for the study identified two candidate states – Minnesota and California. The intersection data from California provides a binary variable for lighting presence (YES or NO) while the Minnesota data includes multiple illumination levels; None, Point, Partial, Full, and Continuous. The Minnesota data was selected because of the availability of multiple illumination levels offers more analysis options. These illumination levels do not represent actual photometric quantities but rather a qualitative measure related to the number and arrangement of luminaires at the roundabout, which can be used as a surrogate for the actual lighting levels a driver is likely to experience given the use of standard luminaires. Table 11 presents an explanation of the different illumination levels/schemes used in the study.

The MN HSIS data used is from 2003 to 2012 and it includes about 78000 crash records per year (state network only). In processing the original crash data from Minnesota, the HSIS staff applied some filters to omit (a) crashes where the estimated damage was less than $1000, (b) crashes for which the investigating officer was not specified in the original police report, and (c) crashes which could not be linked to the roadway file by HSIS staff (Forrest and Yussuf 2007).

Table 11 Explanation of Different Illumination Levels

Illumination Level	**Description**
None	No purposely built lighting on either the approaches or roundabout circle
Partial	Purposely built lighting available either only the roundabout circle or only on the approaches.
Full	Purposely built lighting available on the roundabout circle and also within the transition zone on the approaches
Continuous	Purposely built lighting available on the roundabout circle and also on the approaches. Approach lighting is beyond transition zone and is usually for the length of the whole corridor.

Each annual intersection data file contains data on about 33000 intersection legs and 8000 intersections and interchanges. These are intersections and interchanges of U.S.

highways, intersections of U.S. highways and state routes, and intersections of state Routes. In addition, there are variations in the number of intersections and interchanges in the annual files due to changes in route designations between state and local governments.

Each annual roadway data file contains records covering about 12,000 miles of trunk roads, 33,000 miles of state roads, and 90,000 miles of non-state and local roads. The file also contains estimated AADTs for all roadway sections across the state. However, for some road segments which are intersection legs the AADTs are not current, that is, they do not match the data year. These intersections legs are usually on "intersections within an interchange", e.g., intersections at ramp terminals or exit ramps.

Significantly, the MN data from the HSIS has been designed to facilitate easy matching of crash data, traffic data, roadway data, and intersection data. Each record contains three general variables that can be used for this purpose. The variables are the route system (RTE_SYS), route number (RTE_NBR), and the milepost

3.1.2.1 Issues with the Minnesota HSIS Data

Despite being the best available data source, the MN HSIS data has a number of inherent issues that presently limit the level of sophistication for the safety analysis. First, it is currently not possible to separate the MN HSIS data into a "before" sample and an "after" sample because there is no information on the dates the lights were installed. This makes it impossible to apply a state-of-art approach such as the Empirical Bayes Method.

Second, the MN HSIS data is limited to only intersections on state and/or U.S. routes. However, many roundabouts in Minnesota are not on these routes. This limits the sample size of available roundabouts and makes it difficult to create and test subgroups of the data such as crash severity types, rural/urban locations, AADT categories, and geometric attributes.

3.2 Methodology

This section explains how the annual intersection files in the MN HSIS database were analyzed in order to compute the intersection entering volumes. It also discusses how the annual crash files were treated and how the crashes were assigned to the intersections.

3.2.1 Treatment of MN HSIS Intersection Data

The MN annual intersection files contain data for both intersections and interchanges. However, for the purposes of this study interchanges are not needed so all such records were filtered out to create new annual intersection files containing records of only intersection legs. These new files were subsequently indexed with intersection IDs for easy identification all individual intersection's legs. Each set of intersection legs were identified and matched to the roadway data using the route system (RTE_SYS), route number (RTE_NBR), milepost (MILEPOST), and INT_DESC (a variable that lists the intersecting roads) variables from the intersection files as well as the beginning milepost (BEG_MP) and ending milepost (END_MP) from the roadway files. These matched records were appended with the designated one-way and two-way directions of their corresponding roadway segments.

As mentioned prior, some of the AADTs for intersection legs are not current, i.e., they do not match the data year. These traffic volumes were updated in step-wise manner using yearly population growth rates for Minnesota. Each, yearly population growth rate was computed by comparing the current year's population to that of the previous year. The population data used covers 1990 to 2012. There were some instances where the AADT year preceded 1990. In such cases the AADTs years were assumed to be 1990. The maximum AADT adjustment used was 21 percent to adjust an approach AADT from 1990 to 2010. Table 12 presents the estimated Minnesota population growth rates used to adjust the AADTs.

The last step in the analysis of the intersection data involved recoding the intersection illumination levels. Each annual file has eight original illumination codes; None, Point Lighting, Partial, Partial (Energy Conservation Program), Full, Full (Energy Conservation Program), Continuous, and Continuous (Energy Conservation Program). Analysis on the identified roundabout intersections showed that there were very few "Point Lighting" intersections and so they were merged into the "None" group. Also, an energy conservation program will have an effect on power consumption and not illumination level. Therefore, the analysis combined illumination levels in energy conservation program with their non-program alternatives to create just four illumination levels; None, Partial, Full, and Continuous.

Table 12 Minnesota Population and Estimated Growth Rates from 1990 to 2012

Year	Population Size	Estimated Growth Rate (%)
1990	4,375,099	
1991	4,416,292	0.94
1992	4,469,450	1.20
1993	4,515,118	1.02
1994	4,570,355	1.22
1995	4,626,514	1.23
1996	4,682,748	1.23
1997	4,735,830	1.13
1998	4,782,264	0.98
1999	4,838,398	1.17
2000	4,919,479	1.68
2001	4,977,976	1.19
2002	5,033,661	1.12
2003	5,088,006	1.08
2004	5,145,106	1.12
2005	5,205,091	1.17
2006	5,231,106	0.50
2007	5,263,493	0.62
2008	5,287,976	0.47
2009	5,300,942	0.25
2010	5,303,925	0.06
2011	5,332,246	0.53
2012	5,368,972	0.69

3.2.2 Treatment of the MN HSIS Crash Data

To prepare the crash files for analysis, the first step in the process was to append a new time of day variable (Day or Night) based on the crash date, crash time, and historical sunrise and sunset times that have been adjusted for daylight savings time. Next, each annual crash file was matched to the corresponding annual intersection file and the intersection IDs were appended to the crash records where possible. The crashes were assigned to intersections by a Minimum Distance Algorithm using a buffer of 325 ft. The algorithm uses RTE_SYS, RTE_NBR, and milepost (+/- 325 ft.) of the intersections to compare the RTE_SYS, RTE_NBR, and milepost of the crashes and assigns the accident to the intersection that is closest to the accident location.

Subsequently, scripts were run to create new recoded columns or appended columns with data from the intersection file. The recoded columns include (a) intersection type (roundabout, conventional 4-leg, conventional 3-leg) based on the crash location code, and (b) rural/urban code based on the original crash location population grouping (population density based). The appended columns include (a) traffic control (roundabout, signalized, stop-control) based on the traffic control device code, and (b) a binary lighting presence code based on the previously recoded illumination levels in the intersection file.

3.2.3 Selection of MN Roundabouts for Analysis

The MN HSIS intersection files do not provide a direct identification of roundabouts but the crash files provide an indirect identification through the LOC_TYPE variable. However, this variable was found to be unreliable; there were many crash locations with the same RTE_SYS, RTE_NBR, and milepost as some coded roundabout locations but cross-referencing analysis with Google Earth showed that most of these are not actually roundabout locations.

Therefore, a separate roundabout inventory of Minnesota was developed based on information received from MNDOT and the Kittleson Roundabout Database (Kittleson & Associates). This inventory was further cross-referenced with Google Earth. This inventory identified 125 existing roundabouts with verified crossroad names and year of construction. The roundabout inventory was then cross-referenced against the annual

HSIS intersection files using the INT_DESC to create a new annual file of identified roundabout intersections for merging with the crash files.

3.2.4 Computation of Intersection Entry Volumes

The designated one-way and two-way codes that were previously appended to the intersection legs were used in computing the intersection entering volumes. These codes were as listed below.

- Code D – divided roadway
- Code O – one-way couplet
- Code U – undivided two way road
- Code X – one-way street towards decreasing reference posts
- Code Z – one-way street towards increasing reference posts

Intersection entering volumes were calculated with an assumption of 50/50 split for AADTs on two-way intersection legs (code D and code U) and assigning full AADTs on one-way legs (code O, code X, and code Z). Also, legs with missing “direction of flow” codes were assumed to be two-way and their AADTs split into two. Next, AADTs on one-way legs which exit the intersection were omitted while AADTs on one-way legs which enter the intersection were used in full. The intersection entering AADT was then computed by summing up all the assigned approach AADTs. Annual entering volumes were calculated by multiplying these entering AADTs by 365.

The corresponding nighttime AADTs were computed using a factor of 0.24. This factor is based on analysis of eight randomly selected continuous count locations (ATR008, ATR170, ATR219, ATR305, ATR352, ATR381, and ATR410) in Minnesota.

It is also in agreement with the factor of 0.23 which was used in a previous study (Isebrands et al. 2004) in Minnesota.

3.2.5 Computation of Roundabout Crash Rates

The analysis omits the crash data for a roundabout's lighting installation year since the actual installation dates are not known. Two different methods of crash rates (number of crashes per million entering vehicles) were computed for comparison; an intersection-weighted crash rate and a volume weighted crash rate.

3.2.5.1 Intersection Weighted Crash Rates

The method for intersection weighted crash rates used involves the computation of an annual crash rate for each roundabout within the analysis period. Equation 22 shows the formula for computing the annual crash rate for an individual intersection (*i*). Next, crash rates for sub-groups such as lighted or unlighted roundabouts are then computed by averaging the crash rates within a the sub-group. Equation 23 shows the formula for calculating the crash rate for a sub-group (*s*).

$$crash\ rate_i \quad = \quad \frac{1{,}000{,}000 * total\ crashes\ for\ given\ year}{sum\ of\ annual\ nighttime\ entering\ vehicles\ for\ given\ year} \ldots\ldots\ldots(22)$$

$$crash\ rate_s \quad = \quad \frac{sum\ of\ crash\ rates}{number\ of\ crash\ rates} \ldots\ldots\ldots(23)$$

An analysis of general crash rates in Minnesota within the analysis period of 2003 – 2012 showed a decreasing trend. This trend could be due to improvement in vehicle design, driver education, road signage and markings, and geometric design over the years. Figure 14 shows the decreasing trend in nighttime annual crash rate in Minnesota. Also, further analysis of the MN HSIS illumination data showed that the “Full” illumination roundabout crash data are the most recent within the analysis period while the “None” illumination roundabout crash data are the oldest within the analysis period. Therefore, there could be possible temporal influence/correlation in any computed crash rates and this needs to be corrected. A Bayesian approach was used to develop crash rate adjustment factors normalized to the 2012 general MN crash rate. The adjustment factors were then used to adjust all intersection crash rates computed with Equation 22 before any sub-group crash rates are calculated with Equation 23. Table 13 presents the Bayesian adjustment factors used. In performing the Bayesian analysis no data could be found for year 2003 so the 2004 factor was applied to 2003.

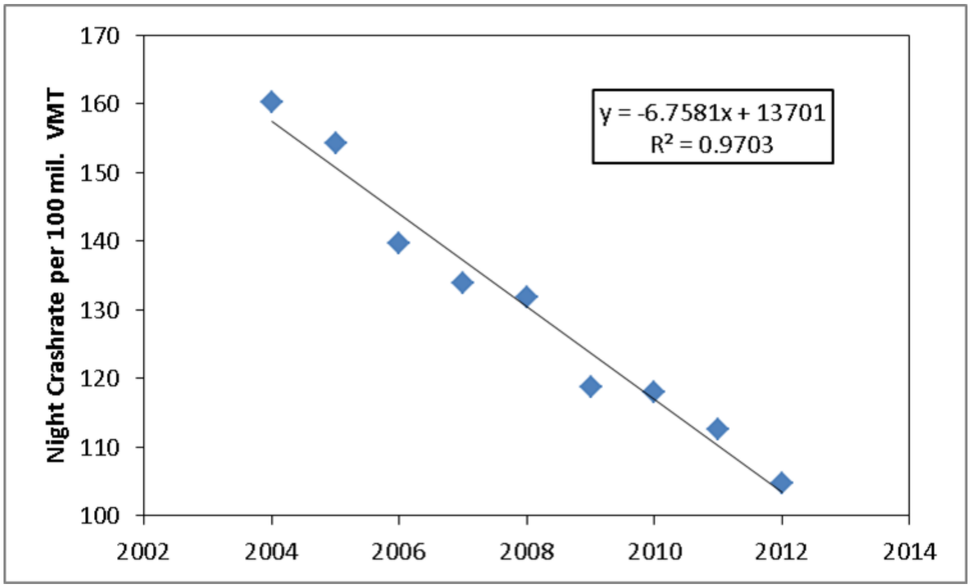


Figure 14 Annual Nighttime Crash Rate in Minnesota

The Bayesian adjustment factor (BCF) for a given year n, normalized to year 2012 can be estimated as shown in Equation 24.

$$BCF\ for\ year\ n = \frac{predicted\ crash\ rate\ for\ 2012}{predicted\ crash\ rate\ for\ year\ n} \dots\dots\dots\dots\dots.(24)$$

Table 13 Bayesian Correction Factors for Nighttime Crash Rates

Year	Nighttime Adjustment Factor	Daytime Adjustment Factor
2003	0.66	0.81
2004	0.66	0.81
2005	0.69	0.83
2006	0.72	0.85
2007	0.75	0.87
2008	0.79	0.90
2009	0.84	0.92
2010	0.88	0.95
2011	0.94	0.97
2012	1.00	1.00

3.2.5.2 Volume Weighted Crash Rates

The volume weighted crash rate method computes the crash rate for a sub-group or intersection over the entire analysis period. Equation 25 shows the formula for computing the volume-weighted crash rate. Because this method computes a single crash rate over the entire analysis period for either an intersection or sub-group, temporal correlations are not an issue (Donnell et al. 2010) and the method does not require Bayesian correction.

$$crash\ rate \quad = \frac{1000000 *\ sum\ of\ crashes\ in\ analysis\ period}{sum\ of\ annual\ traffic\ volume(s)} \dots\dots\dots(25)$$

3.3 Results and Discussions

As stated previously, a few caveats must be recalled when considering these results. First, the utilized HSIS Minnesota crash data covers only US and state road intersections. As many roundabouts exist off the state network the observed crash rates may not represent the true mean crash rates for all Minnesota roundabouts, which may be higher or lower than the stated average. It is also unknown if any sampling bias exists in the lighting policy, e.g., lighting was placed on roundabouts with a higher likelihood of incidents. Similarly, it is not known if any underlying design or operation differences exist between lit and unlit roundabouts. Given these constraints this analysis was undertaken under the tentative assumption that the relationship developed for this subset of roundabouts and the larger population should be reasonably constant. Unfortunately, there is no independent way of verifying this assumption. However, it is expected that these results will provide meaningful initial insights in to the potential impact of illumination on safety until future efforts can address the underlying data accuracy and availability issues.

3.3.1 Descriptive Analysis

A total of 20 roundabout locations were identified but one roundabout was omitted from the analysis because it was the only “Continuous” illumination roundabout. Also, due to the sample size of the identified roundabouts it was not possible to split the data into rural and urban areas and perform separate analysis. Table 14 presents a breakdown of crashes from the 19 identified roundabouts. The data shows that about 33 percent of all crashes happened at night. Figure 15 presents a graph of the observed nighttime and daytime crashes per roundabout per year.

Table 14 Number of Roundabout Crashes from Identified Roundabouts in MN HSIS Data

Year	No. of Identified Roundabouts	Total crashes	Day crashes	Night crashes
2003	2	7	5	2
2004	2	12	9	3
2005	2	7	4	3
2006	3	4	2	2
2007	3	13	7	5
2008	7	26	12	14
2009	11	29	21	8
2010	13	42	28	14
2011	17	48	36	12
2012	19	53	36	17

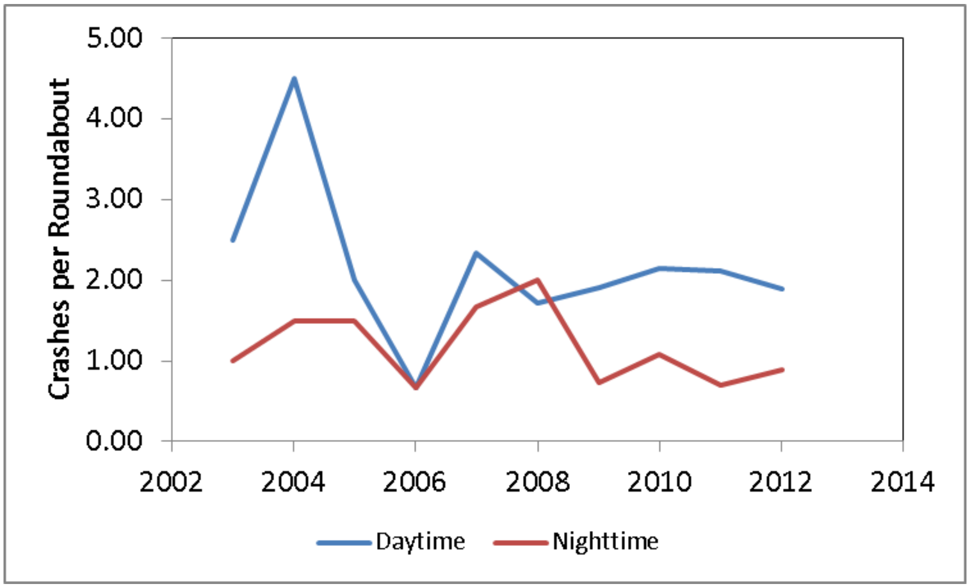


Figure 15 Observed Crashes per Roundabout Location per Year

The analysis further showed that the illumination level at eight roundabouts changed during the analysis period and so their data had to be separated based on illumination level and the separated data treated as data from different roundabouts. This resulted in 27 roundabout illumination datasets with a total of 79 data-years available for the analysis. Also, Table 15 presents a breakdown of the analysis data based on illumination level.

Table 15 Identified MN HSIS Roundabout Characteristics Based on Illumination Level

Roundabout Type	Total Number	Max. Data Years	Min. Data Years	Total Data Years
None Illumination	8	10	1	32
Partial Illumination	7	5	1	17
Full Illumination	12	4	2	30

3.3.2 Effect of Illumination on Crash Rates

The analysis was first performed with just the binary lighting presence variable (lit or unlit). This variable has been the principal variable for past research work. Subsequently, the analysis was performed with the four identified illumination schemes (None, Partial, Full, Continuous) in the Minnesota data described previously. The results presented here are based on only nighttime crashes.

3.3.2.1 Effect of Lighting Presence on Observed Crash Rates at Roundabouts

Table 16 and Table 17 present the results of the lighting presence analysis for intersection weighting and volume weighting respectively. From the results it is seen that roundabouts with lighting experienced a mean crash rate that is about 60 - 62 percent lower than roundabouts that were unlit. Furthermore, the crash rate at unlit roundabouts is at least two and a half times as high as the crash rate at lighted roundabouts.

Table 16 Observed Effect of Lighting Presence at Lit and Unlit Roundabouts (Intersection weighted crashes per million entering vehicles)

	Lit	Unlit
Mean Nighttime Crash Rates	0.70	1.85
Ratio of Mean Nighttime Crash Rates (Unlit/Lit)	2.64	
% Change in Mean Nighttime Crash Rates from Unlit to Lit	-62	

Table 17 Observed Effect of Lighting Presence at Lit and Unlit Roundabouts (Volume weighted crashes per million entering vehicles)

	Lit	Unlit
Mean Nighttime Crash Rates	0.72	1.82
Ratio of Mean Nighttime Crash Rates (Unlit/Lit)	2.51	
% Change in Mean Nighttime Crash Rates from Unlit to Lit	-60	

3.3.2.2 Effect of Illumination on Crash Rates at Roundabouts

Next, the effect of illumination on roundabout safety was analyzed for total nighttime crash rates for multi-level illumination schemes. It should be noted that despite these illumination schemes being qualitative, a comparison of the average illumination installed within each scheme will most likely present a graduated scale increasing from “none”, “partial”, “full”, to “continuous”. Therefore, they represent different quantities of illumination albeit unknown quantities. Table 18 and Figure 16 show the results for the intersection weighted analysis while Table 19 and Figure 17 show the results for the volume weighted analysis.

Table 18 Effect of Different Illumination Levels on Observed Total Nighttime Crash Rates at Roundabouts (Intersection weighted crashes per million entering vehicles)

	None	**Partial**	**Full**
Mean	1.85	0.86	0.60
Standard Deviation	2.17	0.81	0.87
85th Percentile	4.95	1.69	1.64
50th Percentile	1.22	0.63	0
15th Percentile	0	0	0
% Total Change (mean) Compared to “None”		-53	-67
% Incremental Change (mean)		-53	-30

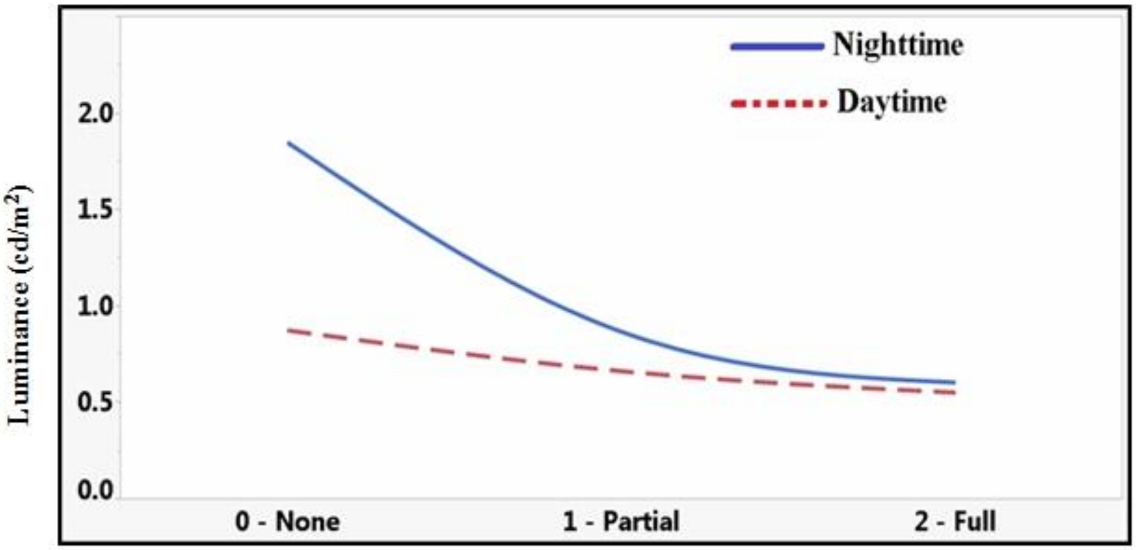


Figure 16 Effect of Different Illumination Levels on Mean Total Nighttime Crash Rates at MN HSIS Roundabouts **(Intersection weighted crashes per million vehicles)**

Table 19 Effect of Different Illumination Levels on Observed Total Nighttime Crash Rates at Roundabouts **(Volume weighted crashes per million entering vehicles)**

	None	**Partial**	**Full**
Mean	1.82	0.79	0.66
% Total Change (mean) Compared to “None”		-57	-64
% Incremental Change (mean)		-57	-16

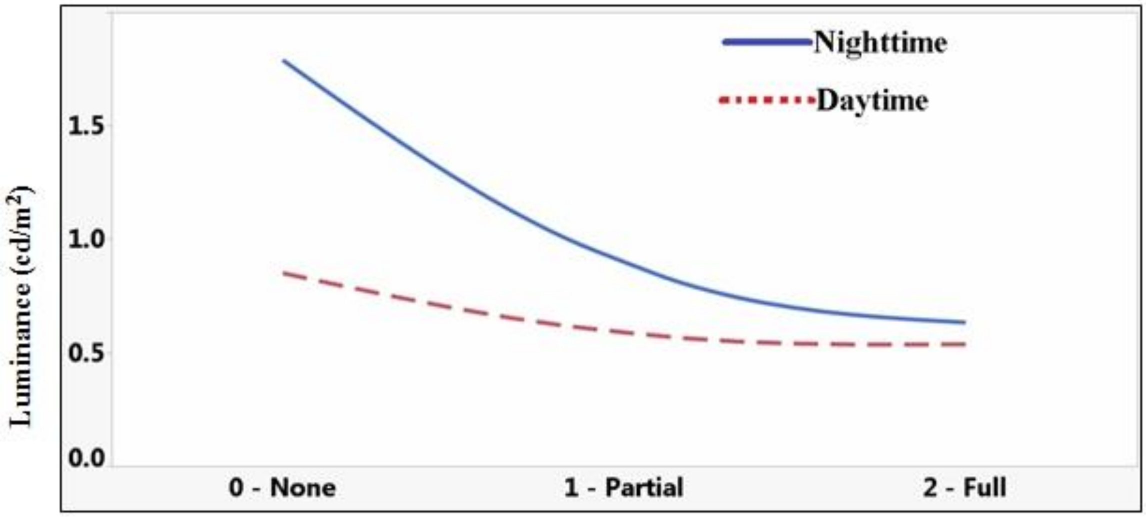


Figure 17 Effect of Different Illumination Levels on Mean Total Nighttime Crash Rates at Roundabouts (Volume weighted crashes per million vehicles)

It can be inferred from the above results that roundabouts with partial illumination experienced about 55 percent reduction in nighttime crash rates compared to roundabouts without illumination. Also, providing full illumination at roundabouts can reduce nighttime crash rates by about 66 percent compared to unlit roundabouts. In addition, converting a roundabout with partial illumination to one with full illumination can provide incremental nighttime crash rate reductions ranging from 16 percent to about 30 percent.

Significantly, about 79 - 89 percent of the benefits that can be gained from full illumination could be achieved with only partial illumination. This finding appears to contradict the logic of increasing the minimum recommended illumination transition zone length from 260ft in NCHRP 572 (Robinson et al. 2000) to 400ft (Rodegerdts et al. 2010) in NCHRP 672.

3.3.3 Effect of Illumination on Crash Severity Rates

The effect of illumination on roundabout safety was further analyzed for different types of crash severities. The crash severities analyzed are fatal crashes, serious crashes, injury crashes, and property-damage-only (PDO) crashes. Due the small sample size of roundabouts and related crashes, possible injury and injury crashes were combined into one severity group. The results from this analysis are presented in Table 20 and Table 21 for the intersection weighted and volume weighted analysis respectively. These results indicate that roundabouts with lighting had about 67 percent lower injury crash rates and 56 - 62 percent lower PDO crash rates. Also, the results indicate that roundabouts with lighting can significantly reduce or eliminate the occurrence of fatal and severe crashes. It should be noted that the analysis data included only one fatal crash over the analysis period.

Table 20 Effect of Illumination on Observed Nighttime Crash Severity Rates for Lit and Unlit Roundabouts (Intersection weighted crashes per million entering vehicles)

			Serious		**Injury**		**PDO**	
	Lit	**Unlit**	**Lit**	**Unlit**	**Lit**	**Unlit**	**Lit**	**Unlit**
Mean	0	0.06	0	0	0.17	0.51	0.56	1.46
Std. Dev.	0	0.33	0	0	0.39	1.07	0.78	1.77
85th Percentile	0	0	0	0	0.66	1.39	1.41	4.26
50th Percentile	0	0	0	0	0	0	1.26	1.26
15th Percentile	0	0	0	0	0	0	0	0
% change (mean)	N/A		N/A		-67		-62	

Table 21 Effect of Illumination on Observed Total Nighttime Crash Severity Rates for Lit and Unlit Roundabouts (Volume weighted crashes per million entering vehicles)

			Serious		**Injury**		**PDO**	
	Lit	**Unlit**	**Lit**	**Unlit**	**Lit**	**Unlit**	**Lit**	**Unlit**
Mean	0	0.05	0	0	0.15	0.45	0.58	1.31
% change (mean)	-N/A		N/A		-67		-56	

3.3.4 Verification of Findings

There are other safety influencing variables which could not be accounted for in this analysis due to the limited data available. Figure 16 and Figure 17 show that even at daytime there is a benefit to have installed illumination at roundabouts. However, the benefit for nighttime is greater and this is shown by the steeper gradient of the nighttime crash rate vs illumination curve. This observed daytime benefit of installed illumination may be due to other safety measures because the warrant for street lighting is hardly applied in isolation. Some of these measures could be better signage and markings. Other possible explanations may be visual cues from seeing light posts ahead which may alert drivers about the intersection ahead resulting in better driver behavior. Despite the data limitations, it is possible to gauge the impact of these unaccounted safety influencing variables by comparing the crash rate ratios at lit and unlit for both daytime and nighttime using the same sample of roundabouts. Table 22 Estimated Crash Rate Ratios at Lit and Unlit Roundabouts. Table 22 presents the calculated crash rate ratios at lit and unlit roundabouts.

Table 22 Estimated Crash Rate Ratios at Lit and Unlit Roundabouts

	Intersection Weighted	Volume Weighted
Mean Nighttime Crash Rate Ratio (Lit/Unlit)	0.38	0.39
Mean Daytime Crash Rate Ratio (Lit/Unlit)	0.68	0.64

It can be inferred from the ratios in Table 22 that during the daytime the average crash rate at roundabouts with installed lighting is about 64 percent of the average crash rate at roundabouts without installed lighting. However, during the nighttime the average crash rate at roundabouts with installed lighting is only 39 percent of the average crash rate at roundabouts without lighting. Therefore, it is obvious that the set of roundabouts with installed lighting generally experienced a lower average crash rate than the set of roundabouts without lighting under both nighttime and daytime conditions. However, the presence of lighting at nighttime further reduced the crash rates experienced at the lighted roundabouts compared to that experienced at unlit roundabouts.

If the nighttime safety benefit of illumination at roundabouts, found in this study, was mainly due to the other safety influencing features rather than illumination then one would have expected the nighttime and daytime ratios in Table 22 to be comparable. However, this is not the case; the nighttime ratios are about 41 percent less than the daytime ratios.

This indicates that the unaccounted safety variables may not have a major impact on the findings from this study. Therefore, the observed findings can be attributed to intersection illumination. Although, a more detailed analysis would have been preferred, the analysis of these ratios presents the most practical approach given the current data limitations.

3.4 Summary Findings

The results presented in this chapter show the relationship between illumination and nighttime safety at roundabouts. While the data is believed to be the best currently available, the data retain significant issues that could impact the validity of the analysis. These include: (a) an inability to separate into before and after case scenarios; (b) the locations and types of roundabouts considered (i.e. only on the State or U.S. highway system); and (c) the number of roundabouts available to analyze (sample size). These challenges limit the scope and nature of analyses that can be performed and affects the level of detail that the analysis can achieve.

Despite these challenges, the results indicate that lighting can provide significant benefits at roundabouts relative to unlit roundabouts. This study finds that the mean nighttime crash rate for roundabouts without lighting is significantly higher than what is experienced at lighted roundabouts. For the studied roundabouts the illuminated roundabouts had approximately 61 percent lower crash rates.

The results also show that different illumination levels or categories provide direct safety benefits compared to the “no light” situation. Also, there are incremental benefits in changing from one illumination category to a higher one. The study finds average reduced crash rates of between 55 percent and 66 percent respectively for “Partial” and “Full” lighting when compared to “None”. Also, converting from “Partial” to “Full” illumination can provide an average incremental safety benefit of 23 percent reductions in nighttime crash rate.

The main difference between “Partial” and “Full” lighting is that the transition zones on the approaches are also illuminated under “Full” lighting while “Partial” lighting focuses on only the roundabout circle. In NCHRP 672 the minimum recommendation for transition zone length was increased from 260ft (Robinson et al. 2000) to 400ft (Rodegerdts et al. 2010). It is fair to assume that this increase of more than 50 percent in the recommended minimum transition zone length would help roundabouts with “Full” illumination to provide significantly higher safety performance than those with only “Partial” illumination. However, this study finds that about 79 - 89 percent of benefits that can be gained from “Full” lighting can be achieved with only “Partial” lighting.

Last, the results further show that the provision of lighting at roundabouts can significantly impact both fatal and severe injury crashes. However, it is critical in considering these potential benefits of lighting to recall that these comparisons are for unlit to lit roundabouts. As seen throughout the literature roundabouts generally have very low crash rates compared to conventional intersections.

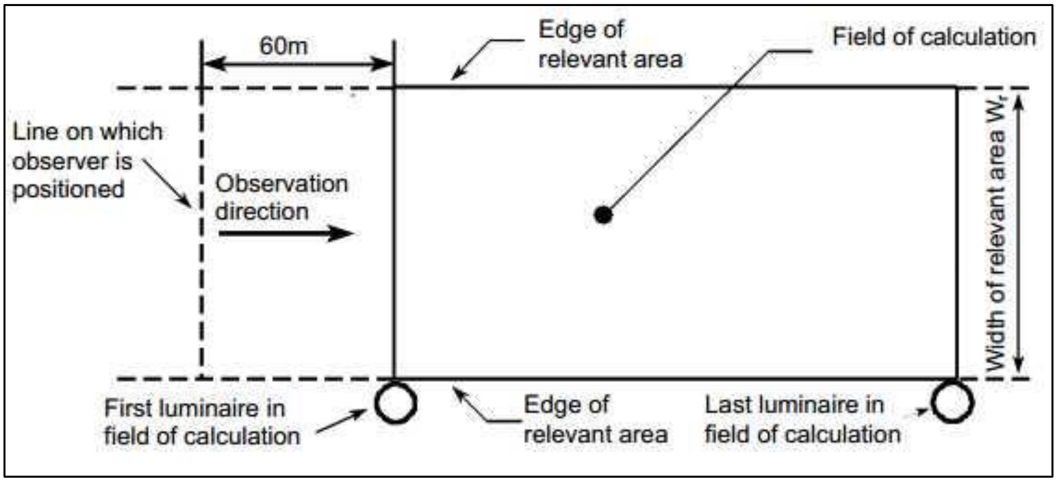
CHAPTER 4: MEASUREMENT METHODS FOR STREET LIGHTING LEVELS

There are several methods for measuring in-situ lighting levels on a roadway. This includes recommendations from the CIE(International Commission on Illumination 2000), recommendations based on a study by Transit New Zealand (Nicholas 1991), recommendations from the IES (Illuminating Engineering Society 1999), and a photography based method. The main methods or protocols are the recommendations from CIE and IES.

4.1 CIE Method: 140-2000

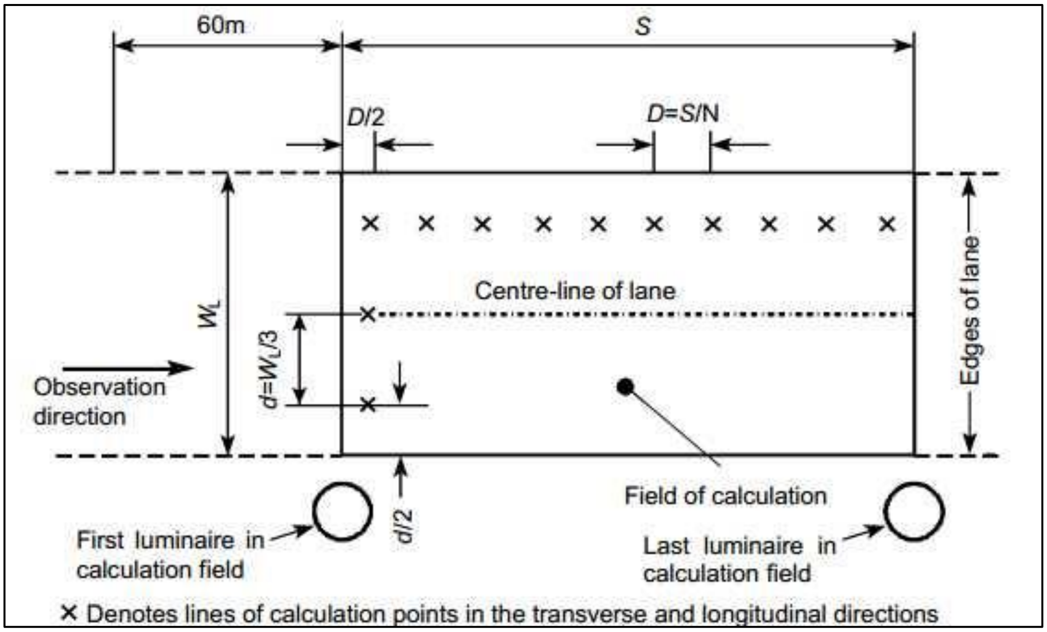
The CIE's technical report (International Commission on Illumination 2000) on "Road Lighting Calculations" which was published in 2000 highlights a method for measuring luminance on streets. This method requires a calculation field between two luminaires on the same road and an observer distance of 60 meters from the near luminaire and with an observation angle of 1^o. Figure 18 shows a sketch of the observer position, luminaires, and calculation field.

The method requires that calculation points should be evenly spaced within the calculation area. The positioning of the calculation points in a lane should be as depicted in Figure 19. For a road with luminaire spacing not greater than 30 meters, the number of calculation points in a lane, N, is 10 and for a road with luminaire spacing greater than 30 meters N is the smallest integer that yields D, $\leq$ 3 meters where D is the spacing between the calculation grid points. Also, even though the observer is longitudinally positioned 60 m from the first luminaire, he must be transversally positioned in the center of each lane in turn for luminance measurements at all the points. All measurements are included in estimating the average luminance and overall uniformity of luminance. Therefore, for a simple undivided two-way lane road with luminaire spacing at 30 meters, at least 120 measurements would be required; 60 measurements from each position (center of each lane) of the observer; about 20 along center of each lane and another 20 along the centerline.



(Source: International Commission on Illumination 2000)

Figure 18 Arrangement of Luminaires and Observer based on CIE 140 -2000



(Source: International Commission on Illumination 2000)

Figure 19 Calculation Points Location within a Lane in the Calculation Area

4.2 Transit New Zealand's Rapid Assessment Method

In 1991 Transit New Zealand sponsored a research project (Nicholas 1991) which had among other aims to provide a uniform and meaningful method of evaluating road lighting for investigation of accident sites. This research project developed a simple method that could give reasonable assessment of existing lighting on roads. It offers a rapid assessment method compared to the CIE's method (International Commission on Illumination 1976) of checking code compliance which required the survey site to be gridded into over a 100 points (at the time of the New Zealand study) and luminance measurements made at these points with a precision photometer mounted at 1^o viewing angle by an observer positioned at 60 meters from the first lantern/luminaire. Complying with the CIE code usually requires several hours to perform a lighting assessment at a site (Nicholas 1991). The findings from the Transit New Zealand study indicate that:

- A minimum of 8 well-chosen points will be sufficient to perform a road lighting adequacy audit; 4 points under the near luminaire and another 4 points halfway between luminaires.
- There is no significant change between pavement reflectance properties with observation angles of 1^o or 2^o.
- Luminance measurements can be made at an observation distance of 33 meters with a luminance meter having $1/3^o$ field of view.

Figure 20 shows a sketch of the field setup proposed in the Transit New Zealand's method for field measurement of street luminance.

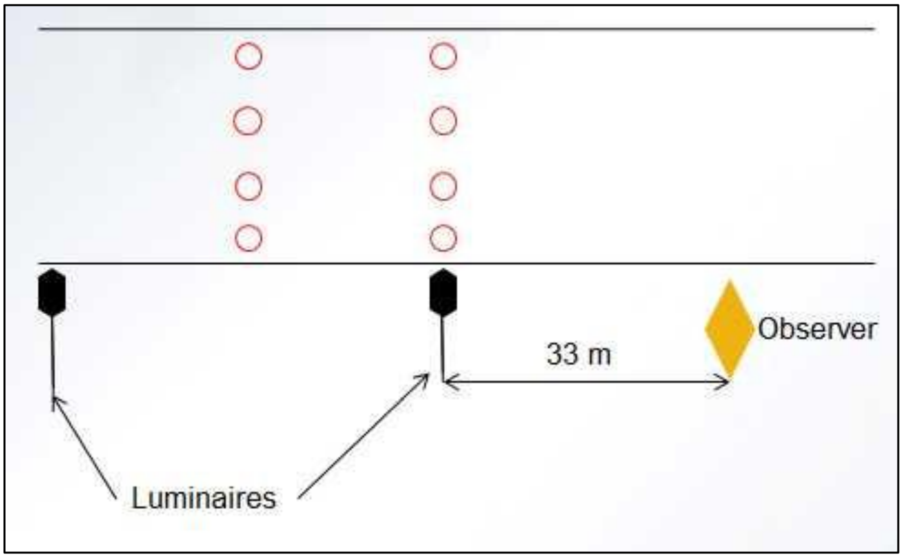


Figure 20 Sketch of the Transit New Zealand Rapid Assessment Method

4.3 The Photographic Method of Luminance Measurement

Illumination levels at a roundabout intersection can be evaluated by using hand-held illumination meters to measure lighting levels at specific points of an imaginary grid. The recommended spacing between grid points is 1.5 meters or 2.0 meters from the European Norm (CEN 2008c) and the American Standard (Illuminating Engineering Society 2008) respectively. This spacing requirement makes data collection very tedious and it is also almost impossible to reproduce measurements at the same points. Also, the sheer number of data points required per intersection poses a huge challenge; especially when a lot of intersections need to be evaluated in a short time. Furthermore, the measurement angle of available illumination meters makes them unsuitable for measuring small details (Wuller and Gabele 2007) such as may be required for an intersection illumination analysis.

The photographic method of evaluating lighting levels offers an easier and effective solution to the challenges involved with using hand-held illumination meters to evaluate intersection illumination levels. Also, the photographic method is able to achieve luminance constancy which reduces variation in luminance during measurements because the luminance is measured/captured the same time (Wuller and Gabele 2007). This is important because luminaire power output is subject to voltage fluctuations. Also, because the luminance information is captured in an image, the method guarantees repeatability of the auditing process. Uncertainties associated with re-identifying the exact points in the field, where measurements were made are eliminated.

The photographic method is an image-analysis approach which can be used to extract pixel-level luminance information from an image taken with a digital camera. A digital camera can effectively serve as a luminance meter because the output from each element of its imaging array is proportional to the luminance of some scene element modified by the optical properties of the lens system and the exposure settings of the camera (Hiscocks and Eng 2011).

Previous studies that demonstrated the use of a digital camera to evaluate luminance levels from a surface can be grouped based on the adopted pixel to luminance conversion method. These methods are the Camera Calibration Constant (the method adopted for this dissertation), Luminance Response Modeling, and Radiometric Self-Calibration.

4.3.1 Camera Calibration Constant Method

By calibrating a digital camera the pixel intensities in an image can be linked to the scene luminance through a specific camera calibration constant (Hiscocks and Eng 2011). The relationship between pixel intensity and scene luminance can be expressed as shown below in Equation 26 (Hiscocks and Eng 2011).

$$N_d = K_c \left(\frac{tS}{{f_s}^2}\right) L_s \ldots\ldots\ldots (26)$$

N_d is the digital number or pixel intensity in the image.

K_c is the calibration constant of the camera.

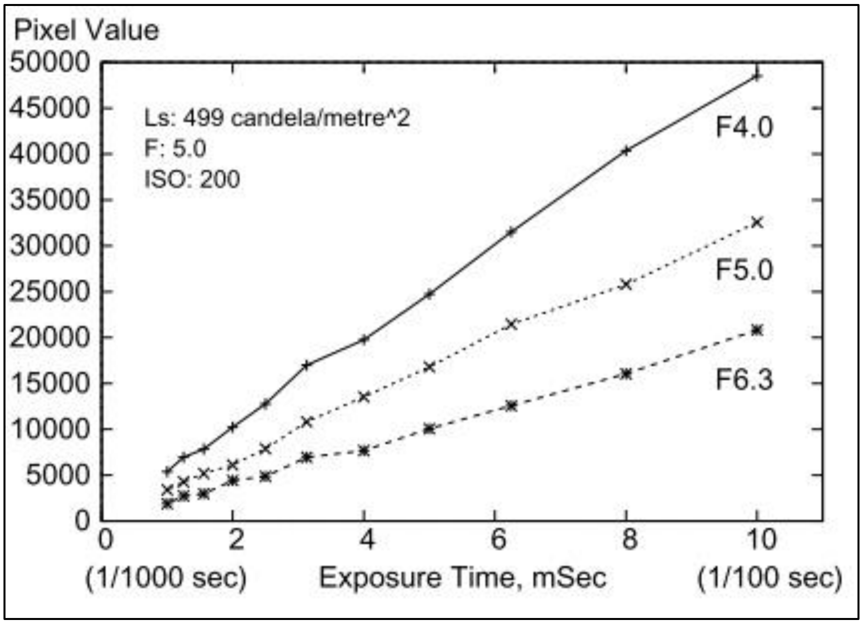
t is the exposure time in seconds.

f_s is the aperture number (f-stop).

S is the ISO sensitivity of the film.

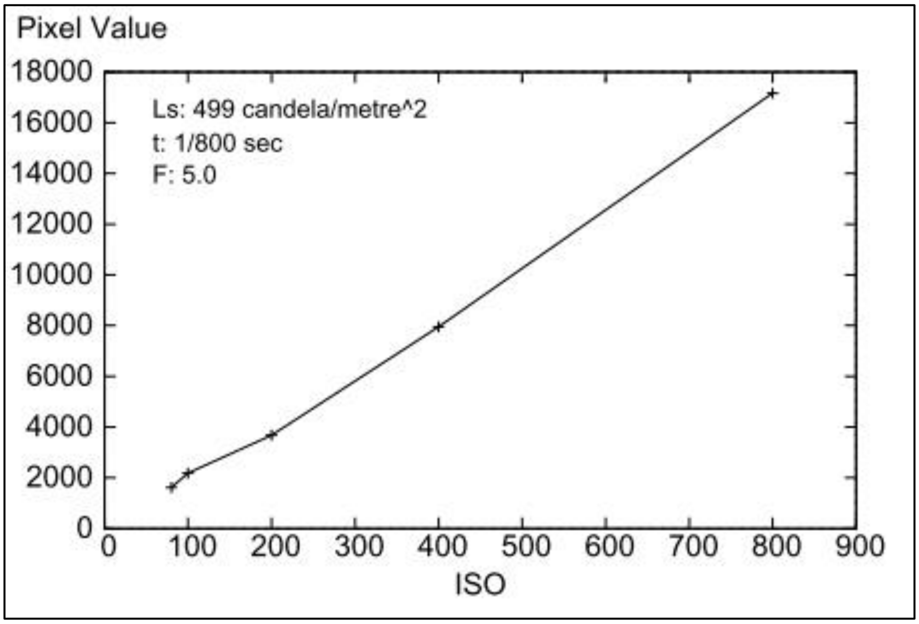
L_s is the luminance of the scene (cd/m^2).

This is essentially an equation of a straight line with slope of K_c and zero intercept and it implies that under proper exposure conditions (i.e. no saturation in the image) pixel intensity (N_d) will vary linearly with the exposure time, the ISO sensitivity, and the squared inverse of aperture. Hiscocks and Eng (2011) showed that this relationship holds true for ISO and exposure time at all exposure settings of a digital camera. Figure 21 shows the relationship between pixel intensity and exposure time while Figure 22 shows the relationship between pixel intensity and ISO. However, he found that at larger apertures, i.e. below F 4.0, the relationship between pixel value and aperture became nonlinear. It is unclear whether the observed threshold between linearity and non-linearity is device specific since he used a single camera in his study and there is no verification of the phenomenon across other devices. Figure 23 shows the relationship between pixel intensity and aperture size.



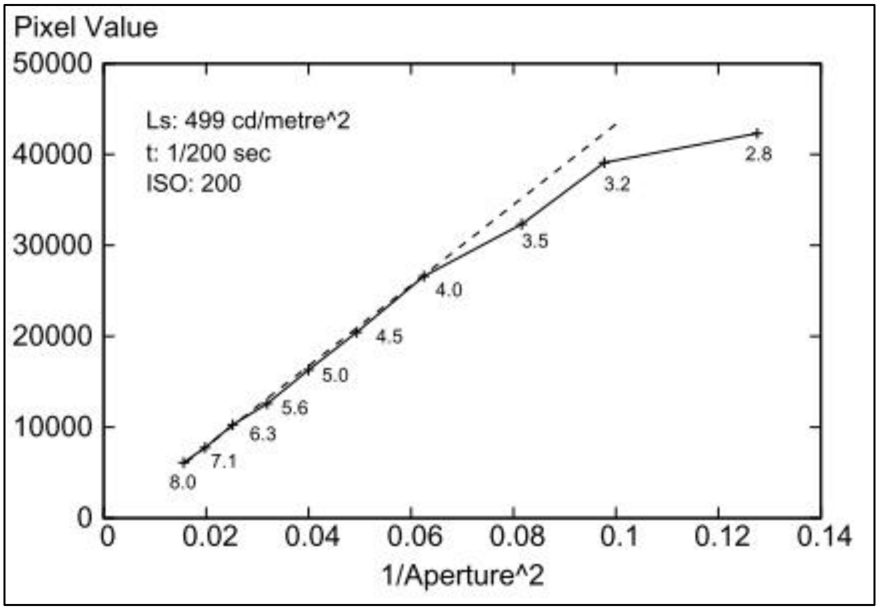
(Source: Hiscocks and Eng 2011)

Figure 21 Exposure Time VS Pixel Intensity



(Source: Hiscocks and Eng 2011)

Figure 22 Pixel Intensity VS. ISO Sensitivity



(Source: Hiscocks and Eng 2011)

Figure 23 Graph of Pixel against Aperture

Also, a digital camera's zoom function does not affect luminance measurement. Even though, luminance is measured in candela per square area, luminous power is measured in lumens per steradian (solid angle) and a change in magnification alters both the solid angle and measurement area in such a way that the effects cancel out (Hiscocks and Eng 2011). For accurate calibration of the camera's constant, it is important that the precautions below are observed in setting up the camera (Wuller and Gabele 2007):

- The auto white balance function of the camera should be set
- Any image enhancement settings such as sharpening and special color should be turned off.
- The flash should be turned off since no additional light is permissible under luminance measurements.

4.3.2 Luminance Response Modeling Method

A digital camera's response to luminance at specific camera settings can also be modeled by collecting pixel data under known luminance sources and fitting the data to a nth order polynomial (Jackett and Frith 2012). The known luminance can be measured with a luminance meter from a set of gray scale targets placed in a uniformly lit environment. The average luminance values obtained with the luminance meter can then compared with the corresponding grey scale pixel values. Unlike the Camera Calibration Constant Method, this method is dependent on the camera's exposure setting at calibration. Therefore, a polynomial response equation must be developed for each combination of camera and exposure setting.

4.3.3 Radiometric Self-Calibration Method

Radiometric self-calibration is a computationally driven calibration process used to relate pixel values in a set of multiple exposure images to real-world luminance values (Inanici 2006). It requires software such as Photosphere® to fuse the set of multiple exposure images into a single high dynamic range (HDR) image and to determine the camera's internal response curve in three (RGB) channels. Each of the curves is a polynomial function that models the accumulated radiometric non-linearities in the image acquisition process without addressing the individual source of each non-linearity. Once a camera's internal response function is determined, photosphere can be used to fuse any set of multiple exposure images at an intersection into a HDR image from which pixel values can be extracted and transformed into CIE XYZ values based on the standard color space reference primaries, CIE Standard Illuminant D_{65}, and standard CIE

Colorimetric Observer with 2^{o} field of view. More information on the transformation process can be found in Inanici (Inanici 2006).

4.3.4 Digital Image Formats

A raw image format contains the pixel values as they were generated by the camera’s sensor without any loss of information. Most often it becomes necessary to convert a raw image to a TIFF image because the raw formats are usually proprietary and image processing programs do not usually accept proprietary formats (Hiscocks and Eng 2011). A TIFF format also preserves the pixel information without any loss. However, the disadvantage of these two file formats is that they produce large images. A TIFF image in color can be as big as 60 MB per image while in monochrome (as is usually the case for luminance measurements) it can be as big as 20 MB per image. Usually there is redundant information in such images and with careful processing the numerical representation of each pixel can be reduced from 16-bit to 8-bits.

A JPEG-compressed image file can be smaller than the TIFF file by a factor of about 800 (Hiscocks and Eng 2011). Although a JPEG format produces smaller sized images and permits faster image processing, it has a nonlinear relationship between exposure value and pixel value (Hiscocks and Eng 2011). This can greatly complicate the analysis. On the other hand, a raw image or TIFF image has a linear relationship between exposure value and pixel value and uses Equation 26 directly.

4.3.5 Maximum Pixel Value

Pixel intensities read inside a digital camera as binary numbers and the range for pixel intensities in any image can be represented as shown in Equation 27 (Hiscocks and Eng 2011):

$$N_{max} = 2^B - 1 \ldots\ldots\ldots (27)$$

B is the number of bits in the binary numbers. Therefore, for a typical 16-bit raw image the range of values is from 0 to 65535. Therefore, it is important to choose the exposure settings (ISO, aperture, and exposure time) such that the maximum pixel number is not exceeded otherwise luminance information will be lost from image.

Also, as the pixel intensity in an image approaches the maximum value the linear relationship between pixel intensity and luminance changes to a non-linear relationship due to image saturation.

4.3.6 Vignetting

Vignetting refers to a phenomenon where the light transmission of a digital camera lens decreases towards the ends of the lens (Hiscocks and Eng 2011). According to Inanici (Inanici 2006), vignetting is dependent on aperture size and increases sharply with increasing aperture size. Therefore, the use of smaller apertures (larger F numbers) is recommended to limit the effects of vignetting. Also, intersection images must be taken such that the layout is centered in the image with a lot of room around it.

4.3.7 Accuracy of Measurements

There are a number of factors that can affect the accuracy of measurements obtained through the photographic method. Some of these factors are as below(Hiscocks and Eng 2011).

- The angle of measurement of a light meter becomes critical where there are both vertical and horizontal components to the light.
- The calibration of the digital camera requires measurement of known luminance with precision light meters which require diffuse lighting sources and controlled environments. These can be difficult to create and often they are unavailable.
- The pixel intensity in a digital image may be saturated due to over exposure or they may exhibit an abnormal response of the image sensor due to under exposure
- There is a lot of stray light which gets caught up in many image capturing systems. In a digital camera this light is often diffused inside the camera body and lenses and it can reduce the output data for luminance measurements. During calibration of a digital camera's image sensor, stray light is considered and the whole measuring space is shielded so that reflection is nonexistent. However, this is an ideal situation which does not exist in real life when using the digital camera to measure luminance
- There is an inherent error associated with the luminance meter. Konica Minolta declares an error of about 2 percent for the LS-110 with an illuminant A. However, the total error (including among other things the error of indication, the error of linearity, etc.) can range from 6 percent to 10 percent.

CHAPTER 5: DEVELOPED PROTOCOL FOR COST-EFFECTIVE AND RAPID MEASUREMENT OF INTERSECTION ILLUMINATION

+--The process of calibrating a camera involves the collection of multiple data pairs of luminance and pixels from a surface under different ‘known’ luminance sources and/or exposure settings and using these data pairs to determine an average calibration constant for the camera. This section describes the data collection and analyses performed to calibrate two digital cameras for luminance measurements at the conventional intersections and roundabouts that will be used in the case study. The discussion is divided into the six sub-sections listed below.

a) Required Equipment
b) Exploratory Data Collection
c) Analyses of the Exploratory Data
d) Comparison of Two Luminance Meters
e) Comparison of Two Digital Single Lens Reflex (DSLR) Cameras
f) Final Calibration Analysis

A goal of the exploratory data collection and analyses was to determine the boundary settings of the linear portion of the camera’s calibration/response curve. Once this is determined, the camera can be operated in the field such that the average pixel intensity in a digital image of road scene will fall within or will be close to this linear portion. This will ensure that scene luminance can be determined free of non-linear distortions due to image saturation.

5.1 Required Equipment

5.1.1 Digital Single Lens Reflex Camera (DSLR)

The photographic method of luminance measurement requires a digital single lens reflex (DSLR) camera because it requires manual control of a camera’s exposure settings (aperture size, shutter speed/exposure time, and ISO). Also, the method requires that all image enhancing functions of the camera should be turned off to ensure that the output is not altered by the camera firmware. For this dissertation, a Canon EOS Rebel T3® and a Canon EOS Rebel T5® DSLR cameras were used. Each camera had an interchangeable 18-55 mm focal lens. For ease of reference in the rest of this document the Canon EOS Rebel T3® DSLR is referred to as *T3* while the Canon EOS Rebel T5® is referred to as *T5*.

T5 was a latter addition to this study and hence the two cameras were not calibrated at the same time. *T5* was obtained to speed up the data collection process. These cameras were chosen because they are readily available, affordable, and they also meet the requirements of the task. Table 23 lists the settings applied to both cameras for luminance measurement.

Table 23 Camera Shooting Functions and Required Settings for Luminance Measurements

Shooting Functions	Required Setting
Shooting Mode	Manual (aperture size, shutter speed, and ISO were manually controlled. ISO was fixed at 3200
Focus Mode	Automatic
Stabilizer	On
Exposure Compensating	None
Flash Exposure Compensating	0
Image Effect: Sharpness	0
Image Effect: Contrast	0
Image Effect: Filter Effect	None
Image Effect: Toning Effect	None
White Balance	Automatic
Auto Correct Image Brightness and Contrast	Off
Flash	Off
Auto Focus Mode	One Shot
Self-Timer	2 Seconds
Metering Mode	Evaluative
Image Type	Raw
Picture Style	Monochrome
Auto Lighting Optimizer	Off

5.1.2 Luminance Meter

To calibrate a camera for luminance measurements, a luminance meter is required to measure different luminance levels from a target surface. This dissertation used two luminance meters; the Konica Minolta LS-110® (with 1/3° view angle and 2 percent absolute error) and the Gossen Starlight2® (a photography exposure meter and flash meter which could be set to read luminance with either 1° or 5° view angle). The Gossen Starlight2® meter was used to cross check the Konica Minolta meter's sensitivity. Hereafter, the Gossen Starlight2® meter is referred to as *Starlight2* while the Konica

Minolta LS-110® is referred to as *LS-110*. Table 24 presents the applied settings for various measurement functions of the Konica Minolta LS-110.

Table 24 Settings for Luminance Meter

Item/Parameter	**Setting**
Response (Fast or Slow)	Fast (ideal for non-flickering light source)
Calibration Type	Preset (from Factory)
Measuring Mode	Absolute
Peak/Continuous Measuring	Continuous (gives average reading over the measurement time)
Measurement Type	Luminance
Units	cd/m^2

5.1.3 Illuminance Meter

An illuminance meter is also needed during the camera calibration process to monitor incident light output from the source. The readings are used to confirm that the data collection is done under fairly constant luminance. This ensures that variation in average pixel intensities from the different target images is truly a function of variations in the camera's exposure settings or source luminance, and not voltage fluctuations. This study used the EXTECH HD450® illuminance meter. It has a measurement range up to 400,000 Lux, maximum resolution of 0.1 Lux, and an absolute error of 3%.

Figure 24 shows pictures of the *T3*, the *LS-110*, and the EXTECH HD450 illuminance meter.

Figure 24 Digital Camera, Luminance Meter, and Illuminance Meter used for the Calibrating the Camera.

5.1.4 Tripod

A standard photographic tripod with a camera mountable plate is needed to hold the camera and/or luminance meter firmly in the same plane during measurements. This helps to reduce measurement errors due to vibrations when the devices are held in the hand.

5.2 Exploratory Data Collection and Analysis

A series of preliminary data collection experiments identified some factors which must be controlled in order to improve the accuracy of the final calibration. The exploratory data collection was done both outdoors and indoors and on different types of surfaces (e.g. photographic gray cards, asphaltic road pavements, concrete sidewalks, and walls).

The data collection procedure involved two primary tasks. First, a high precision luminance meter with a small viewing angle was used to collect ‘known’ luminance values from a target surface. Different luminance values were obtained by using lamps of different luminous outputs, or using a dimmable lamp adjusted to different output levels. These measurements were made with the luminance meter mounted on a tripod. The second task involved mounting the camera on the tripod and taking several shots of the target surface (for each measured luminance) at different exposure settings. These exposure settings covered the whole range of the exposure level scale, i.e., from +3 to -4 exposure levels (EL). A positive EL levels indicate overexposure and while negative EL levels indicates underexposure. The ISO was kept constant at 3200. For a fixed aperture and ISO sensitivity, consecutive changes in the shutter speed were used to increase/decrease the exposure level in 1/3-stop intervals. This data collection procedure was used to collect data in eight different exploratory experiments with the *T3* and *LS-110*. In all, 1748 digital images were collected for the exploratory analysis. All the images were collected in the raw format but were converted into 16-bit TIFF images for analysis Table 25 explains the various exploratory data collection tasks.

Table 25 Description of Various Exploratory Analysis Tasks

Task ID.	Date	Images Taken	Details
1	10/1/14	720	Data collection was performed outdoors on three target surfaces. The first surface was a concrete pavement, second surface was an asphalt pavement with a lot of light colored aggregates, and third surface was an asphalt pavement with darker aggregates.
2	10/21/14	235	Data collection was performed indoors. A light bulb was placed inside a sealed box which had a small hole at the top. The bulb was connected to a dimmer and measurements were performed at two dimmer settings.
3	11/07/14	163	Data collection was performed outdoors on a road segment. Data was collected at over a grid with 2 rows and 5 columns of points separated by 2 feet.
4	11/10/14	41	Data collection was performed indoors on a wall surface. The light source was placed at the same distance from the wall as the tripod carrying the light meter and camera. Measurements were made by aiming at the center of a marked area on the wall. The size of the marked area was 1 inch by 2 inches.
5	11/14/14	160	Data collection was performed indoors on a gray card placed on the floor under diffused light source. The illuminance meter was used to determine the most diffused spot by checking incident light levels on the floor in the room.
6	11/20/14	92	Data collection was performed indoors on a wall surface. Measurements were made at the center and corners of a 1 inch by 2 inches marked area on the wall. Two different light sources and a dimmer were used to create four different luminance conditions.
7	11/21/14	55	Data collection was performed indoors on a wall surface. Measurements were made at the center and corners of a 1 inch by 2 inches marked area on the wall. A dimmer was used to create two different luminance conditions with one light source.
8	11/22/14	282	Data collection was performed outdoors. No luminance data was collected. The distance of the camera from a target area on an asphalt car park was varied to simulate different observation angles.

5.2.1 Influence of Surface Homogeneity

The results of the exploratory analysis indicate that rougher surfaces with a non-uniform surface color showed more spread in luminance measurements than smoother surfaces with uniform surface color. The term ‘spread’, as used in this document, is defined as the standard deviation divided by the mean and expressed as a percentage. Smaller values of spread indicate less variation in measured spot luminances. Table 26 presents the calculated spread for luminance measurements on different surfaces. This finding indicates that the final camera calibration data needs to be collected on a target with smooth and uniformly colored surface.

Table 26 Calculated Spread in Luminance Spot Measurements on Different Surfaces

Surface Type	Location	Calculated Spread in Measured Luminance Data
Concrete Sidewalk	Outdoors	4.81
Asphalt with Light Colored Aggregates	Outdoors	11.26
Asphalt with Dark Colored Aggregates	Outdoors	2.10
Wall Surface	Indoors	1.33

5.2.2 Impact of Diffused and Non-Diffused Light Sources

The analysis further highlighted the impact of non-diffused light sources on luminance spot measurements. The results in Table 27 show that the spread in successive luminance measurements under diffused lighting was smaller than the spread in successive luminance measurements under non-diffused lighting. The wall luminance measurements were performed by mounting the *LS-110* meter on a tripod and aiming at the center of a 1 inch by 2 inch marked area on the wall. The grey card luminance measurements placed the 18 percent grey card (Kodak®) in the most diffused spot determined by the illuminance meter (i.e., the same illuminance at the corners and center of the 4x5 inch grey card). Luminance readings were then obtained using the tripod mounted luminance meter located vertically over the card and aimed at its center. Measurements using non-diffused lighting were significantly more variable even though the measurement area was smaller; 1 inch by 2 inches. These results imply that greater care must be exercised to ensure that the luminance measurements are always made from the same spot and tripod/meter location when non-diffused source is used.

Table 27 Comparison of Spot Measurements under Diffused and Non-Diffused Lighting

	Wall Surface Under Non-Diffused Lighting	Gray Card Surface Under Diffused Lighting
Mean (cd/m^2)	7.19	40.23
Standard Deviation	0.096	0.198
% Spread	1.33	0.49

Next, the 1 inch by 2 inch measurement area on the wall was further sampled across all four corners and the center for luminance levels. The results are shown in Table 28 and it shows that there can be substantial variation across such a small area due to the non-diffuse source. This implies that luminance spot measurements with luminance meters under non-diffused lighting can vary significantly and can be difficult to repeat. Therefore, the measurement of the 'known' luminances values for the calibration process must be performed under the most diffused light source possible and/or the measurement area must be very small to limit the influence of non-diffused lighting.

Table 28 Variation of Spot Measurements under Non-Diffused Light Sources

	Source #1	Source #2	Source #3	Source #4	Source #5	Source #6
Mean	5.56	4.53	3.38	1.84	6.28	7.98
Standard Deviation	0.231	0.173	0.133	0.035	0.184	0.364
% Spread	4.16	3.82	3.92	1.92	2.93	4.57

5.2.3 Camera Response Analysis

As shown in Equation 28, the relationship between pixel intensity and scene luminance can be simplified into a straight line equation. The term RHS represents the interaction of all of the camera's exposure settings and scene luminance.

$$N_d = K_c \left(\frac{tS}{{f_s}^2} \right) L_s = (RHS)K_c + C \ldots\ldots\ldots (28)$$

N_d = pixel intensity value

RHS = interaction term for exposure time (t), ISO sensitivity (S), and aperture (f_s), and scene luminance (L_s).

C = intercept = 0

K_c = camera calibration constant.

Figure 25 presents the plot of pixel intensity versus RHS for the exploratory data

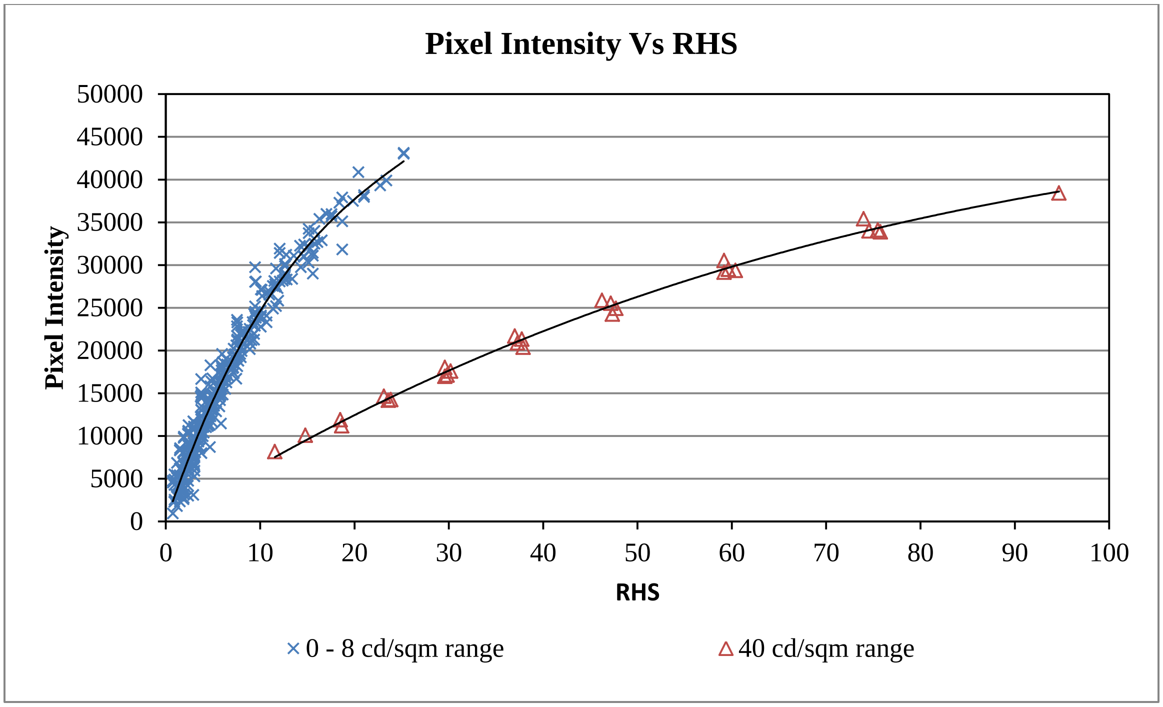


Figure 25 Pixel Intensity Vs RHS

This plot shows that the camera's response is not completely linear as indicated by the equation. There is a small portion, which could be fitted to a linear model. However, there is even a bigger portion of the curve which can best be fitted to a non-linear model. The non-linearity seen in the curve is due to image saturation. Furthermore, the plot shows that the camera response curve and image saturation rate might vary depending on the range of luminance being measured. The curve on the left is based on a luminance range of about 0 – 8 cd/m^2 while the curve on the right has an average luminance of about 40 cd/m^2. Roadway luminance values fall in the range of 0.3 – 2.0 cd/m^2 (International Commission on Illumination 2010) and so this range was used in all subsequent analyses.

Detailed analyses were conducted to identify the range of pixel intensities where the response of the system was linear relative to RHS. Figure 26 presents the plot of pixel intensity versus RHS for the 0-8 cd/m^2 range. Based on this curve, it was determined that the operational limits of this system is within 0 – 10,000 pixels with the corresponding camera exposure level range from -2.00 to -4.00.

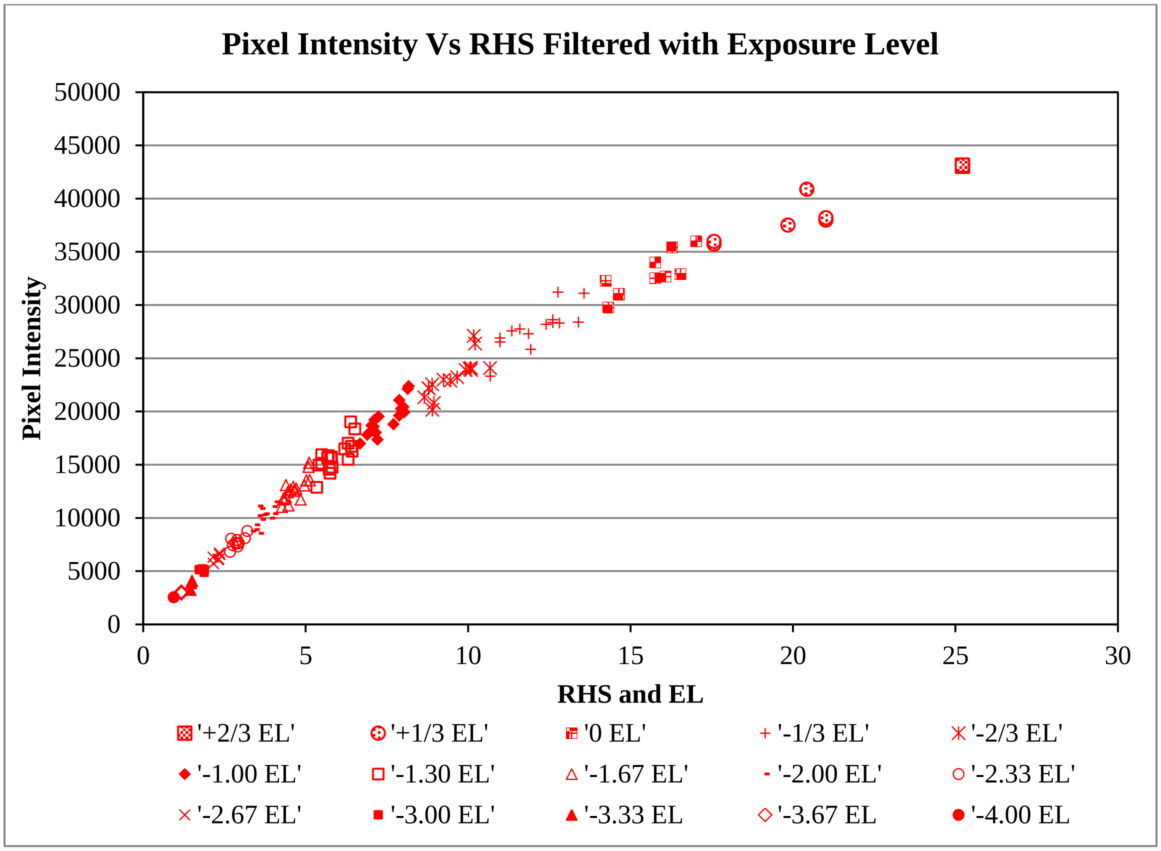


Figure 26 Plot of Pixel Intensity Vs RHS under a Filter of the Exposure Level

Figure 27 shows two plots of the extracted linear portion. One plot is based on pixel intensity data within the range of 0 – 10,000. The other plot is based on pixel intensity data that falls between -2.00 to -4.00 on the camera's exposure level scale. It can be seen that the data selected by these two approaches match well.

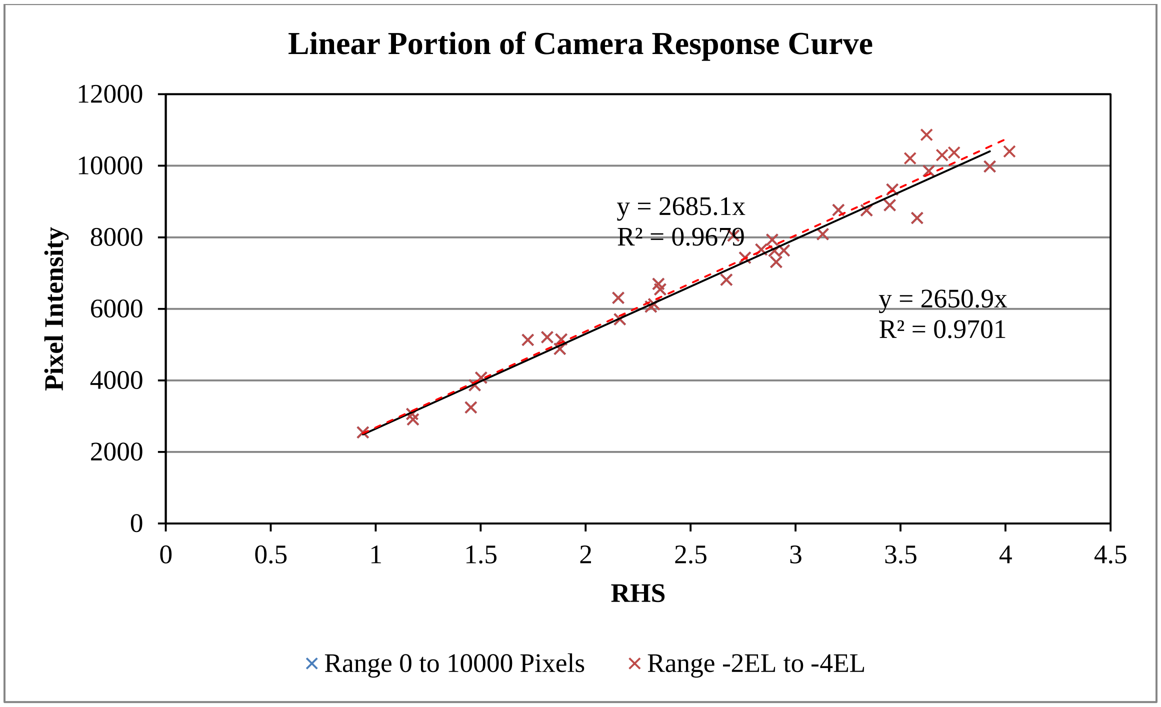


Figure 27 Linear Portion of Camera Response Curve Based on Exploratory Data

5.2.4 Comparison of Two Luminance Meters

The *LS-110* luminance meter used in the exploratory data collection was calibrated from factory and in order to assess the reasonableness of its sensitivity, the *Starlight2* was obtained. Both meters were used to generate parallel calibration data for comparison. Figure 28 shows a picture of the two meters.

Figure 28 Picture of the Gossen meter (left) and the Konica Minolta meter (right)

The meters were used to collect luminance readings from the surface of a photographic gray card with a known reflectance of 18 percent. For each luminance measurement, an illuminance reading on the surface of the gray card was also taken so that an estimate of card's reflectance can be calculated and used as a check on the accuracy of the luminance meters. This approach assumes that the illuminance meter is accurate. The EXTECH® HD-450 illuminance meter was used to measure the illuminance on the surface of the gray card. Figure 29 compares the measurements from the two meters.

Table 29 shows the various illuminance and luminance readings as well as the estimated reflectance based on the two luminance meters. From Figure 29 it can be seen that the two light meters show very comparable sensitivity at luminances less than 2 cd/m^2. As shown prior, this is the normal range for roadway luminance. Table 29 gives further indication, based on the calculated gray card reflectance values, that the sensitivity of the two light meters generally fall in the same ballpark.

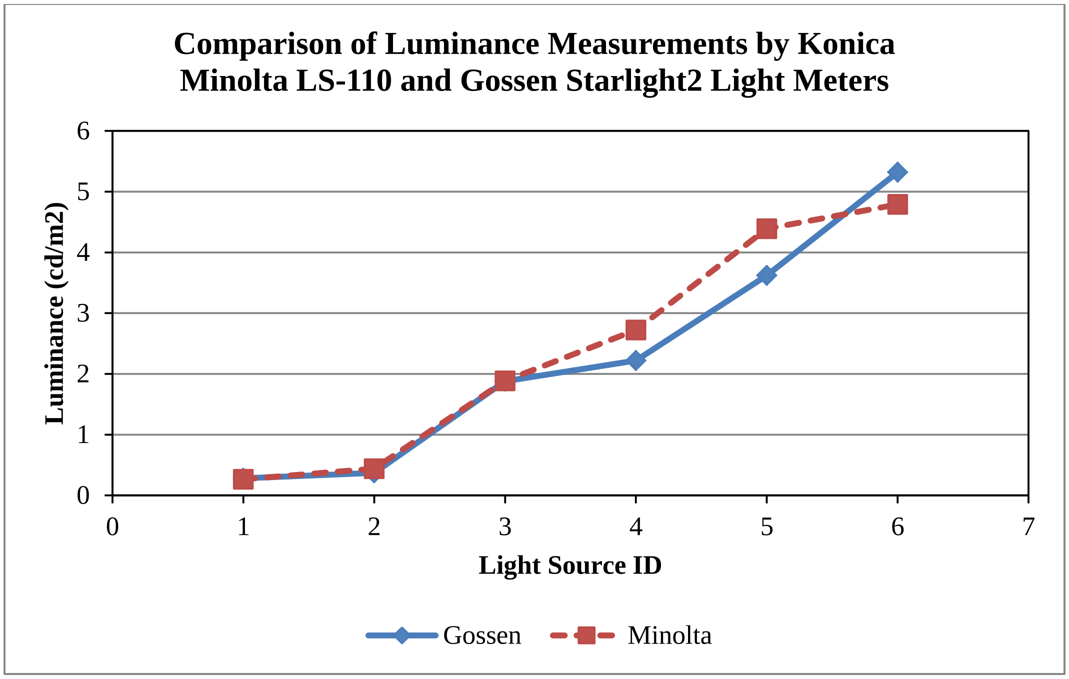


Figure 29 Comparison between Luminance Measurements by Konica Minolta LS-110 and Gossen Starlight2 Light Meters

Table 29 Estimated Reflectance of Gray Card Based on Luminance Readings from the Konica Minolta and Gossen Light Meters

Light Source ID	**Illuminance (Lux)**	**Luminance (cd/m^2)**		**Estimated Reflectance (%)**	
		LS-100	***Starlight2***	***LS-100***	***Starlight2***
1	67.8	4.39	3.62	20	17
2	40.6	2.72	2.22	21	17
3	6.1	0.44	0.37*	23	19
4	90.4	4.79	5.32	17	19
5	32.6	1.89	1.88	18	18
6	4.3	0.27	0.28*	19	20

*Measured at 5° view angle because the device goes out of range at 1°.

5.3 Final Calibration Analysis

The preliminary findings about the influence of surface homogeneity and non-diffused lighting were incorporated into the procedure for collecting the final calibration data sets for the *T3* camera and the *T5* camera. The known luminance values were measured by focusing the luminance meters at the center of a 1 x 2 inches area of a wall with smooth surface and uniform color. The luminance meters and the digital cameras were all mounted on a tripod at a height 0.84 meters and distance of 1.2 meters in front of the wall.

It should be noted that the two cameras were not calibrated at the same time because as mentioned prior *T5* was obtained later to help speed up the field data collection. The 'known' luminance values used in calibrating the *T3* were obtained with both the *LS-110* luminance meter as well as the *Starlight2* luminance meter. However, only the *Starlight2* meter could be used in the case of the *T5* because by then the *LS-110* luminance meter had developed an intermittent 'fault' which causes continuously decreasing readings for successive measurements under the same light source. It was unknown what triggered this intermittent 'fault' and unfortunately the issue could not be fixed by the Konica Minolta repair center because the problem never showed up when it was sent for repairs. This is not expected to impact the calibration negatively because the two meters have been proven to have comparable sensitivity within the luminance range of interest.

For the *T3* camera, the analysis developed separate calibration curves/equations from the data collected by the two luminance meters. For both camera's, the plots show the linear portion of the camera response curve and in both cases the curves are tailored to the range of expected road luminances, 0 – 2 cd/m^2. The *Starlight2* was generally unable to measure luminances less than 0.6 cd/m2 when set to the 1^o viewing angle. Therefore, the 5^o viewing angle was used for such low luminances. The final calibration data for the *T3* included 110 images relating to the *Starlight2* meter spot measurements and 175 images relating to the *LS-110* meter spot measurements. Similarly, the final calibration data for the *T5* included 734 images all related to the *Startlight2* meter spot measurements.

5.3.1 Comparison of Canon EOS Rebel T3 and Rebel T5 DSLR Cameras

Figure 30 plots pixel intensity versus RHS for the *T5* camera and Figure 31 presents the similar plot of pixel intensity versus RHS for the *T3* camera. It can be seen that while the data for the *T5* separate into two distinct curves, the data for T3 does not. This behavior is likely due to improvements in technology between the *T3* and *T5* product line. Also, it is an indication that the two cameras, although just one generation apart, may have very different sensitivity, especially at low luminance.

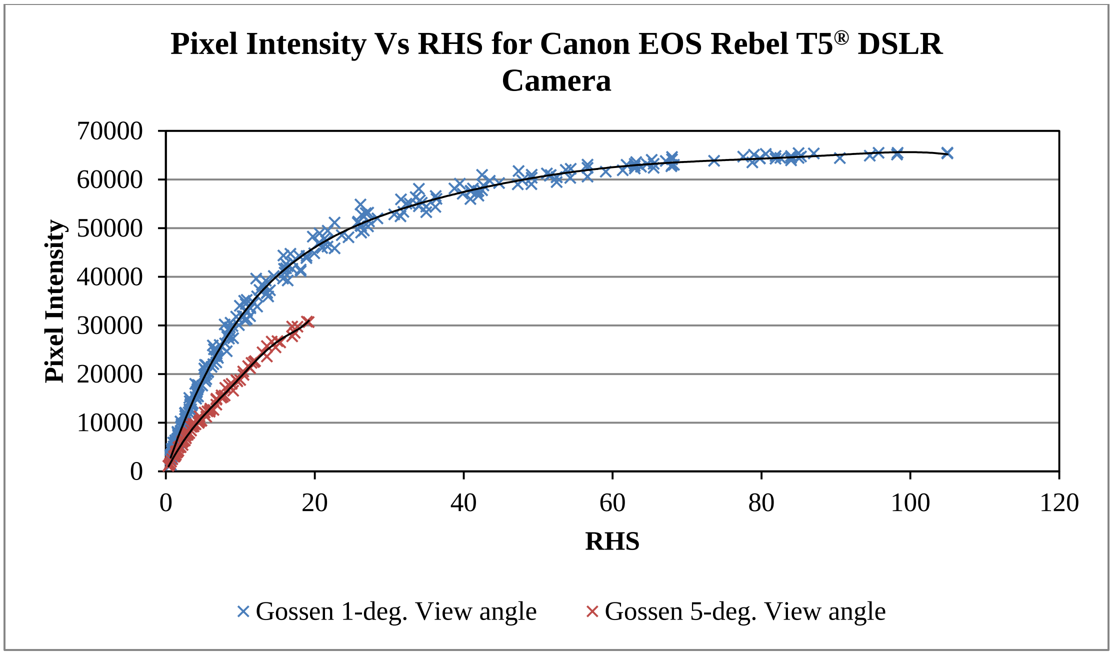


Figure 30 Plot of Pixel Intensity versus RHS for Canon EOS Rebel T5® DSLR Camera

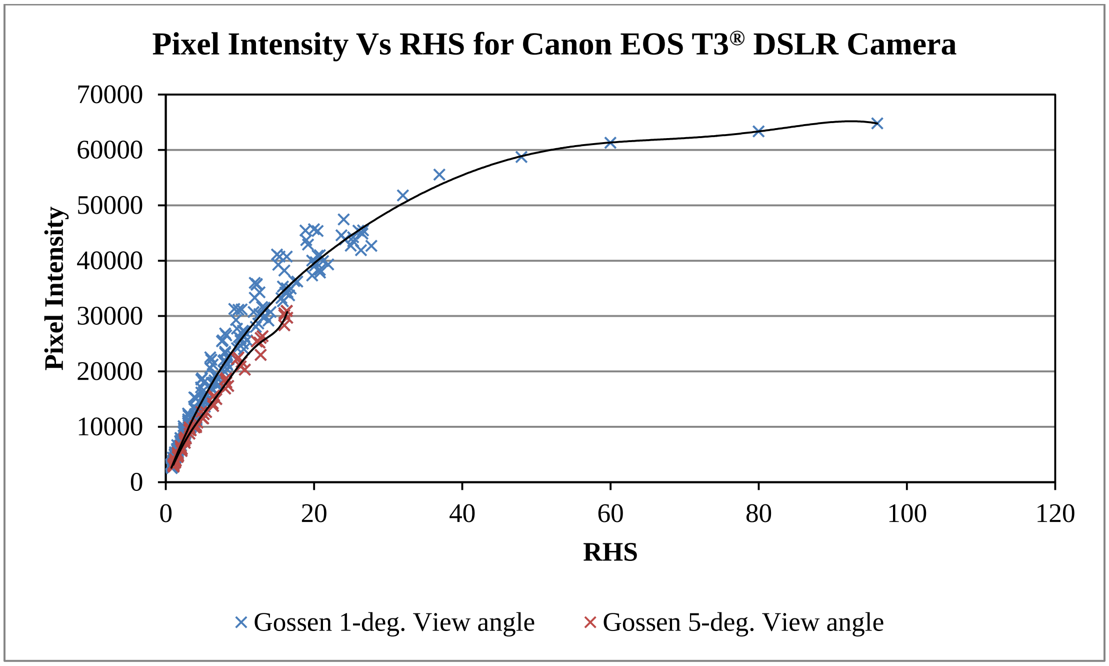


Figure 31 Plot of Pixel Intensity versus RHS for Canon EOS Rebel T3® DSLR Camera

Next, the procedures for auditing of road luminance with hand-held luminance meters indicate that higher precision luminance meters with smaller view angles generally are better than meters with larger view angles (Nicholas 1991). Therefore, the calibration curves/equations developed for the *T5* omit the 5^{o} *Starlight2* data in preference for the 1^{o} *Starlight2* data because of the clear separation between the data relating to these view angles as seen in Figure 30.

5.3.2 Final Calibration Curves for Canon EOS Rebel T3® DSLR Camera

Figure 32 shows the calibrated camera response curves for the *T3* camera. The solid line curve at the top was developed using *Starlight2* luminance data while the bottom, dashed line curve was developed with the *LS-110* luminance data. It can be inferred that the sensitivity of the luminance meter influence the estimated constant.

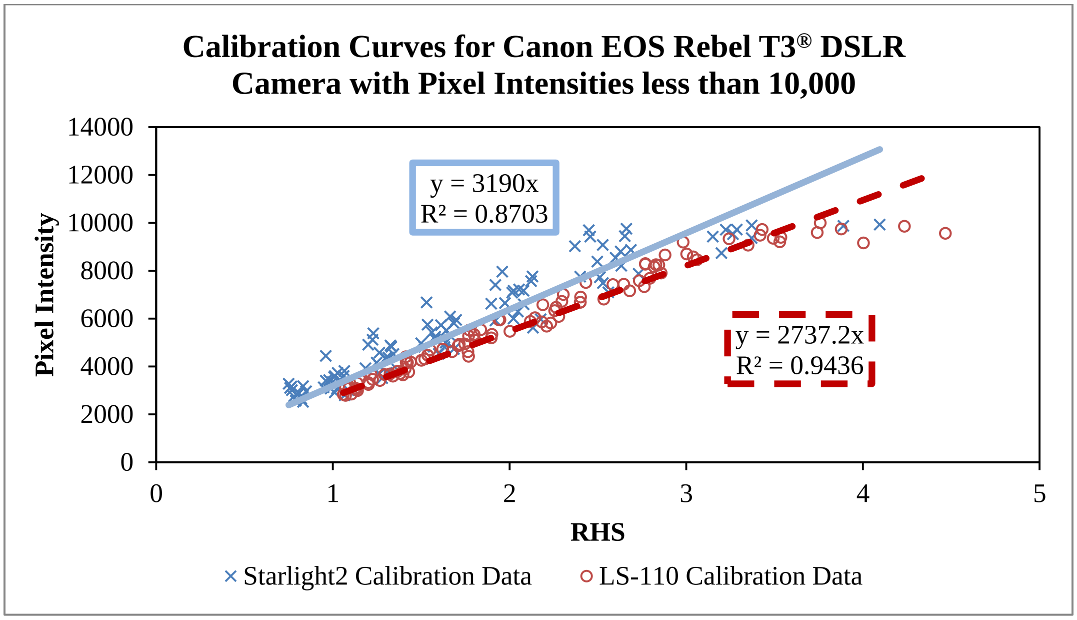


Figure 32 Estimated Calibration Curves Developed for Canon EOS Rebel T3® DSLR Camera with Pixel Intensities less than 10,000

5.3.3 Final Calibration Curve for the Canon EOS Rebel T5® DSLR Camera

Figure 33 shows the final calibrated camera response curve developed with only the 1° *Startlight2* luminance data for the T5 camera.

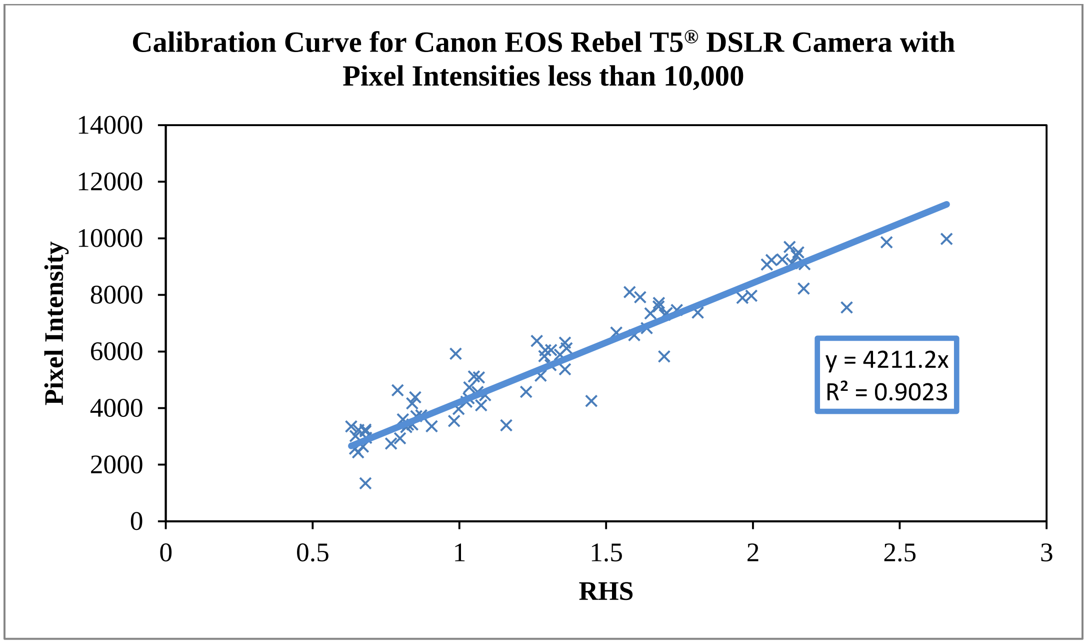


Figure 33 Estimated Calibration Curve for Developed for Canon EOS Rebel T5 DSLR® Camera with Pixel Intensities less than 10,000

5.4 Field Tests

The calibrated camera response curves for the *T3* were field tested on a 16 feet wide concrete walkway and an asphalt road pavement on Georgia Tech campus. The concrete walkway is located near the Industrial and Systems Engineering Classrooms (ISYE) while the asphalt road pavement is in front of the Sustainable Education Building (SEB).

The ‘known’ in-situ luminance levels on the walkway and road pavement were collected with the *Starlight2* and *LS-110* meters respectively. The luminance levels were sampled based on the Transit New Zealand method (Nicholas 1991).

Figure 34 and Figure 35 respectively shows an image of the concrete walkway at the ISYE and asphalt road pavement at the SEB test sites with the test areas highlighted.

Figure 34 Concrete Walkway Test Site with the Luminance Measurement Area Highlighted in Yellow.

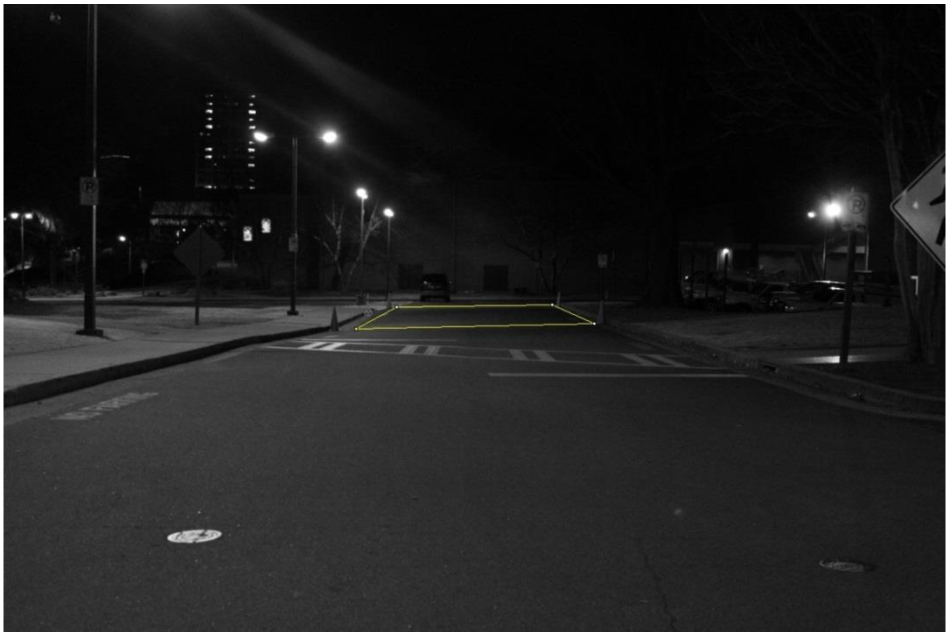


Figure 35 Asphalt Pavement Test Site with the Luminance Measurement Area Highlighted in Yellow.

5.4.1 Spot Measurements and Characteristics of Test Sites

All spot measurements were done with the luminance meters mounted on a tripod at a height of 1.24 meters (49 inches) and at a distance of 38 meters (125 feet) from the near/first luminaire, resulting in a 1.87^o observation angle at the first luminaire. This setup ensured that all the measurements will fall within the acceptable range of 0.5^o – 2.0^o observation angle (International Commission on Illumination 1976; International Commission on Illumination 2000; Nicholas 1991). Figure 36 shows a sketch of the setup and resulting observation angle.

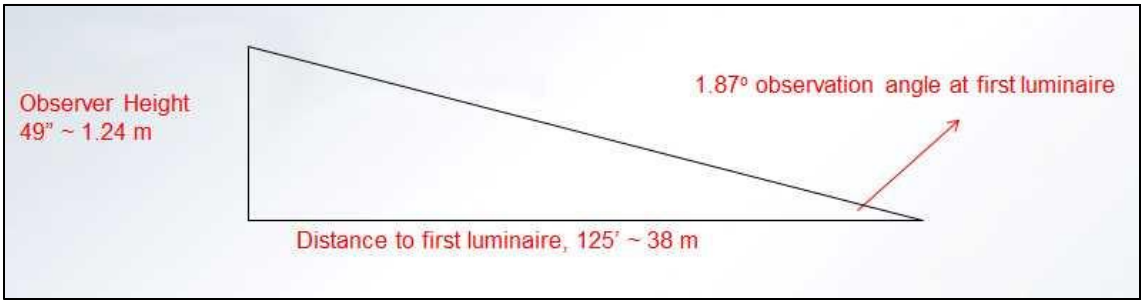


Figure 36 Campus Field Test Setup and Observation Angle

Using high precision luminance meters with small view angles to make spot measurements from long distances, often results in focusing an elliptical measurement area which is larger than the intended spot. These elliptical areas can overlap if the distance between the spots is not long enough. Therefore, the Transit New Zealand method requires the luminaires to be spaced at least 30 meters apart and this limits overlapping between the elliptical areas for the 8 spots. This spacing requirement will also ensure correct sampling of the maximum and minimum bands of luminance on the road pavement between the luminaires.

At the concrete walkway test site, luminaire spacing was just about 15 meters and so the elliptical areas overlapped the measurement spots longitudinally. The observed elliptical area with the *Starlight2* set at 1^o view angle was about 46 feet long and 3 feet wide. This meant that 4 and not 8 measurement spots were possible. Figure 37 presents a sketch of an elliptical area overlapping two spots on the concrete pavement. Despite this, little or no adverse impact is expected on the test results because the walkway was uniformly lit over the test area without clear maximum and minimum luminance bands.

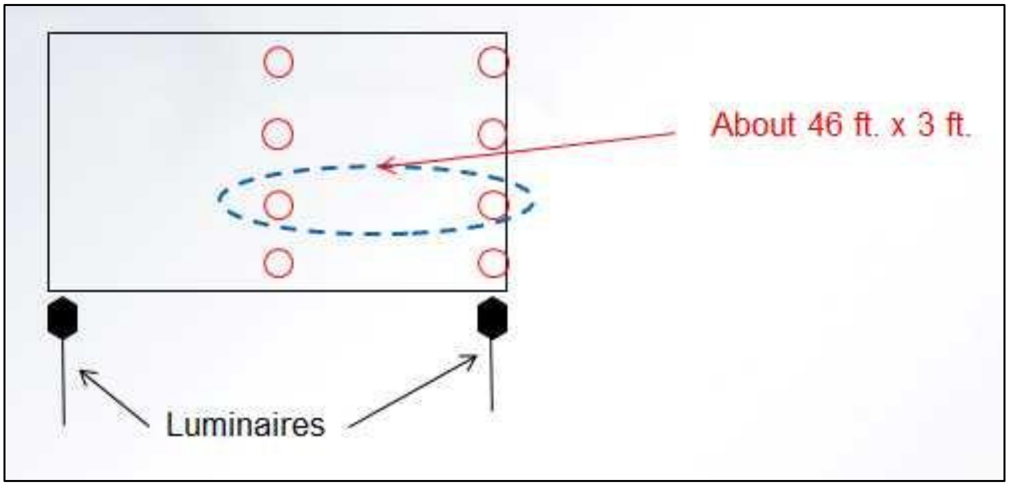


Figure 37 Luminance Meter’s View Area Overlapping Two Measurement Spots during Luminance Measurements at the Concrete Walkway Test Site

At the asphalt pavement test site the luminaire spacing along the road was about 20 meters and the elliptical areas did not overlap the measurement spots but rather overlapped each other at the top and bottom longitudinally as shown in Figure 38. Also, the orientation of the installed luminaire heads along the road alternated between parallel and perpendicular to the road edge as depicted in Figure 38.

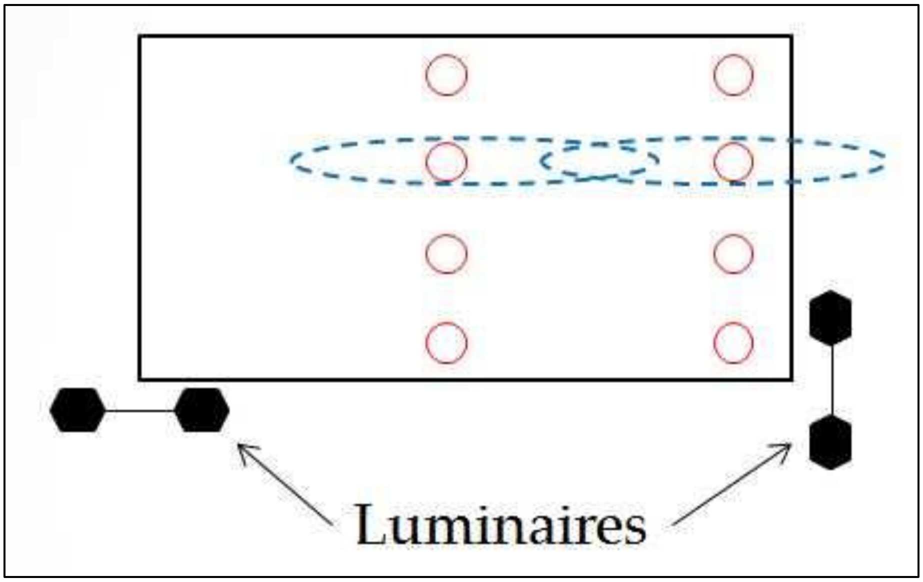


Figure 38 Overlapping View Areas of Luminance Meter at the Asphalt Pavement Test Site

5.4.2 Photographic Luminance Measurements

The photographic luminance measurements were all taken with the camera mounted on a tripod similar to the procedure for luminance meters. The images were taken at four different apertures settings of F4.0, F4.5, F5.0, and F5.6 and fixed ISO of 3200. For each aperture, the shutter speed was varied so that a total of 7 images corresponding to exposure levels of -2.00 to -4.00 with 1/3 stop increments were obtained.

5.4.3 Analysis of Field Test Data

All the ‘known’ luminance measurements for each site were averaged, resulting in a mean site luminance of 1.97 cd/m^2 on the concrete walkway and 2.06 cd/m^2 on the asphalt road. Next, all the images were converted from the raw image format to 16-bit

TIFF image format and for each image the average pixel intensity over the measurement area was estimated using ImageJ® (Schneider et al. 2012), an image analysis software. The derived pixel intensities were then converted into luminance values according to Equation 29. See Appendix E for detailed procedure to use the macro function in ImageJ to automate pixel extraction from the images.

$$Luminance = \frac{RHS * Aperture^2}{Exposure\ Time * ISO} \ldots\ldots\ldots(29)$$

5.4.4 Results

The result for the concrete walkway is shown below in Figure 39. It can be seen from the plot that the derived luminance values from the images closely match the observed site luminance of 1.97 cd/m^2. Also, the average of all the derived luminance values from all the images is 1.90 cd/m2 and this is only about 3.6 percent different from the 1.97 cd/m2 average of the actual spot measurements.

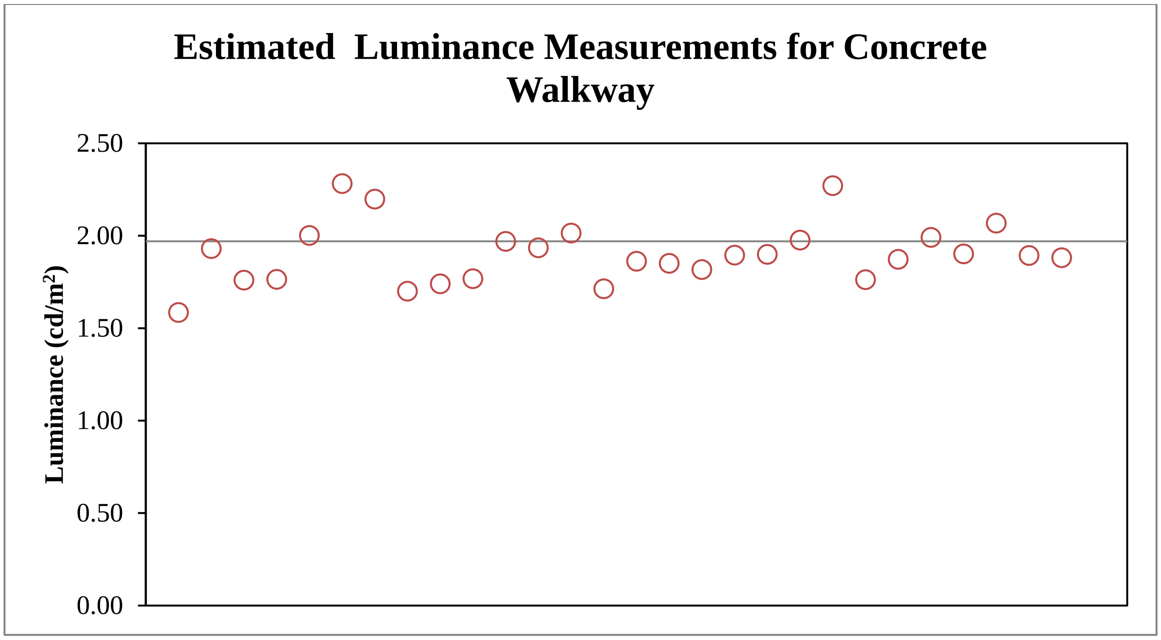


Figure 39 Estimated Luminance on Concrete Walkway Based on the Calibrated T3 Camera Response Curve Developed with Gossen Starlight2 Meter

Next, the result for the asphalt pavement is shown below in Figure 40 and it can be seen that derived luminance values from the images do not match the observed site luminance value of 2.06 cd/m^2 well.

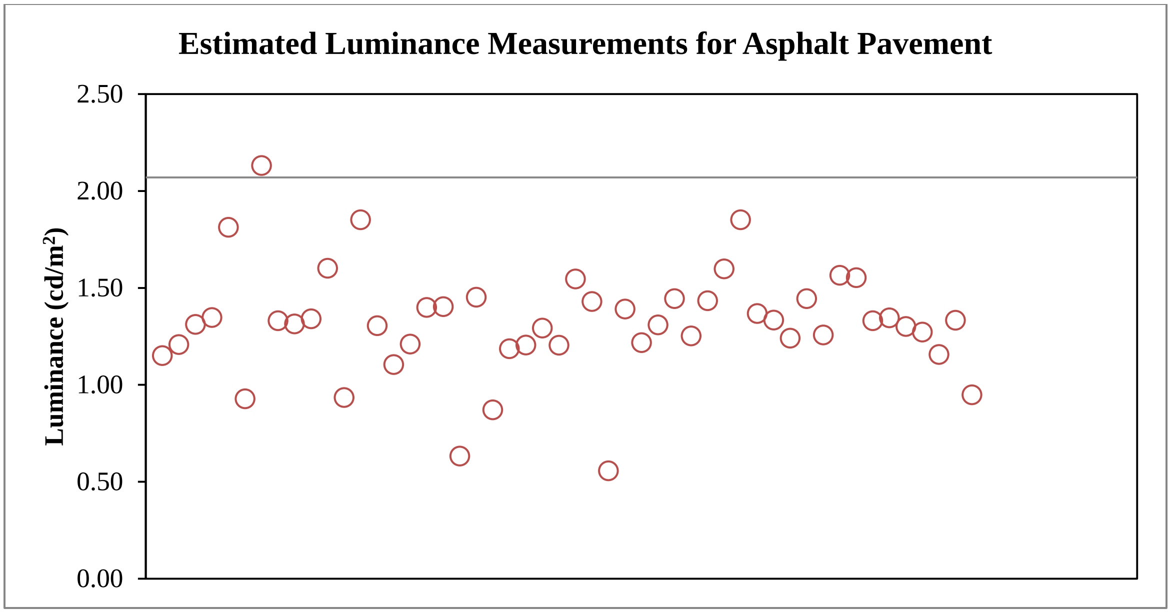


Figure 40 Estimated Luminance on Asphalt Pavement Based on Calibrated T3 Camera Response Curve Developed with Konica Minolta LS-110® Meter

Detailed analyses showed that this observation is largely due to the alternating orientation of the installed luminaire heads which creates a non-uniform luminance gradient between the luminaires. The Transit New Zealand method (Nicholas 1991) which is used in this study for luminance spot measurements assumes the presence of a uniform luminance gradient between the luminaire poles. The effectiveness of the method is linked to the ability to sample the clear patches/bands of brightness and darkness across the road; the brightest patch being under the luminaires and the darkest patch being halfway between the luminaires. Figure 41 shows a sketch of the different luminous flux distributions around the luminaires due to the orientation of the installed luminaire heads. This distribution of luminous flux alters the expected luminance gradient such that the darkest patch is no longer across the road at the halfway point between the luminaires but rather shifted to the farthest point away from the luminaires towards the other side of the pavement. Therefore, brightest spots will now be obtained along Spot 1 and Spot 5, followed by Spot 2 and Spot 6 with the lowest luminance being obtained along Spot 4 and Spot 8. This shift in the expected luminance patches is confirmed by the measured spot luminances from the pavement surface which is shown in Table 30.

In order for the Transit New Zealand method to work effectively under such luminous flux distribution, more than 8 measurement spots may be required. Otherwise, the average of 8 spot measurements taken with a luminance meter will likely have a higher mean than the overall site average (between the luminaires) from photographic measurement method as is seen in Figure 40.

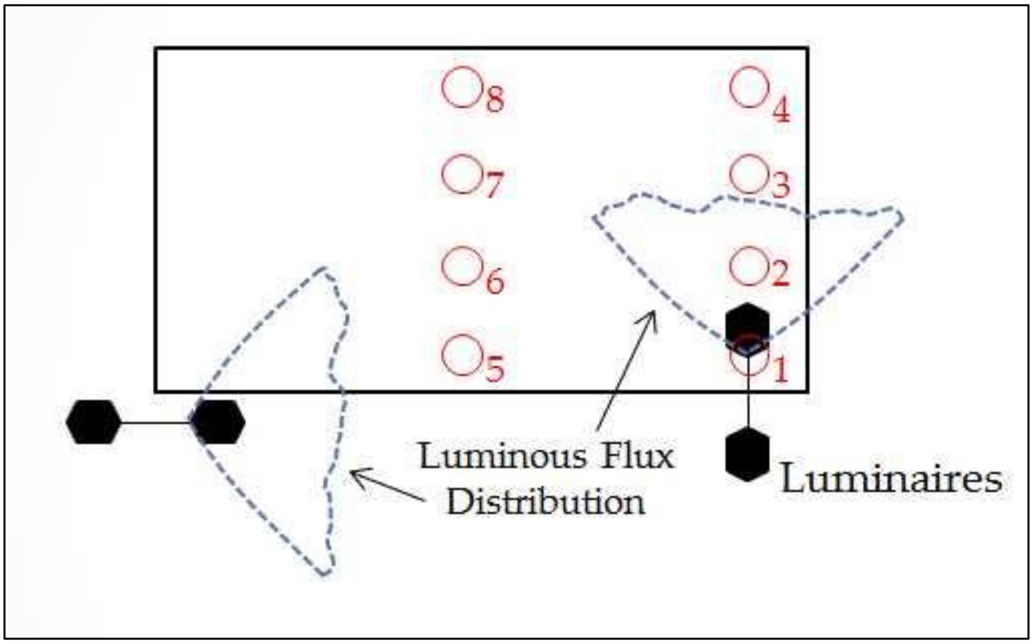


Figure 41 Distribution of Luminous Flux around the Luminaires along Asphalt Road Pavement.

Table 30 Luminance Spot Measurements from the SEB Test Site

Spot ID	**Luminance (cd/m^2)**
1	3.62
2	2.31
3	1.38
4	0.94
5	3.28
6	2.08
7	1.64
8	1.28

5.5 Additional Field Demonstrations

An application of this photographic method for luminance measurements was performed at a conventional 4-leg intersection in Cochran, GA (intersection of Sarah Street and East College Street). This intersection is located on the campus of Middle Georgia State College (MGSC). Figure 42 shows the nighttime images of the intersection. The numbers displayed on the images correspond to approach IDs. It can be seen from the images that the intersection area appears brightest from approach 2 and approach 3 while approach 1 and approach 4 appear to be equally less bright.

Four images at different exposure settings were taken per approach and luminance values based on the *Starlight2* and *LS-110* calibration curves were estimated for each image. Figure 43 shows the derived luminances for each of the four approaches. Starting from left to right the four blocks shown in Figure 43 corresponds to approach 1, 2, 3, and 4 respectively. For each approach and calibration curve the four data points represent the derived average luminance over the intersection (area bounded by crosswalks) from the four images/exposure settings. The relative luminances derived for the four approaches correspond well with the perceived brightness on the approach images.

Figure 42 Nighttime Images of Approaches to Intersection at Middle Georgia State College

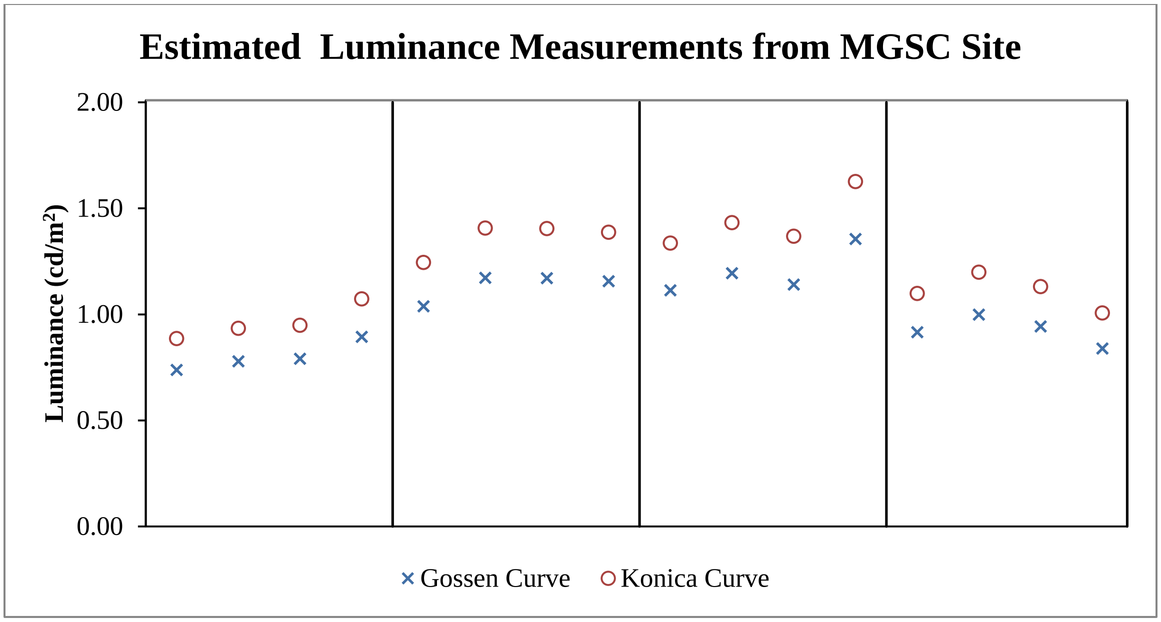


Figure 43 Estimated Luminances Measured from the Four Approaches to the Middle Georgia State College Site

Also, the usefulness of the developed method was further demonstrated in the ability to also use it to develop luminance contours or uniformity plots over an intersection. Figure 44(b) shows the picture of an intersection taken with the *T5* camera from a height of 30 feet. Average pixel intensity data was extracted for each grid cell and to account for the offset of the camera from the center of the intersection, each pixel intensity value was divided by the cosine of θ, where θ is the angle between the camera and the center of each grid cell on the road surface. Figure 44(a) shows the resulting plot of luminance contours for the intersection area bounded by the crosswalks. The contours where generated in R®, with the estimated average luminances for the grid cells.

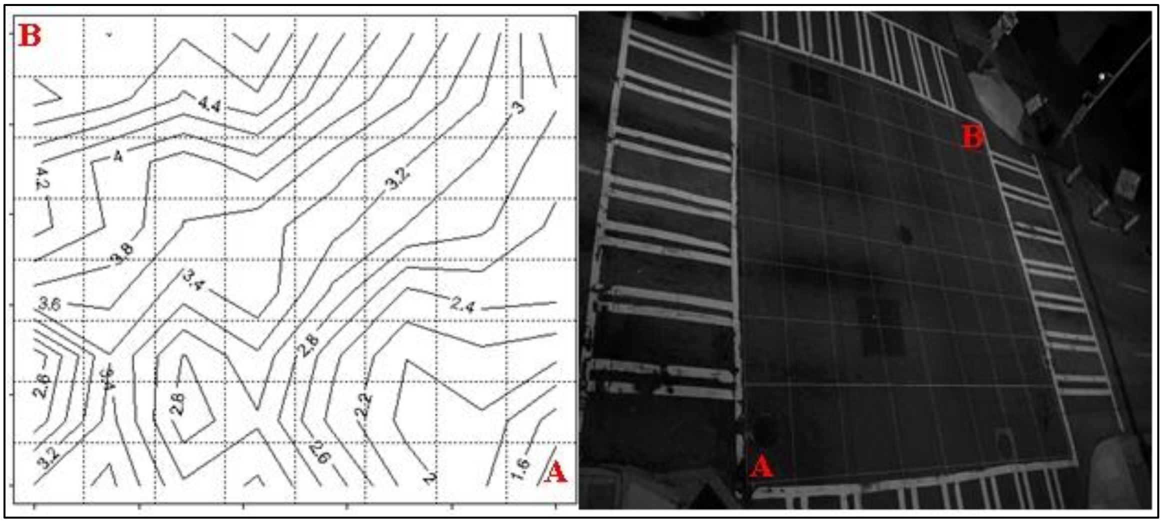


Figure 44 Plot of Luminance Contours within an Intersection Area
(a) Generated Contours over an Intersection Area
(b) Intersection Area with Overlaid Reference Grid

CHAPTER 6: APPLICATION OF INTERSECTION ILLUMINATION MEASUREMENT PROTOCOL IN CASE STUDY

Nighttime luminance measurements were performed at 60 conventional intersections and 44 roundabouts. Appendix B shows the list of these roundabouts and conventional intersections. Information on the physical features of intersections was obtained from Google Maps® and/or Google Earth®. Satellite images stored in Google Earth allowed the layout of intersections to be verified for each analysis year. Also, additional information on features of the intersections was obtained through a civil survey. Some of these features included posted speed limits, presence of intersection ahead warning signs, presence and width of sidewalks and shoulders, number and width of lane widths, presence of horizontal curves, and presence of rumble strips on intersection approaches.

The average intersection luminance was converted to the corresponding illuminance information using the equations developed by Uncu & Kayaku (Uncu and Kayaku 2010) and Fotios (Fotios et al. 2005) as discussed in literature review.

6.1Selection of Surveyed Roundabout Intersections

Almost all of the Georgia roundabouts surveyed as part of this study were identified through a search of the Kittleson Roundabout Database (Kittleson & Associates). The list was later supplemented with additional roundabouts identified through a search of a Georgia roundabout database (Schmitt 2013) developed by a former student at the School of Civil and Environmental Engineering at Georgia Tech. The following two filters were applied to obtain the final list of roundabouts. First all roundabouts which were constructed later than 2014 were dropped from the list. Next, a search was conducted in the GDOTs RC-LINK database for each roundabout and roundabouts that could not be found were also eliminated from the list. In addition, roundabouts that are in the RC-LINK database but have missing approach AADT were also omitted.

6.1.2 Selection of Surveyed Conventional Intersections

The conventional intersections were selected from areas around four cities; Dalton, Atlanta, Cochran, and Brunswick. The selection process for these intersections involved the steps described below.

6.2.2.1 GIS Analysis

First, an ArcGIS network file containing nodes within the Georgia road network was used to spatially analyze a shapefile of the Georgia road network to extract nodes (intersections) with appended names of connecting links (road segments). Next, duplicate nodes were eliminated and also nodes with either less than three or more than five connecting legs were eliminated.

Next a spatial buffer analysis of the file was then performed to select all intersections within 50 miles of the four cities. This buffer analysis was followed by a database analysis on the attribute table to further select only the nodes with at least one link on the state route network. Last, ArcGIS was used to extract the latitude and longitude of each intersection.

6.2.2.2 Google Earth Analysis

All the latitude and longitude pairs were then uploaded into Google Earth® and each of the intersection sites was visually checked to ensure that no interchanges or interchange terminals have been selected. Also, the streetview function in Google® Earth was used to check each approach up to about 400ft upstream of the stop line to collect information on posted speed limits. Additionally, streetview was used to identify and omit signalized intersections and intersections where all the legs are not paved. Signalized intersections were omitted because they would complicate the analysis for illumination impact. Also, intersections with unpaved legs were omitted because unpaved roads are associated with low levels of traffic exposure. Also, the streetview function was used to identify the layout of luminaires on the approaches as well as the presence of abutting buildings/facilities such as stores and gas stations which might unintendedly serve as other sources of lighting for drivers approaching the intersection.

All the intersections were then assigned to one of three illumination groupings based on the identified luminaire layout. The first illumination category is “None” and it refers to a site where there is no purposely-built street light on the approaches. Thus, a site with no fixed street lighting but a gas station located at the intersection corner with bright lights that illuminate parts of the intersection would still be considered “None”. The second category is “Partial” and it refers to a site where (a) some of the approaches have no installed lighting, (b) there are luminaires within 400 feet upstream of the intersection on the approach but no luminaire at the intersection itself or (c) lighting is provided at the intersection but there is none on the approaches. Last, “Full” illumination category applies to sites with installed fixed lighting on both its approaches as well as the intersection.

6.2.2.3 Entering Volume Analysis

The entering volume for each analysis year for each of the selected intersections was computed using the approach AADTs from the RC-LINK database. In order to accurately determine the entering volumes, all approaches with designated one-way roads needed to be identified. Also, it was important to note if a one-way leg was exiting or entering the intersection. AADT on exiting one-way roads were not included in the analysis while AADT on entering one-way roads were included without splitting the volume. AADT on two-way approaches were split into two and only one half was included in the analysis. The assumed 50/50 split was necessary because the actual split of traffic between the two directions on a two-way road was not available in the RC-LINK files.

The daily entering volumes (DEV) was computed for each intersection by summing all the approach AADTs. The computed DEVs were then used to assign each intersection an exposure code of “High” or “Low”. Intersections with DEV not exceeding 4000 vehicles were assigned to “Low”. Also, all locations with DEV less than 500 were omitted. This final filter resulted in a total of 148 candidate intersections.

Each of the 148 intersection had an illumination category code as well as a DEV code. Therefore, there were 6 unique combinations of None-Low, None-High, Partial-Low, Partial-High, Full-Low, and Full-High. Next, 10 intersections were randomly selected from each of these combination groupings to obtain a final selection total of 60 conventional intersections.

6.2 Training and Field Data Collection

Data collection at the 60 conventional intersections was handled by an external data collection team while the data collection at the roundabouts was done by the author. Before the external team commenced, they were trained in the proper handling and set up of the equipment as well as identification and recording of intersection safety features.

6.2.1 Training the Data Collection Team

The training for the data collection team included one 3-hour in-class training session, five supervised field setups and data collection activities, and two unsupervised field data collection exercises. To facilitate these training sessions, two technical documents on field deployment for the nighttime luminance surveys and daytime civil survey for intersection safety influencing features were produced. These documents are attached as Appendix C and Appendix D respectively.

All the training sessions were held at Middle Georgia State College (MGSC) in Cochran GA. The in-class and supervised field setups and data collection exercises were all done on March 20, 2015. The two unsupervised data collection sessions were done over two days; one on March 30, 2015 and the other on March 31, 2015. The results of the unsupervised data collection were used to provide a final feedback to the external data collection team.

6.2.2 Summary Steps for Luminance Data Collection

A summary of the activities required for successful nighttime data collection in the field is provided below in the bulleted list. The list must be repeated for each intersection leg. See Appendix C for the detailed documentation on the nighttime luminance data collection procedure.

- Mount the camera on a tripod and set it up on the edge of the road, away from the active travel lanes, at a distance of 38 meters from either the intersection stop line or corner. The camera must be at a height of 1.24 meters. This ensures that the observation angle to different areas of the intersection falls within 0.5^o and 2^o (International Commission on Illumination 1976; International Commission on Illumination 2000; Nicholas 1991).
- Orient the camera so that the intersection area is centered in the view with enough room around it. The intersection area must not fill the whole image.
- Take pictures of the intersection at any two of these apertures; F3.5, F4.0, F4.5, and F5.0. For each selected aperture, adjust the shutter speed so that at an image each can be captured from any two of the following underexposed exposure levels at -2.0, -3.0, or -4.0.
- Underexposed nighttime images of an intersection can be too dark to allow correct identification of the intersection layout for image analysis. Therefore, one or two images in the overexposed range, say at +1.0 and/or +2.0 should also be captured.

CHAPTER 7: DEVELOPED PROTOCOL FOR IDENTIFYING INTERSECTION RELATED CRASHES

7.1 Overview of the crash data

GDOTs crash database contains about 46 sub datasets which can be electronically merged through the incident ID variable. One of these datasets is the incident file. The incident data file primarily contains information on incident ID, incident date, incident location variables (city, county, latitude, longitude), main road on which crash occurred, nearest intersecting road, distance to nearest intersection, and a variable indicating whether the crash occurred at an intersection, near an intersection, at an interchange, or on a private property. The narrative data file contains information on incident ID and crash description as recorded by the investigating police officer.

Similar to most crash databases, the GDOT database has a lot of data quality issues, chief amongst them are missing variable information and wrongly entered information. Identification of incident records with missing variable information can be easily accomplished with a simple database query. However, deciphering the incident records with wrongly entered data required a rigorous QAQC strategy. Table 31 shows the number of missing records for selected data variables in the 2009 – 2014 crash data used in this study.

Table 31 Missing Records for Selected Variables in Available 2009 – 2014 Crash Data

Crash Data Variable	Number Missing
Latitude/Longitude	530,713
Incident date	0
Information for road on which crash Occurred	6,180
Information for nearest intersecting road for crashes occurring at or near an intersection	294,507
Distance from Nearest intersection for crashes occurring at or near an intersection	108,841

7.2 QAQC Strategies

A meticulous QAQC strategy was used to determine the best way to match crashes to intersections. Both automated matching and manual matching were explored. The manual approach was eventually adopted because it offered the least potential of wrongly matching crashes and intersections.

7.2.1 Initially Explored Automated Matching Approaches

Different automated approaches for matching crashes to intersections were explored with each approach either tightening or relaxing the requisite conditions for a successful match. A database of the latitude/longitude, county FIPS code, road names, alternate road names, prefixes, suffixes, and road number(s) (where applicable) was developed for all the study’s intersections These were used by Perl® scripts to pattern match similar information contained from the incident file. The main variables from the incident file used in the pattern match tests are the road on which a crash occurred and the nearest intersecting road, and the indicated distance of the crash location from the nearest intersection. All the script explorations were performed with crashes that have been pre-coded in the incident files as occurring at or near an intersection. A buffer distance requirement was also explored based on distance between latitude/longitude of crashes and study's intersections. In all a total of nine different scripts were explored. Table 32 shows the number of total crashes that were matched to intersections by the most relevant scripts while Table 33 shows the same results for only nighttime crashes.

Table 32 Total Crashes Matched to Intersections by Different Exploratory Scripts

Script ID	Pattern Matching Requirement	All Intersections	Conventional Intersections	Roundabout Intersections
1	[Primary Road OR Secondary Road] AND county code	52,985	29,100	23,885
2	[Primary Road AND Secondary Road] AND county code	1,993	1,065	928
3	County code AND [buffer dist.]	572	301	271

Table 33 Nighttime Crashes Matched to Intersections by Different Exploratory Scripts

Script ID	Pattern Matching Requirement	All Intersections	Conventional Intersections	Roundabout Intersections
1	[Primary Road OR Secondary Road] AND county code	36,528	20100	16,428
2	[Primary Road AND Secondary Road] AND county code	1,332	694	638
3	County code AND [buffer dist.]	377	201	176

Next, a quick manual check was performed on selected results from the more exact pattern matching in Script #2. Five roundabouts and five conventional intersections were selected from each group such that each group included a location with:

(a) AADT closest to the mean of the group.

(b) AADT closest to the upper 95% mean of the group.

(c) AADT closest to the lower 95% mean of the group.

(d) AADT one standard deviation higher than the mean of the group.

(e) AADT one standard deviation lower than the mean of the group.

Table 34 and Table 35 respectively show the number of crashes selected with Script #2 and the number selected from this quick manual check. The results indicated that a manual matching approach could yield significantly different results.

Table 34 Comparison of Number of Crashes Matched to Selected Roundabouts by Automated Script and Manual Analysis

	Selection Criteria	AADT	Original Number of Crashes	Number of Crashes after Checks
1	Closest to Mean	7,369	16	11
2	Closest to Upper 95% Mean	9,232	15	2
3	Closest to Lower 95% Mean	5,506	0	10
4	One Std. Dev. Above Mean	13,116	48	50
5	One Std. Dev. Below Mean	1,622	3	2

Table 35 Comparison of Number of Crashes Matched to Selected Conventional Intersections by Automated Script and Manual Analysis

	Selection Criteria	AADT	Original Number of Crashes	Number of Crashes after Checks
1	Closest to Mean	5094	0	0
2	Closest to Upper 95% Mean	6233	31	19
3	Closest to Lower 95% Mean	3955	3	0
4	One Std. Dev. Above Mean	9226	0	0
5	One Std. Dev. Below Mean	962	0	0

7.2.2 Adopted Manual Protocol for Matching Crashes to Intersections

The adopted manual protocol used to identify the intersection related crashes from the incident files is conceptually structured as a decision making tree with 16 branches. Each branch ends in a decision concerning a unique data quality condition. The crash data for use in this manual protocol was preselected with the automated Script #1 which yields the largest possible set of candidate crashes. Table 36 shows the decision logic for identifying intersection related crashes. Table 37 explains the decision codes shown in Table 36.

Table 36 Decision Logic for Developed Manual Protocol Used to Identify Intersection Related Crashes

Does Roadway Name or Number for Crash Location Match Intersection?	Does Intersecting Road Name or Number Match Intersection?	Is Lat. & Long. Data for Crash Location Available?	Is Distance from Nearest Intersecting Road Available?	Decision Code
Yes	Yes	Yes	Yes	MLD
Yes	Yes	Yes	No	L
Yes	Yes	No	Yes	D
Yes	Yes	No	No	AP
Yes	No	Yes	Yes	L
Yes	No	Yes	No	L
Yes	No	No	Yes	APM or RFN
Yes	No	No	No	APM or RFN
No	Yes	Yes	Yes	L
No	Yes	Yes	No	L
No	Yes	No	Yes	APM or RFN
No	Yes	No	No	APM or RFN
No	No	Yes	Yes	L or APBM
No	No	Yes	No	L or APBM
No	No	No	Yes	APBM or RFBN
No	No	No	No	R

The decision to accept a crash as intersection related depends on whether the value of distance from the nearest intersection variable in the incident file or the estimated distance between crash location and intersection based on their respective latitudes and longitudes fall within a given buffer distance. A distance of 250 feet was used for conventional intersections while a distance of 325 feet was used for roundabouts. The roundabout buffer assumes an average inscribed diameter of 150 feet; thus half the diameter plus the standard 250 feet buffer.

Table 38 shows the decision tree and the percentage distribution of roundabout crash records among the 16 branches before the recommended decisions were applied. It can be seen from Table 38 that at least 25 percent of the potential roundabout crash records would need further checking of the accident reports.

Table 37 Explanation of Decision Codes

Decision Code	**Explanation**
MLD	Decision is based on minimum of either distance between lat. & long. values or the distance from nearest intersection value
L	Decision is based on distance between lat. & long. values
D	Decision is based on the distance from nearest intersection value
AP	Check the accident report if there is information on either lat. & long. or distance from nearest intersection. Reject if information is missing.
APM	Check the accident report if the unmatched road information is actually missing from the incident file
APBM	Check the accident report if the information for the unmatched roads are actually missing from the incident files
RFN	Reject crash record if the unmatched road information is not missing but just does not match the corresponding intersection values or the accident report is not available for further checking
RFBN	Reject crash record if the information for the unmatched roads are not missing but they just don’t match the corresponding intersection values or accident report is not available for further checking
R	Reject the crash record

Table 38 Distribution of Roundabout Crashes Among Decision Tree Branches

Does Roadway Name or Number for Crash Location Match Intersection?	Does Intersecting Road Name or Number Match Intersection?	Is Lat. & Long. Data for Crash Location Available?	Is Distance from Nearest Intersecting Road Available?	Decision Code	Distribution of Roundabout Crash Records
Yes	Yes	Yes	Yes	MLD	10.7%
Yes	Yes	Yes	No	L	0.1%
Yes	Yes	No	Yes	D	1.6%
Yes	Yes	No	No	AP	0.2%
Yes	No	Yes	Yes	L	20.1%
Yes	No	Yes	No	L	1.1%
Yes	No	No	Yes	APM or RFN	7.4%
Yes	No	No	No	APM or RFN	1.1%
No	Yes	Yes	Yes	L	16.1%
No	Yes	Yes	No	L	0.8%
No	Yes	No	Yes	APM or RFN	4.7%
No	Yes	No	No	APM or RFN	0.5%
No	No	Yes	Yes	L or APBM	23.4%
No	No	Yes	No	L or APBM	0.6%
No	No	No	Yes	APBM or RFBN	11.3%
No	No	No	No	R	0.5%

CHAPTER 8: APPLICATION OF INTERSECTION RELATED CRASH IDENTIFICATION PROTOCOL

The developed manual protocol for identifying intersection related crashes was applied to the GDOT crash data and the results were compared with similar results obtained by automated matching with Script #2. During this dissertation, the accident reports for the incidents analyzed were not available to aid in further checking where recommended by the developed manual protocol. Consequently, the decision codes of AP, APBM or APM defaulted to the corresponding reject options of R, RFBN and RFN respectively. However, this should not greatly impact the ability of the study to be informative, although future study is needed to confirm the impacts of these assumptions.

Figure 45 shows the results of the comparison. The results showed that the manual protocol selected 62 percent fewer candidate intersection related crashes compared to the automated Script #2. Also, the number of crashes identified by both the automated Script #2 and the developed manual protocol formed only about 26 percent of the candidate crashes selected by script #2. Therefore, the manual protocol rejected 74 percent of the candidates selected by script #2 but it also found about 12 percent more crashes that script #2 could not identify.

Total number of roundabout and conventional intersection crashes identified are 406 and 349 respectively.

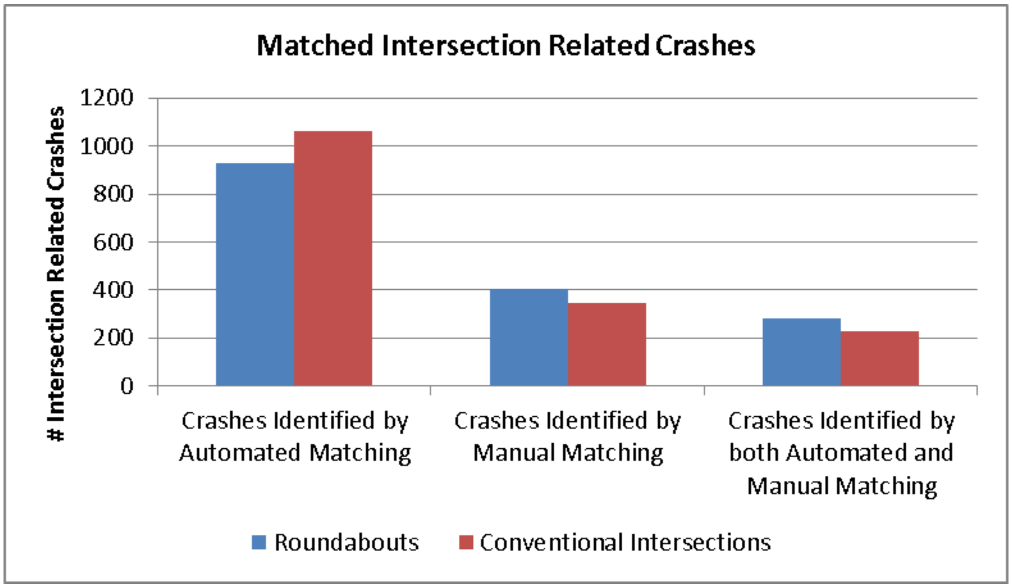


Figure 45 Comparison of Intersection Related Crashes Identified by Automated Matching and the Developed Manual Matching Protocol

CHAPTER 9: ANALYSIS, RESULTS, AND DISCUSSION OF CASE STUDY IN GEORGIA

9.1 Nighttime Luminance and Intersection Feature Surveys

This section presents the results of an analysis of roundabout crash and illumination data. The results for a similar analysis for the conventional intersections will be included in a GDOT report.

Only 37 out of the 44 selected roundabouts could be surveyed; four were omitted due to safety reasons, two were omitted because they lacked a raised central island, and one was omitted because it is located at an uncompleted mall site. Two locations in the original list of conventional roundabouts were converted into roundabouts within the analysis period. Therefore, these were added to the list of roundabouts to make a total of 39 roundabouts available for inclusion in this case study. Please see Appendix F for maps showing the location of each intersection as well as satellite images giving the full layout of each intersection.

Intersection luminances were obtained by first extracting the pixel information from the images with the help of ImageJ® (Schneider et al. 2012) and then converting the pixels with the calibrated camera response equations as outlined in Section 5.4.3. Next, the luminance values were transformed into the illuminance equivalents according to Equation 21 Section 2.5.4. An average pavement reflection quotient of 0.145 and 0.27 was used for asphalt and concrete pavements respectively. Appendix E shows how to use

ImageJ® macros to automate the pixel extraction analysis. Figure 46 shows a plot of the derived illuminances at both roundabouts and conventional intersections.

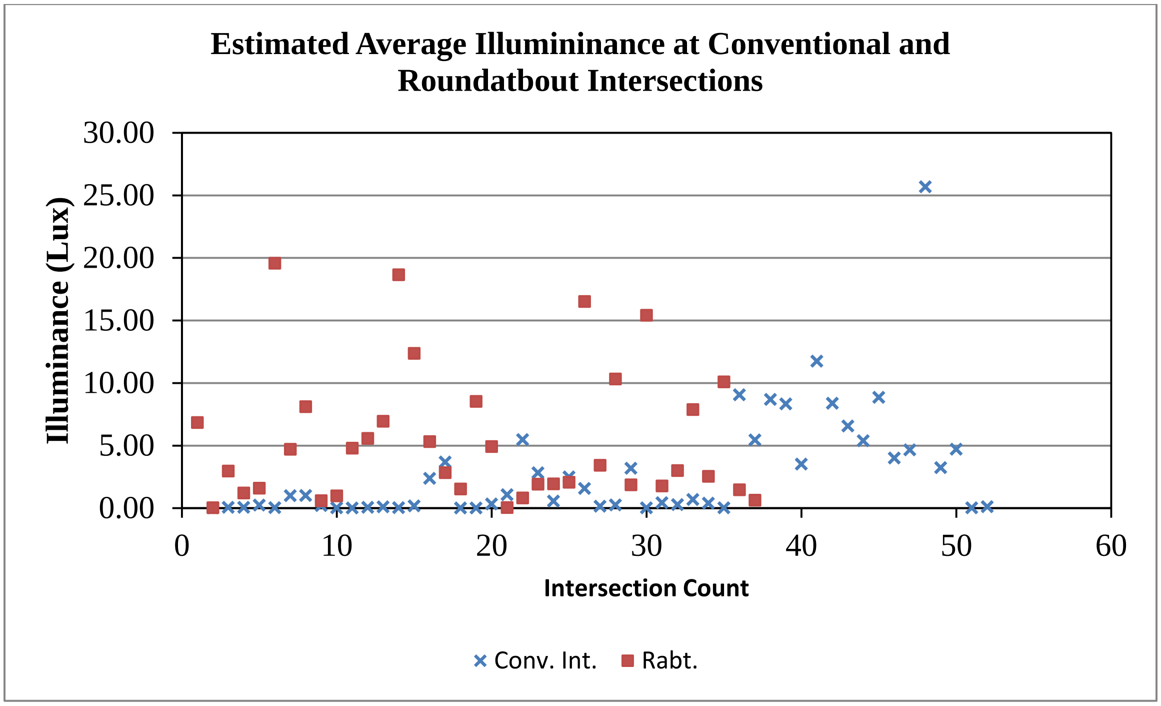


Figure 46 Estimated Intersection Illuminances

9.2 Correcting for Possible Trend Effects

Georgia crash rates have been reducing over the years. Figure 47 presents a plot of annual Georgia crash rates (per 100 million VMT) from 2007 to 2014. This downward trend may be due to many factors including better vehicle designs, improved geometric designs of roads, better driver education, and better road signage. These factors could introduce a temporal correlation into estimated crash rates. It has been argued (Donnell et al. 2010) that when crash data is treated as non-panel data (i.e., crash data is summed for an intersection over the whole project period rather than creating individual annual sums) issues of temporal correlation might not be an issue. However, this dissertation corrected for possible temporal correlation even though the data is treated as non-panel data. A Bayesian approach was used to develop crash frequency adjustment factors based on annual crash rates normalized to the 2014 general Georgia crash rate. Georgia highway statistics was obtained from the Governor’s Office of Highway Safety program (Georgia Governor's Office of Highway Safety) and used with a linear regression model to obtain predicted annual crash rates which were normalized to 2014. The normalized annual rates where used as the BCFs. Table 39 presents the Georgia highway safety statistics data and the estimated Bayesian Correction Factors.

Table 39 Georgia Highway Safety Statistics and Estimated Bayesian Corrected Factors

Year	Total (Fatal and Injury)	Annual VMT (Millions)	Crashes / 100M VMT	Estimated Crash Rate / 100 M VMT	Bayesian Correction Factor
2007	129,956	112541	115.4743605	111.1837	0.92
2008	117,373	109057	107.6253702	109.8528	0.93
2009	124,253	109258	113.7243955	108.5219	0.94
2010	111,379	111722	99.69298795	107.191	0.95
2011	105,755	108454	97.51138732	105.8601	0.96
2012	116,810	107488	108.672596	104.5292	0.97
2013	117,637	109167	107.7587549	103.1983	0.99
2014				101.8674	1

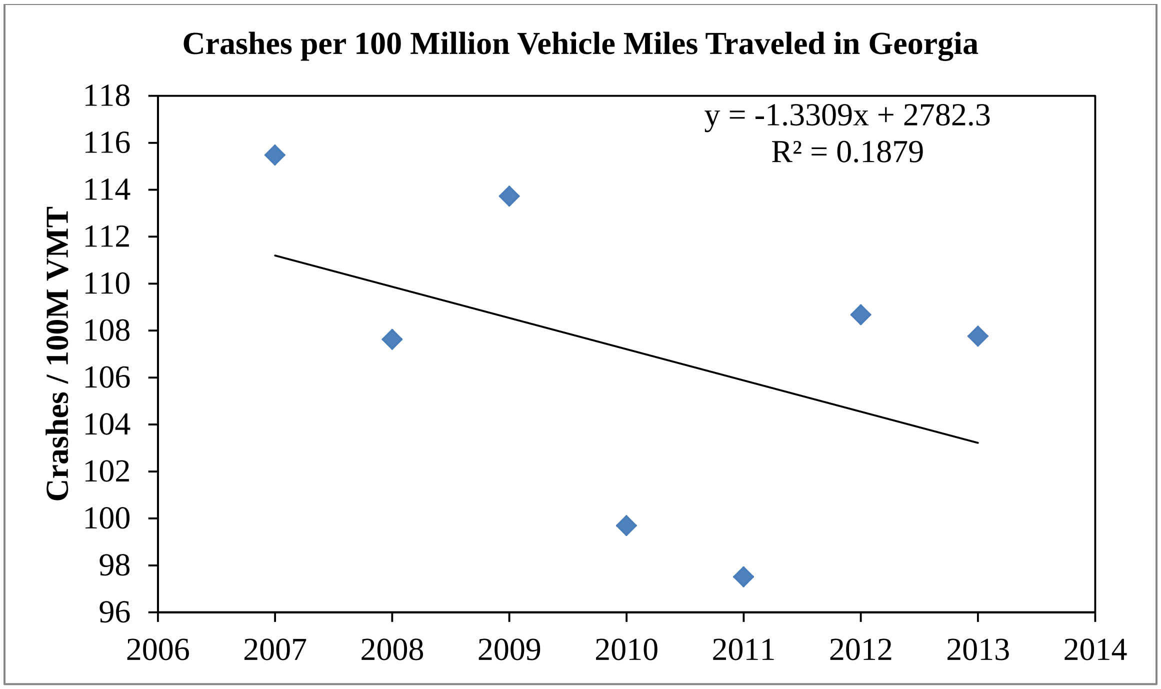


Figure 47 Number of Crashes per 100 Million VMT in Georgia

9.4 Potential Issues Affecting Nighttime Crash Analysis

There are a couple of issues noted with this study that could potentially confound the findings of crash rate or expected crash frequency analysis. These issues could not be fully addressed in this case study of roundabouts in Georgia. Therefore, the results from the crash analysis must be cautiously interpreted or applied.

9.4.1 Limited Number of Crashes

Overall there weren't enough crashes recorded over the study period to undertake a comprehensive study. There were only 406 crashes at the 39 roundabouts over the 6 year analysis period. Moreover, most of the roundabouts were within residential areas and had to be omitted from the analysis. This resulted in a total of 18 roundabouts with

223 nighttime and 109 daytime crashes. All of these 18 roundabouts were used in the trend analysis showing variation in observed average intersection illumination with different intersection characteristics. Also, due to concerns with the quality of traffic data, roundabouts with average entering AADTs less than 10,000 were not included in the crash analysis. In all a total of 10 roundabouts with 174 nighttime crashes and 94 daytime crashes within the analysis period were used for the subsequent analysis.

9.4.2 Possible Selection Bias

There are a couple of selection bias issues which could possibly confound the results of the crash rate and expected crash frequency analysis.

9.4.2.1 Conventional Intersections versus Signalized Intersections

One of the three crash experience warrants for signalizing conventional stop-control and uncontrolled intersections requires that “Five or more reported crashes, of types susceptible to correction by traffic signal control, have occurred within a 12-month period, each crash involving personal injury or property damage apparently exceeding the applicable requirements for a reportable crash” (McGee et al. 2003). Since this work does not consider signalized intersections there exist a potential selection bias in that only the intersections with a “good” crash experience have been considered in this work. This can under estimate the potential safety impacts of illumination at conventional intersections compared to roundabouts.

9.4.2.2 State Route versus Non-State Route

The conventional intersections considered in this work are those with at least one intersecting road designated as a state route or county highway while the roundabout selection criteria did not include this provision. In addition, this work does not include any conventional intersections at an interchange. These selection criteria will impact our ability to estimate the mean values for the full population of intersections as well as potentially impacting the comparison between the roundabouts and conventional intersections.

9.4.2.3 Roundabout Installation Policy

A traffic safety countermeasure such as a roundabout is normally applied to a site with a recent or proportionately higher crash rate. However, it is not known if any such an installation bias exists in the roundabout locations used in this study associated with GDOTs roundabout installation policy. This selection bias, if it exists, would imply that efforts must be made to separate the safety effects of roundabouts from any additive benefits due to illumination.

Also, for states such as Georgia which are making significant public education efforts to improve road user acceptance of roundabouts, it is possible that roundabouts installations will be deliberately avoided at locations where the initial experience might provoke public resistance to roundabouts in general. Should a roundabout “good will” policy exist, intentionally or otherwise, it could introduce a possible selection bias into the analysis.

9.4.2.4 Georgia Roundabouts are Generally New

Most roundabouts in Georgia where built no earlier than 2005 and majority of the roundabouts used in the case study were built even later. This might mean that roundabouts generally incorporate the best design values and roadway elements such as signs and markings. Consequently, they are “corrected problems” which might contribute to their observed effectiveness compared to other older intersections.

9.4.2.5 Illumination Policy

It is also unknown if any sampling bias exists in the lighting policy, e.g., lighting was placed on roundabouts with a higher likelihood of incidents. Also, warrants for lighting are usually applied with other operational considerations so other safety influences may be influencing the results.

9.4.2.6 Recording of Accident by Police Officers

Accident recording forms used by police departments are generally made for conventional intersections and it is unknown how the difference in geometrical layout of roundabouts and conventional intersections impact estimation of ‘distance from nearest intersection’, which is a key crash analysis variable. ‘Distance from nearest intersection’ refers to the distance between crash location and the nearest intersection.

Conventional intersections usually have small widths and some police departments might use either the center of the intersection or the stop line on the approach to determine this distance. On the other hand, roundabouts may have a large diameter and it is possible that some police departments use the middle of the center island, the entry/exit point at the circulatory lane, or yet still the start point of the splitter island upstream of the entry/exit point on the approach to determine the ‘distance from nearest intersection’. Furthermore, the length of the splitter island can vary significantly. These issues can influence the number of intersection crashes identified based on the assumed with of the intersection influence area.

9.4.3 Treatment of Selection Bias in Illumination and Safety Studies

In order to address issues of selection bias in highway safety analysis previous studies (Bo et al. 2009; Hauer 1997; Hauer 2005; Persaud and Lyon 2007) have proposed Bayesian before-and-after studies in which the observed effect of a treatment is compared to an estimate of the expected number of crashes that would have occurred if the treatment had not been applied. However, these empirical Bayesian approaches require information on illumination installation dates which is often unavailable.

Therefore, researchers such as (Bhagavathula et al. 2015; Donnell et al. 2010) have used negative binomial regression models that permit the controlling of other safety influences. The main challenge with this approach is the availability of data variables that describe each confounding attribute or additional safety feature that needs to be controlled.

9.5 Analysis of Roundabout Crashes

9.5.1 Observed Variation in Average Illuminance with Crash Rates

As explained prior the roundabout nighttime crash rate analysis included only roundabouts with AADT of at least 10,000 entering vehicles. It was observed that nighttime crash rate at locations with higher average illumination was smaller than at locations with lower average illumination. Figure 48 presents the observed relationship between nighttime crash rate and average illumination level for these roundabouts.

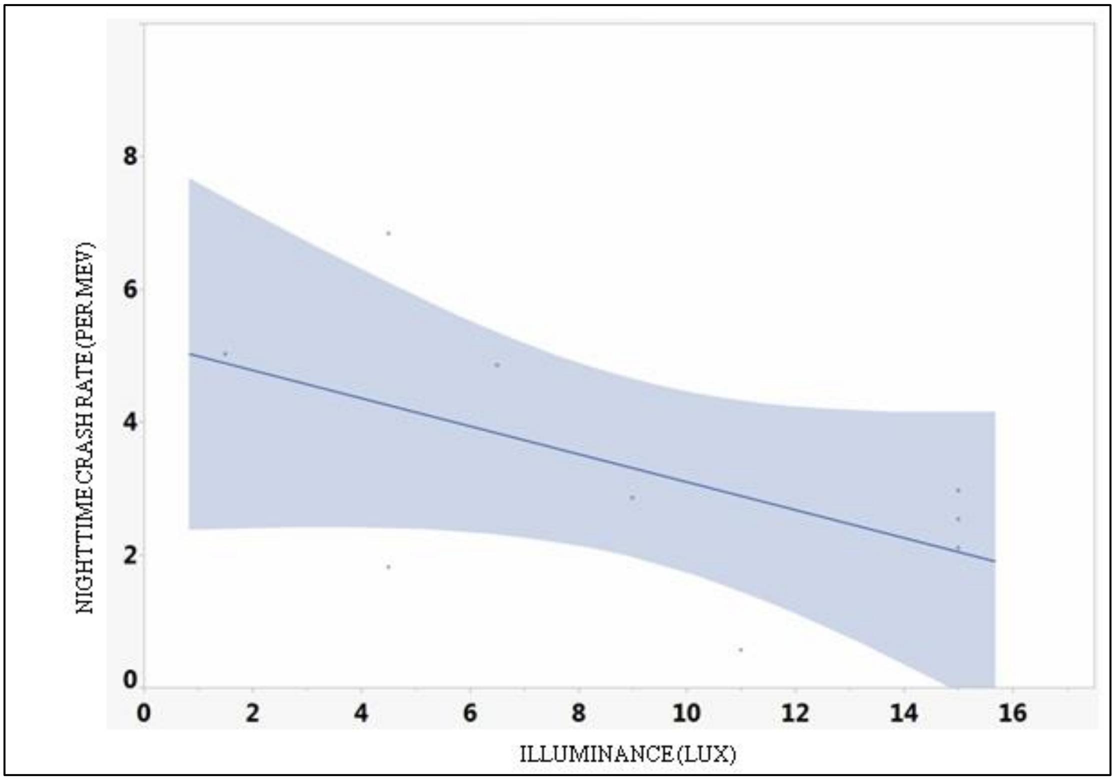


Figure 48 Variation in Nighttime Crash Rate with Illuminance at Roundabouts with at least 10,000 AADT

9.5 2 Estimating a Potential Roundabout Illumination Crash Modification Factor

Despite the data limitation and the potential issues of selection bias it is expected that the model results and estimated quantitative roundabout illumination crash modification factor will provide meaningful initial insights on the impact of illumination level on nighttime safety at roundabouts until future efforts can address the underlying data availability and selection bias issues.

In line with other published studies this dissertation uses a multivariate negative binomial regression to mode to estimate the change in the expected number of nighttime crashes and the associated illumination crash modification factor for roundabout locations with at least 10,000 AADT. The model was built using the SAS® University Edition statistical package.

Table 40 presents the results of the full model while and Table 41 presents the results of the null model. The directions of the parameter estimates in the full model indicate that increasing illuminance by 1 lux, changing from a 3-leg to 4-leg roundabout, and locating a roundabout on a state road all have the effect of decreasing the expected number of nighttime crashes. On the other hand, changing the upstream approach speed limit from a value below 45 mph to one that is at least 45 mph or increasing the intersection skew angle to a value that is at least 20 degrees all have the effect of increasing the expected number of crashes at the studied roundabouts.

A Chi-Square value -20.72 for the full model compared to the null model was estimated as shown in Equation 30:

$$X^2 = -2 * \left(LL_{full\ model} - LL_{null\ model}\right) = -20.72 \ldots \ldots (30)$$

Therefore, with 5 degrees of freedom the full model has a *p-value* of 0.000915. This implies that the full model is very significant. The expected percentage change in the expected number of crashes due to a 1 lux increase is -4.72 percent as has been shown in Equation 31.

$$100 * \left(e^{\beta_n} - 1\right) = e^{-0.0483} - 1 = -4.72\% \text{ .... } (31)$$

Table 40 Full Model Results

Analysis Of Maximum Likelihood Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	3.3477	0.2768	2.8051	3.8903	146.24	<.0001
Illuminance	1	-0.0483	0.0149	-0.0776	-0.0191	10.47	0.0012
Four_Legs (4legs = 1)	1	-1.0691	0.3344	-1.7246	-0.4137	10.22	0.0014
Road_Type (State Rd = 1)	1	-1.4108	0.3786	-2.1528	-0.6688	13.89	0.0002
Posted_Speed (at least 45 = 1)	1	1.0618	0.3297	0.4157	1.7080	10.37	0.0013
Skew_Angle ..(at least 20 =1)	1	1.5277	0.2403	1.0567	1.9988	40.40	<.0001
Dispersion	1	0.0100	0.0237	0.0001	1.0601		

Criteria for Assessing Goodness of Fit

Criterion	DF	Value	Value/DF
Deviance	4	9.1803	2.2951
Scaled Deviance	4	9.1803	2.2951
Pearson Chi-Square	4	9.7265	2.4316
Scaled Pearson Chi-Square	4	9.7265	2.4316
Log Likelihood		363.3450	
Full Log Liklihood		-27.4101	
AIC (smaller is better)		68.8202	
AICC (smaller is better)		124.8202	
BIC (smaller is better)		70.9383	

Model Information

Distribution	Negative Binomial
Link Function	Log
Number of Observations Read	10
Number of Observations Used	10

Note: The negative binomial parameter was estimated by maximum likelihood

Table 41 Null Model Results

Analysis Of Maximum Likelihood Parameter Estimates							
Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept	1	2.8528	0.2332	2.3957	3.3099	149.63	<.0001
Dispersion	1	0.4862	0.2319	0.1909	1.2385		
Criteria for Assessing Goodness of Fit							
Criterion				DF	Value		Value/DF
Deviance				9	10.5391		1.1710
Scaled Deviance				9	10.5391		1.1710
Pearson Chi-Square				9	11.6716		1.2968
Scaled Pearson Chi-Square				9	11.6716		1.2968
Log Likelihood					352.9860		
Full Log Liklihood					-37.7692		
AIC (smaller is better)					79.5384		
AICC (smaller is better)					81.2527		
BIC (smaller is better)					80.1435		
Model Information							
Distribution				Negative Binomial			
Link Function				Log			
Number of Observations Read				10			
Number of Observations Used				10			
Note: The negative binomial parameter was estimated by maximum likelihood							

9.6 Observed Variation in Illumination by Different Intersection Characteristics

A civil survey was used to collect information on different conventional intersection and roundabout characteristics. The observed average illumination at the roundabouts were analyzed against some of these characteristics to identify any possible trends.

9.6.1 Observed Variation in Illuminance with AADT

Roundabouts with higher average entering AADTs were observed to have higher installed illuminance levels. This may be an indication that illumination is being used as a safety treatment since higher AADTs usually imply higher risk of crash occurrence. Figure 49 presents the plot for average roundabout illuminance and AADT.

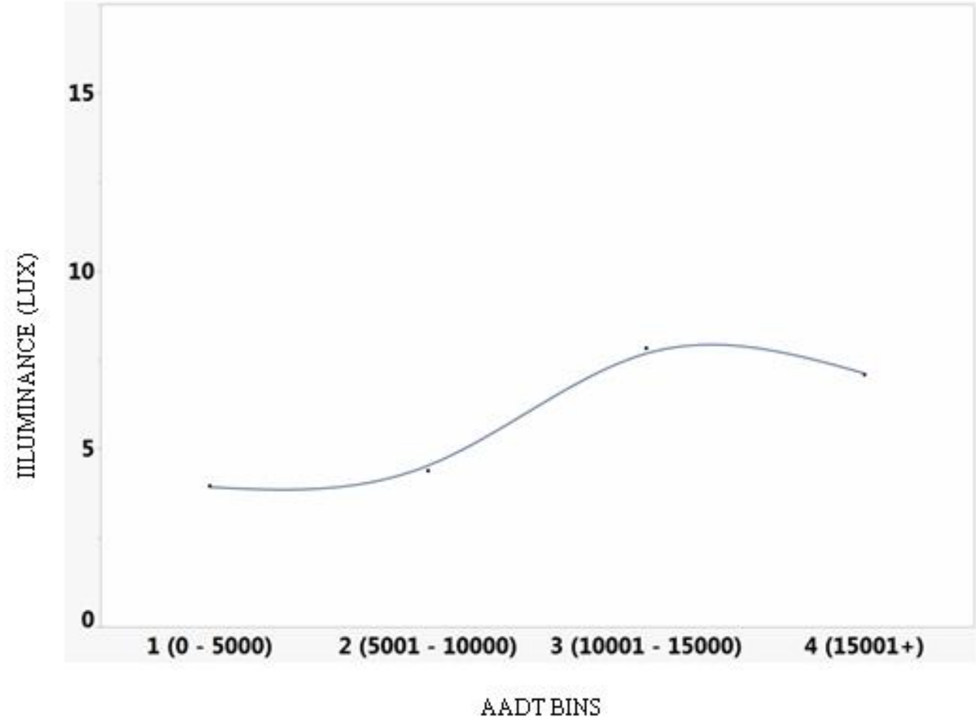


Figure 49 Variation of Illuminance with AADT at Roundabouts

9.6.2 Observed Variation in Illuminance with Upstream Approach Posted Speed

The variation of illuminance with posted upstream speed, checked within 400 feet of the roundabout yield or stop line, was also evaluated. The analysis shows that higher speed roundabout locations were associated with higher average illuminance as can be seen from Figure 50

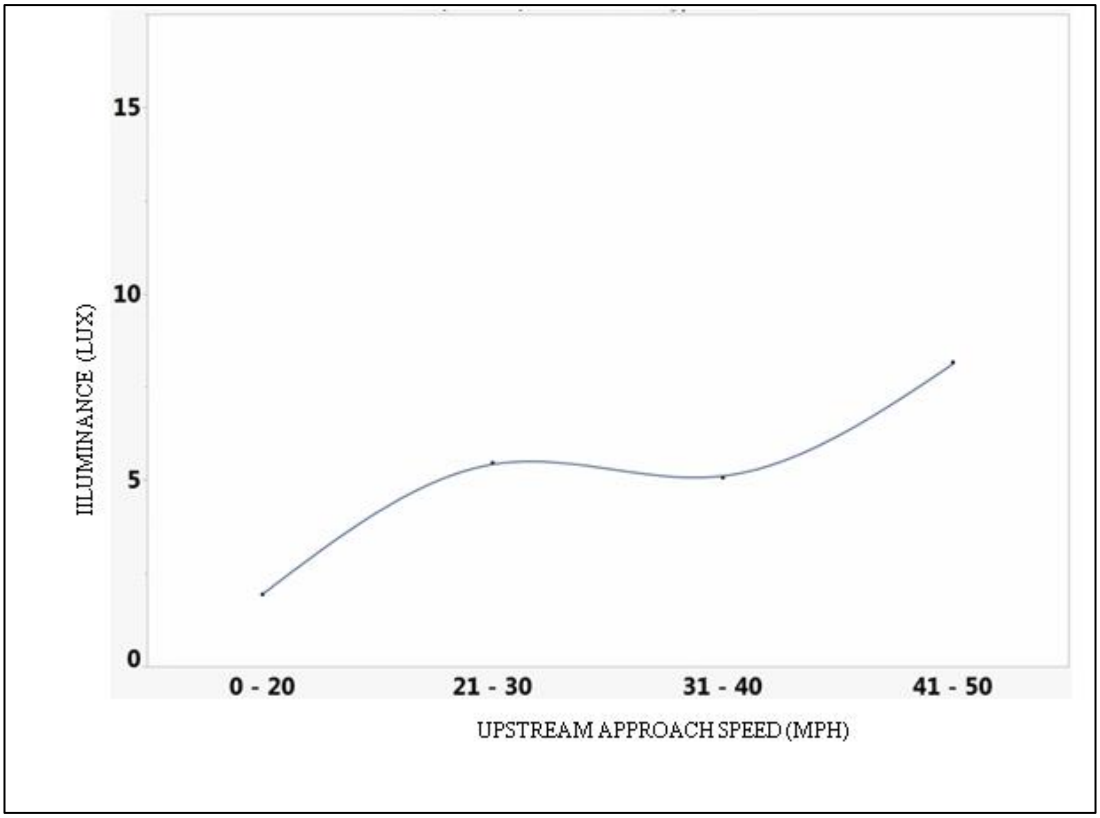


Figure 50 Variation of Illuminance with Upstream Approach Posted Speeds at Roundabouts

9.6.4 Observed Variation in Illuminance with Skew Angle

Skew angles can negatively impact the ability of drivers to properly visualize the layout of an intersection. It was observed that skew angle seemed to have a step effect rather than a continuous effect. This is probably due to the available data. Higher average illuminance was observed at roundabout locations with a skew angle of 20 and more. Figure 51 shows the results for illuminance variation with skew angle at roundabouts.

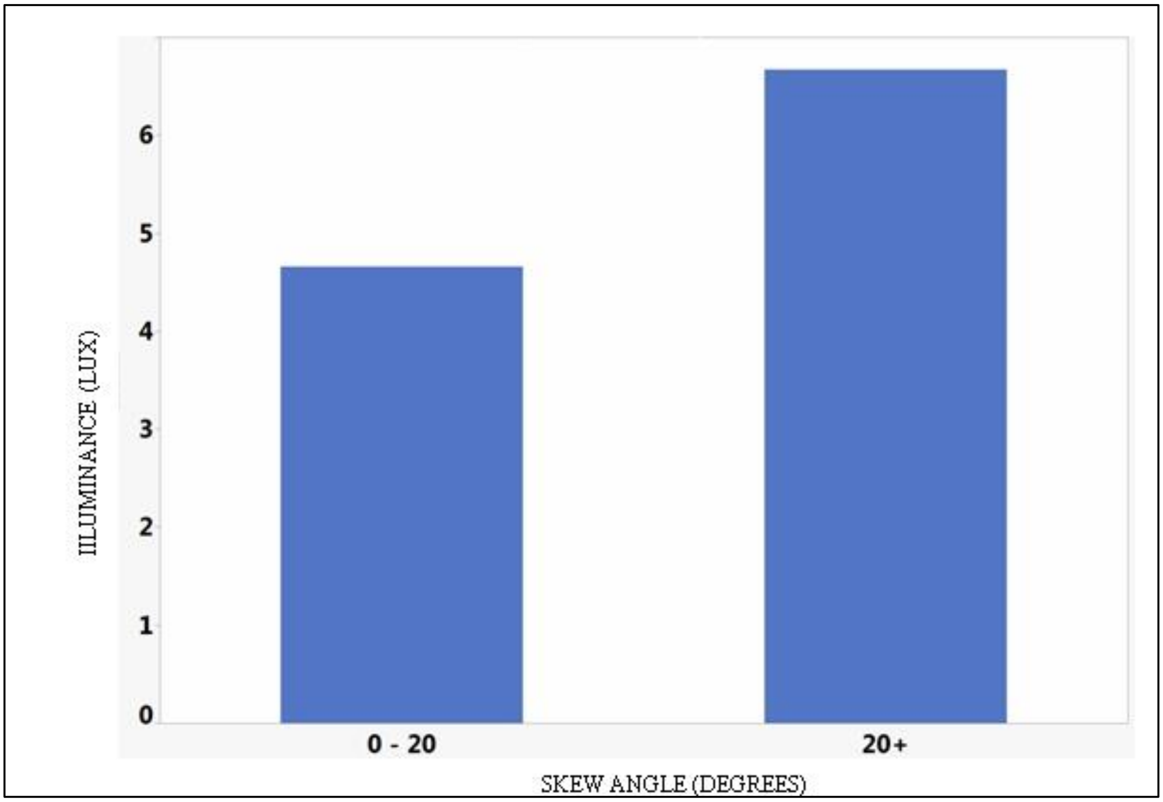


Figure 51 Variation in Illuminance with Skew Angle at Roundabouts

9.6.6 Observed Variation in Illuminance with Number of Intersection Legs

Figure 52 shows that there may be an association between observed average illuminance and the number of intersections legs. Roundabouts with at least 4-legs were observed to have higher illuminance levels than those with 3 legs.

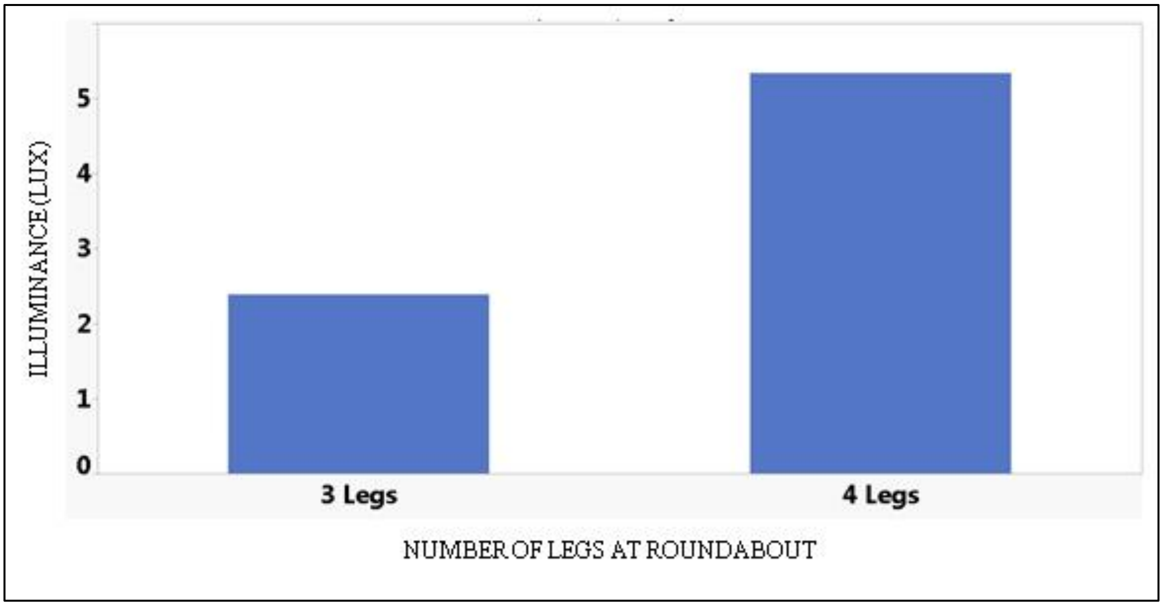


Figure 52 Variation of Illuminance with Number of Legs at Roundabouts

CHAPTER 10: CONTRIBUTIONS, LIMITATIONS, AND FUTURE WORK

10.1 Contributions

This work makes multiple contributions to current knowledge and research efforts related to the impacts of illumination levels on nighttime safety at intersections, especially roundabouts.

First, this work is the first quantitative study of the impacts of illumination levels on nighttime safety at roundabouts. It extends all highway safety research regarding intersection illumination beyond the status-quo of the less informative binary (Yes/No) illumination value. The developed measurement protocol gives researchers the ability to cost effectively, rapidly, and accurately collect quantitative illumination data Decision. This has the potential to also help DOTs and other transportation agencies to undertake a more informative trade-off analysis to maximize the benefit-to-cost ratios.

Secondly, this dissertation is the first application of the photographic method of luminance measurement to roundabouts. Previous applications of the method to transportation research have been predominantly been related to road segments. Similarly, this work is the first documented application of the camera specific calibration constant approach to transportation field measurement. Previous applications of the photographic method use an exposure specific calibration approach which requires the camera to be operated in the field at the same calibration exposure conditions. However, light conditions at rural intersections can vary significantly and there is often the need to adjust the exposure settings for more accurate measurement of luminance.

Next, this work presents the first developed procedure to develop uniformity (contour) plots from the photographic method. Additionally, this work develops easy to follow procedures for collecting luminance data from the field.

Also, this work can serve as the basis for initial efforts to create an illumination specific quantitative crash modification factor (CMF) for both roundabouts and conventional intersections. CMFs are estimated changes in expected crash frequency and/or crash severity at a site in response to a specific treatment (AASHTO 2010). The current edition of the Highway Safety Manual lacks this important safety parameter. The available illumination CMF for stop-control and signalized intersections is related to the binary (Yes/No) illumination variable which indicates an estimated change in lighting presence without any discrimination between different levels of installed lighting at a site. With the capability afforded by the developed protocol, illumination level data can now filter into future studies and the development of a quantitative illumination CMF is now possible.

Furthermore, this dissertation contributes a documented database of both conventional intersections and roundabout illumination levels in the state of Georgia. Prior to this dissertation there were no available records of quantitative intersection illumination data for use by researchers. The developed database can be used in future years to refine the results of this study. It can also be expanded to include other intersections in future.

Overall, this dissertation advances the frontiers of highway intersection safety research regarding the impact of illumination on nighttime intersection safety. Also, the ability to rapidly and cost-effectively audit the adequacy of installed illumination can also lead to significant improvements in highway safety maintenance with regards to performance of installed illumination overtime.

10.2 Limitations

There are a few limitations facing this study that should be mentioned. First, it is difficult to get the camera to focus well at locations of complete darkness. An improperly focused camera will impact the pixel data in an image and thus the luminance information that will be extracted. For this dissertation work, the work around method was to shine a bright light source on the pavement area of interest to enable the camera to focus, turn off the light source, then take the image. However, it is unknown if the camera’s sensitivity or focus changes when the light source is turned off. This can also not be verified with the images since they are completely dark. Consequently, it is recommended that estimated illuminances less 0.1 lux should be treated as zero.

The developed protocol used in this study has not been tested under cold weather conditions. Most devices with sensitive electronic and/or optical parts usually have a defined working range. Thus, the applicability of this protocol in cold regions will depend on the type of camera that is used.

Also, the developed protocol is not applicable to wet surfaces because the measured luminance is the reflected light from the road surface and the presence of water on the surface would distort the reflective property. Therefore, it is advised that the method should be used on a completely dry surface, usually a day or two after a downpour.

Next, the analysis and results presented in this study were limited by the availability of quality crash data. Despite the meticulous manual selection used there may still be possible undetected errors because on the general unreliability of latitude and longitude information in the incident files. For example, there were some crashes where the roadway name, intersection road name, and distance to nearest intersection information strongly matches one of the study’s intersections. However, when the latitude and longitude information from the incident file is checked in Google Maps it shows that the crash should have occurred say about 3 miles down the road at a Waffle House. It is easy to assume that the officer entered the data later while parked at the Waffle House but most rural police agencies do not have electronic accident report forms which are linked to the automatic vehicle location detection units in the police cars. Therefore, this is very confounding and needs further investigation.

10.3 Future Work

The most significant short to medium term research needed to further this work is the continued collection of more quantitative illumination data and intersection characteristics data which could be used to conduct a more comprehensive evaluation of illumination level impacts on safety at intersections. For Georgia, continued sponsorship from GDOT to collect this data will be very helpful. Georgia also needs to invest in cleaning up the crash database because only then can the state take advantage of available illumination level data to improve trade-off analysis which can maximize the benefit-cost ratios of illumination projects as well as help to make sound decisions about the adequate level of illumination required to maintain nighttime safety at roundabouts and conventional intersections in Georgia.

For the long term, there is a need for some kind of umbrella national or regional Lighting and Intersection Safety Data System (LISDS) that will provide both financial and administrative support for DOTs to collect this information. The program must also create a system to warehouse all the data. It can be managed by one of the University Transportation Centers, such as the southeaster center which is managed by Georgia Tech. On the other hand, it is possible to incorporate this program into the mandate of the Highway Safety Information System (HSIS). However, the existing stringent data availability requisites for states to participate in the HSIS, which has historically limited the number of participating states to just a few, might be a disincentive to states who may not meet HSIS requirements but would be interested in participating in the proposed program. Therefore, it will be advantageous for this program to be administered separately and the data requisites should be limited to quantitative intersection illumination data and a few defined set of intersection characteristics data.

Also, a short term research project could be dedicated to better understanding of the GDOT crash data. One strategy will be to analyze the data by police agencies to identify those with the most consistent errors. This can enable the discovery and development of agency or region specific sanitizing techniques that may even lend themselves to automating.

APPENDIX A

A REVIEW OF INTERNATIONAL ROUNDABOUT LIGHTING PRACTICES, POLICIES, AND STANDARDS

GDOT Research Project No. RP 12-01

Evaluation of Current Practice for Illumination at Roundabouts: Safety and Illumination of Roundabouts-Phase I

Technical Report

A REVIEW OF INTERNATIONAL ROUNDABOUT LIGHTING PRACTICES, POLICIES AND STANDARDS

By:

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Contract with

Georgia Department of Transportation

In cooperation with

U.S. Department of Transportation
Federal Highway Administration

July 2015

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Georgia Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Technical Report Documentation Page

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16. Abstract (MAXIMUM 200 WORDS)

As part of a research effort sponsored by the Georgia Department of Transportation (GDOT), this report presents the findings of a review of international roundabout illumination policies and standards. The countries evaluated include 22 European Countries, 12 Asian Countries, 2 African Countries, and 9 Countries in the Americas outside of the U.S. The findings presented in this report are first presented for Europe, followed by Asia, Americas, and Africa. The report concludes with a summary of systematic lighting practices at rural roundabouts among the evaluated countries.

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INTRODUCTION

Illumination is perhaps of greatest interest to the modern roundabout than any other type of highway intersection because of its unique design features such raised splitter islands with flared ends at the exit/entry points to the circular path and raised central island with a radius wide enough to cause the travel path from the approaches to be deflected into a circular path. These features are essential to achieving reduced speeds and eliminating or significantly reducing fatal and severe crashes at roundabouts. However, during nighttime driving these features need to be visible otherwise they can become potential sources of hazard for drivers. Also, because of the deflection of the travel path into the circulating roadway, a vehicle's headlight beam is often more tangential to the circular path and does not illuminate objects and/or conflicting movements from the left side of the vehicle. This implies that drivers will often be looking into darkness as they navigate the roundabout (Illuminating Engineering Society 2008). Consequently, the overall safety of a roundabout at night can be enhanced with provision of purpose-built street lighting.

Consequently, the national guidelines (Illuminating Engineering Society 2008; Rodegerdts et al. 2010) for roundabout illumination in the U.S. recommend systematic illumination of roundabouts in both rural and urban areas. However, highway illumination is expensive and in most nations, including the U.S., conventional at-grade rural intersections can be kept unlit. Since widespread roundabout programs by state highway agencies in the U.S. are relatively new there is a knowledge gap in terms of whether rural roundabouts should be treated differently than other conventional at-grade rural intersections. As more states adopt widespread roundabout programs state transportation agencies and local governments would have to decide whether to adopt the recommended systematic illumination, with its implied costs, in all areas or whether to make discriminations based on location. Therefore, a review of the standards and policies for illumination of roundabouts in other nations, especially in nations with comparable transportation systems, would be beneficial to states and local governments who are actively building their roundabout programs.

As part of a research effort sponsored by the Georgia Department of Transportation (GDOT), this report presents the findings of a review of international roundabout illumination policies and standards. The countries evaluated include 22 European Countries, 12 Asian Countries, 2 African Countries, and 9 Countries in the Americas outside of the U.S. The findings presented in this report are first presented for Europe, followed by Asia, Americas, and Africa. The report concludes with a summary of systematic lighting practices at rural roundabouts among the evaluated countries.

EUROPE

Most European countries have adopted the European Union standard, European Norm EN 13201 (hereafter called EN), wholly or with some modification as the basis for illuminating their roundabouts. The EN which is composed of four parts has been approved by the European Committee for Standardization since 2003 (Modus 2012) and it includes both warrants and standard for roadway and intersection illumination.

The first part of the EN, CEN/TR 13201-1 Road Lighting Part 1: Selection of Lighting Classes (European Committee for Standardization 2004) outlines the warrants for illumination. It specifies warranting conditions which are based on vehicle speed, traffic type, traffic volume, and road environment. Table A1 describes these warrants and their lighting situation sets. The EN prescribes appropriate lighting classes for illuminating mainly for situation sets A and B. The prescription of appropriate lighting classes for illuminating for situation sets C, D, and E is generally left to the determination of the various national road agencies. For all the prescribed lighting classes, the EN requires that average luminance should be used as the design criterion for all road segments and average illuminance should only be used in cases where cases where viewing distances are short (such as roundabouts and other conventional intersections) and other factors prevent the use of the luminance criterion (European Committee for Standardization 2004). Also all uniformity standards are based on the luminance criterion.

There are three main lighting classes prescribed for roads in the EN; ME/MEW, CE, and S (Modus 2012). Lighting class ME/MEW is for roads with medium to high speed limits (30 km/h and above). The “W” signifies an overwhelmingly wet surface. Lighting class CE is for road within conflict areas such as commercial avenues, complicated cross-roads, roundabouts, conventional intersections, congestion prone places, etc. Lighting class S is for roads mainly used for pedestrians and cyclists.

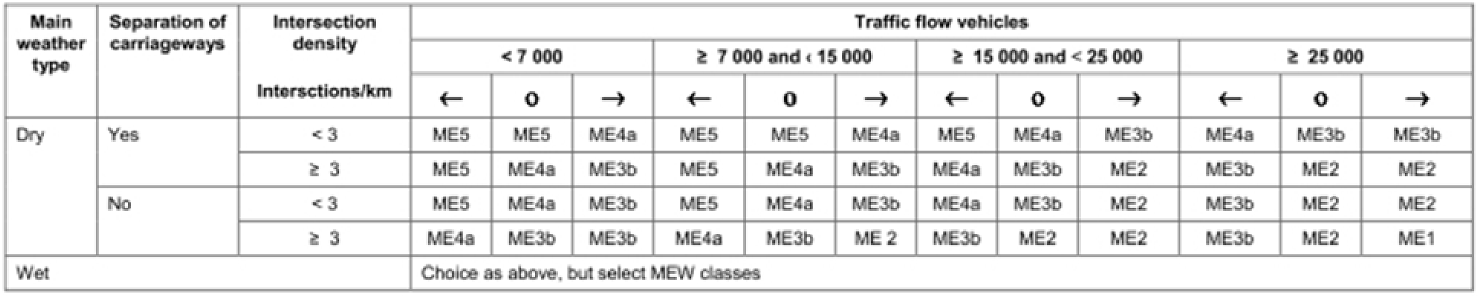
For each lighting class, EN provides other sub-group classes based on different factors. For example, the ME/MEW class has other sub-groups based on the weather, carriageway separation, intersection density, and traffic volume. Table A2 shows the recommended range of lighting class for situation set A3. For a roundabout with major road falling into situation set A3, Table A2 gives a three sub-group range for the ME/MEW class based on the traffic volume category of the major road. Therefore, additional factors are provided to select the correct sub-group class from the range. Table A3 presents the recommended selection from the range. The applicable ambient luminance and other factors from Table A3 determines the correct sub-group (**←**, **0**, **→**) from the range.

Table A1 Grouping of Lighting Situations

<table>
<tr><th rowspan="2">Typical speed of main user km/h</th><th colspan="3">User types in the same relevant area</th><th rowspan="2">Sets of lighting situations</th></tr>
<tr><th>Main user</th><th>Other allowed user</th><th>Excluded user</th></tr>
<tr><td rowspan="3">> 60</td><td rowspan="3">Motorized traffic</td><td></td><td>Slow moving vehicles, cyclists, and pedestrians</td><td>A1</td></tr>
<tr><td>Slow moving vehicles</td><td>Cyclists and pedestrians</td><td>A2</td></tr>
<tr><td>Slow moving vehicles, cyclists, and pedestrians</td><td></td><td>A3</td></tr>
<tr><td rowspan="3">>30 and ≤ 60</td><td>Motorized traffic
Slow moving vehicles</td><td>Cyclists
Pedestrians</td><td></td><td>B1</td></tr>
<tr><td>Motorized traffic
Slow moving vehicles
Cyclists</td><td>Pedestrians</td><td></td><td>B2</td></tr>
<tr><td rowspan="2">Cyclists</td><td rowspan="2">Pedestrians</td><td rowspan="2">Motorized traffic
Slow moving vehicles</td><td rowspan="2">C1</td></tr>
<tr><td rowspan="5">>5 and ≤ 30</td></tr>
<tr><td rowspan="2">Motorized traffic
Pedestrians</td><td></td><td>Slow moving vehicles
Cyclists</td><td>D1</td></tr>
<tr><td>Slow moving vehicles
Cyclists</td><td></td><td>D2</td></tr>
<tr><td>Motorized traffic</td><td>Slow moving vehicles
Pedestrians</td><td></td><td>D3</td></tr>
<tr><td rowspan="2">Motorized traffic
Slow moving vehicles
Cyclists
Pedestrians</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">D4</td></tr>
<tr><td rowspan="3">Walking speed</td></tr>
<tr><td rowspan="2">Pedestrians</td><td></td><td>Motorized traffic
Slow moving vehicles
Cyclists</td><td>E1</td></tr>
<tr><td>Motorized traffic
Slow moving vehicles
Cyclists</td><td></td><td>E2</td></tr>
</table>

(Source: CEN/TR 1320-1)

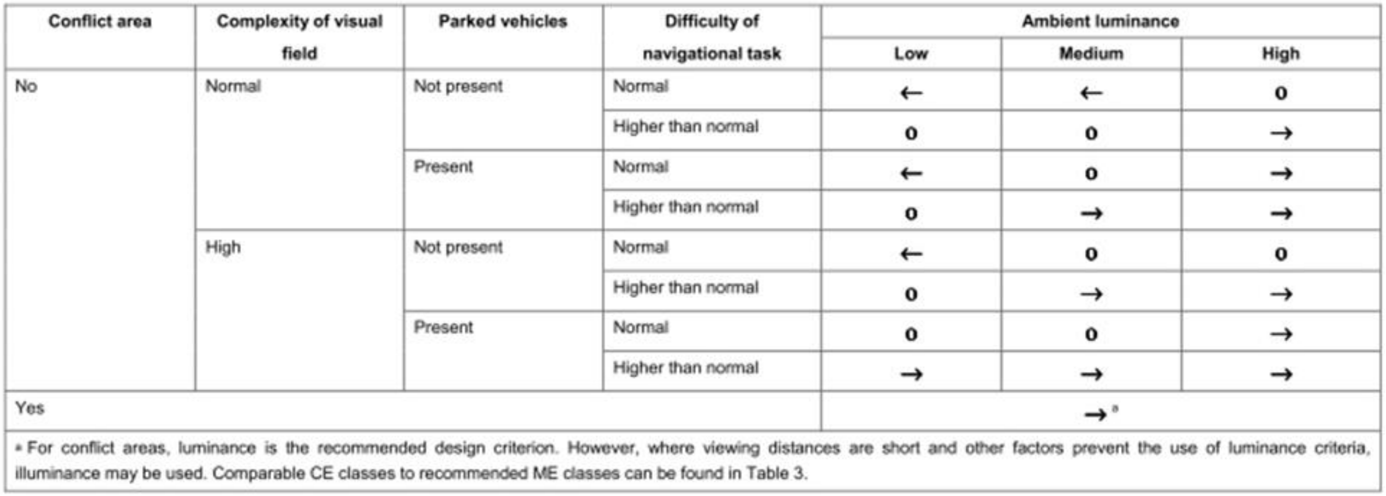
Table A2 Recommended Range of Lighting Classes for Situation Set A3



Main weather type	Separation of carriageways	Intersection density Intersctions/km	Traffic flow vehicles											
			< 7 000			≥ 7 000 and < 15 000			≥ 15 000 and < 25 000			≥ 25 000		
			←	o	→	←	o	→	←	o	→	←	o	→
Dry	Yes	< 3	ME5	ME5	ME4a	ME5	ME5	ME4a	ME5	ME4a	ME3b	ME4a	ME3b	ME3b
		≥ 3	ME5	ME4a	ME3b	ME5	ME4a	ME3b	ME4a	ME3b	ME2	ME3b	ME2	ME2
	No	< 3	ME5	ME4a	ME3b	ME5	ME4a	ME3b	ME4a	ME3b	ME2	ME3b	ME2	ME2
		≥ 3	ME4a	ME3b	ME3b	ME4a	ME3b	ME 2	ME3b	ME2	ME2	ME3b	ME2	ME1
Wet			Choice as above, but select MEW classes											

(Source: CEN/TR 13201-1)

Table A3 Recommended Selection from Range of Lighting Classes for Situation Set A3



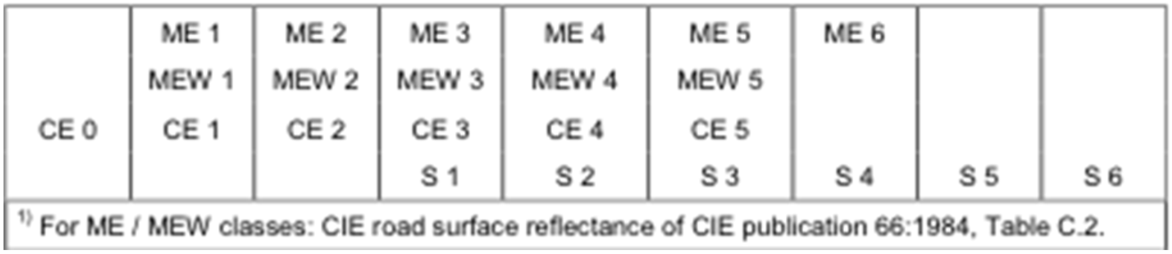
Conflict area	Complexity of visual field	Parked vehicles	Difficulty of navigational task	Ambient luminance		
				Low	Medium	High
No	Normal	Not present	Normal	←	←	o
			Higher than normal	o	o	→
		Present	Normal	←	o	→
			Higher than normal	o	→	→
	High	Not present	Normal	←	o	o
			Higher than normal	o	→	→
		Present	Normal	o	o	→
			Higher than normal	→	→	→
Yes				→[a]		

[a] For conflict areas, luminance is the recommended design criterion. However, where viewing distances are short and other factors prevent the use of luminance criteria, illuminance may be used. Comparable CE classes to recommended ME classes can be found in Table 3.

(Source: CEN/TR 13201-1)

Once the sub-group lighting class is determined, it can be compared with the CE lighting class which is applicable for roundabouts, intersections, and other conflict areas. Table A4 shows the chart for matching lighting classes of comparable lighting level.

Table A4 Lighting Classes of Comparable Lighting Level



	ME 1	ME 2	ME 3	ME 4	ME 5	ME 6		
	MEW 1	MEW 2	MEW 3	MEW 4	MEW 5			
CE 0	CE 1	CE 2	CE 3	CE 4	CE 5			
			S 1	S 2	S 3	S 4	S 5	S 6

1) For ME / MEW classes: CIE road surface reflectance of CIE publication 66:1984, Table C.2.

(Source: CEN/TR 13201-1)

The actual illuminance level for the appropriate CE class can be found in the second part of the EN, EN 13201-2 Road Lighting Part 2: Performance requirements (European Committee for Standardization 2003). Table A5 presents horizontal illuminance levels of the CE series of lighting classes.

Table A5 Performance requirements for CE Series of Lighting Classes

Class	Horizontal illuminance (Lux)	
	E [minimum maintained]	U_o [minimum]
CE0	50	0.4
CE1	30	0.4
CE2	20	0.4
CE3	15	0.4
CE4	10	0.4
CE5	7.5	0.4

(Source: EN 13201-2)

Austria

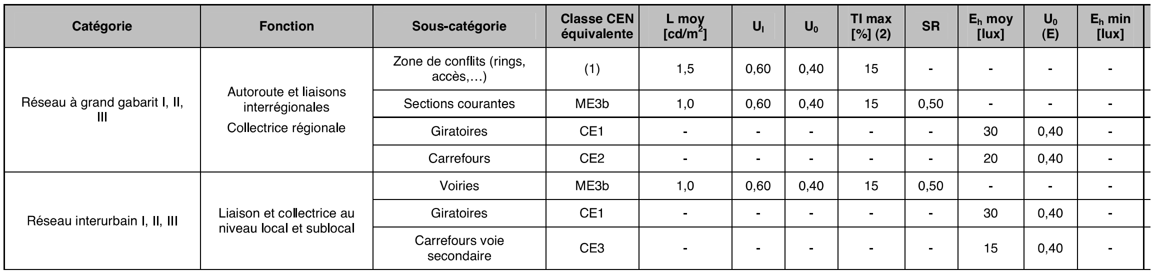
In Austria all road sections, including roundabouts in urban areas must have street lighting. However, in rural areas there is generally no lighting except at dangerous sections which must be determined on a case-by-case basis by the highway safety engineer (CEDR's TG Road Safety 2009). Therefore, there is no systematic policy to illuminate roundabouts. Lighting that is provided at roundabouts must meet the standards set in parts 2, 3, and 4 of the EN (CEDR's TG Road Safety 2009)

Belgium

Road authorities in Belgium use part 1 of the EN as the main warrant for roundabout illumination. This is supplemented by an additional warrant prNBN L 18-004:2010: Public lighting – Selection of lighting Classes (Institut belge de l'éclairage – Belgisch instituut voor verlichting 2010). This supplemental warrant provides complementary parameters in assigning road segments to the lighting classes in the EN. It also prohibits a difference of more than two equivalent lighting classes on adjacent road sections

(Lorphevre 2012). For such cases the higher illumination level must be used. For lighting standards, Belgium road authorities use parts 2, 3, and 4 of the EN (Lorphevre 2012). Table A6 shows the lighting performance standards used in Belgium. All publicly owned roundabouts (Giratories) are illuminated under the CE1 lighting class with a minimum average illumination of 30 lux (Institut belge de l'éclairage – Belgisch instituut voor verlichting 2010; Lorphevre 2012). Therefore, roundabouts will be systematically illuminated.

Table A6 Belgium Lighting Parameters



Catégorie	Fonction	Sous-catégorie	Classe CEN équivalente	L moy [cd/m^2]	U_l	U_0	TI max [%] (2)	SR	E_h moy [lux]	U_0 (E)	E_h min [lux]
Réseau à grand gabarit I, II, III	Autoroute et liaisons interrégionales Collectrice régionale	Zone de conflits (rings, accès,…)	(1)	1,5	0,60	0,40	15	-	-	-	-
		Sections courantes	ME3b	1,0	0,60	0,40	15	0,50	-	-	-
		Giratoires	CE1	-	-	-	-	-	30	0,40	-
		Carrefours	CE2	-	-	-	-	-	20	0,40	-
Réseau interurbain I, II, III	Liaison et collectrice au niveau local et sublocal	Voiries	ME3b	1,0	0,60	0,40	15	0,50	-	-	-
		Giratoires	CE1	-	-	-	-	-	30	0,40	-
		Carrefours voie secondaire	CE3	-	-	-	-	-	15	0,40	-

(Source: prNBN L 18-004:2010 (F))

Bulgaria

Bulgarian road authorities use part 1 of the EN as warrant for roundabout illumination. They also comply with parts 2, 3, and 4 of the EN for lighting performance standards. The EN replaced the Bulgarian standard BSS 5504/1982 in 2005. There is no policy to systematically illuminate rural roadways (including roundabouts). The decision to illuminate is made by local governments or municipalities and the Executive Road Agency considering local situations and availability of funds (E-Street Initiative 2008).

Czech Republic

In the Czech Republic, a translated and slightly modified version of the EN is used. The Czech standard is also in four parts and it offers further guidance on the selection of lighting classes. It also offers significant variation in parameter values for different periods of the night to account for ambient luminance and traffic flow. Nominal lighting levels can be reduced up to 50 percent or up to 25 percent in case of extreme variation in traffic flow (E-Street Initiative 2008). A change in ambient luminance can also allow a reduction in nominal lighting values. However, for road segments or conflict areas with high nighttime crime risk or nighttime accident frequency the reduction in nominal lighting level is not recommended (E-Street Initiative 2008; Kotek 2012). Also, there is no systematic requirement to illuminate rural roads – including roundabouts – road authorities decide whether or not to illuminate on a case-by-case basis. The general practice is to only illuminate if at least one adjacent road is illuminated (E-Street Initiative 2008; Kotek 2012)

Denmark

Danish road authorities use all the four parts of the EN. Part 1 is the warrant for illumination and Parts 2, 3, or 4 apply to performance values and measurements (Danish Ministry of Transport 2005). However, the local Danish recommendation which was published in 1999, Vejbelysningsregler (Illumination levels on State Routes) is also still in force (Danish Ministry of Transport 2005; E-Street Initiative 2008). Generally, all roundabouts in urban areas must be illuminated but those in rural areas must be decided by the different road authorities (CEDR's TG Road Safety 2009). Therefore, Denmark does not systematically illuminate roundabouts.

Estonia

The Estonian road authorities use the EN part 1 to warrant the illumination of roundabouts. Also, they comply with the prescriptions of EN parts 2, 3 and 4 for the lighting levels for various lighting classes. In Estonia, illumination is provided on rural roundabouts that have at least one illuminated adjacent roadway section or have pedestrian crossings (CEDR's TG Road Safety 2009). In urban areas all roadways, including roundabouts must have lighting provided (CEDR's TG Road Safety 2009).

Finland

In Finland the National Code of Practice for Road Lighting, TIEH 21003-v-06, serves as both a warrant and a standard for roadway illumination. The warrant component is based on the part 1 of the EN but makes further distinction between types of road sections and accounts for weather conditions. The standard component is also based on the EN parts 2, 3, and 4. The standard also recommends and provides performance requirements for adaptive lighting when feasible (E-Street Initiative 2008). The Finnish National Road Administration has the responsibility for planning and designing, the installation and maintenance of public road lighting. According to the National Road Lighting Policy, roundabouts must generally be illuminated (CEDR's TG Road Safety 2009).

France

The current French policy on illumination of highway intersections is contained in The Design of Interurban Intersections on Major Roads (SETRA - Service d'Etudes Techniques des Routes et Autoroutes 1998) which was published by the Service for Roads and Highway Technical Studies (SETRA) in 1998. For specific reference to roundabouts the earlier publication; Technical Guide: Roundabout Illumination (Guide Technique: Eclairage des Carrefours à Sens Girratoires) (Centre d'Études des Transports Urbains 1991) is the principal document unless there is contrary recommendation in the current policy mentioned prior. In cases where none of these documents can be referenced, the EN is applied in full. Generally, roundabout intersections in rural areas are not illuminated (similarly to other at-grade intersections) in France. However, an exception is made when there are illuminated areas in the immediate vicinity, one of the adjacent legs is illuminated, or there is a pedestrian crossing on the roundabout.

Germany

Germany uses a translated version of the EN as the warrant and standard for roundabout illumination. The German standard also includes provisions for the dimming of lights in cases of reduced traffic. Normally roads in urban areas are lit if the area is built-up or the road leads to a built up area. In rural areas, the application of road lighting is not frequent. The decision to light a location is done on a case-by-case basis. (CEDR's TG Road Safety

2009). Therefore, there is no systematic requirement for rural roundabout illumination in Germany.

Greece

Road authorities in Greece use part 1 of the EN as the warrant to illuminate roundabouts. Also, there is compliance with parts 2, 3 and 4 of the EN for performance requirements on lighting classes. Generally, roundabouts on the national road network must be illuminated if it is at a main junction or on a road section connecting urban areas. For roundabouts that are off the national network, the local authorities must decide whether or not to illuminate (CEDR's TG Road Safety 2009). Therefore, Greece also does not have a systematic requirement for lighting roundabouts in rural areas.

Holland

Dutch road agencies use the Handboek Openbare Verlichting-2007 (Public Lighting Handbook) (Dijkstra and Roosenboom 2009) as warrant for illumination of roundabouts and they use Nederlandse Praktijk Richtlijn (Practical Dutch Guidelines) (Dutch Lighting Committee 2002) as their standard. These documents are translated and slightly revised versions of the EN. However, the documents do not differ from the EN with regards to roundabout illumination. The standard emphasizes energy saving, minimizing life-cycle costs (LCC), and the use of adaptive lighting (E-Street Initiative 2008). In Holland, regions are responsible for defining their own policy and local road authorities decide whether or not to illuminate rural roundabouts. The policies differ across the country (E-Street Initiative 2008).

Iceland

Even though Iceland is not part of the European Union, the Icelandic road authorities have adopted all four parts of the EN as the warrant and standard for illumination of roundabouts. The Icelandic policy for roundabout is to systematically illuminate in both urban and rural conditions (CEDR's TG Road Safety 2009).

Ireland

The Irish road authorities use the British Standard BS 5489-1:2003 (British Standards 2003) as the warrant roundabout illumination (E-Street Initiative 2008). However, for lighting standard they use parts 2, 3, and 4 and the EN. In Ireland, rural roundabouts are systematically lit (CEDR's TG Road Safety 2009).

Italy

Italy uses a translated and slightly modified version of the EN Part 1, UNI 11248 Illuminazione Stradale – 2012 (Roadway Illumination) (Soardo 2013), as the warrant for roundabout illumination. This document does not differ from the EN with regards to roundabout illumination. The parts 2, 3, and 4 of the EN are used as standard for illumination (CEDR's TG Road Safety 2009; Soardo 2013). In 2006 Ministry of Infrastructure and Transportation outlined the policy for roundabout illumination. Rural roundabouts with split-level maneuvers or grades must be illuminated. If a roundabout belongs to neither of these two categories then it is the responsibility of the local road authorities to decide whether or not to illuminate.

Luxembourg

In Luxembourg the “service électromécanique” uses part 1 to 4 of the EN as the warrant and standard for roundabout illumination. The EN was transposed into law in 2005 (CEDR's TG Road Safety 2009).

Norway

The Norwegian Public Roads Administration publishes its own warrant and standard. The standard is based on parts 2, 3, and 4 of the EN (E-Street Initiative 2008). The warrant is based on traffic volume and the presence of physical separation of carriageway (i.e. divided highway or barrier separation). Table A7 presents the recommended lighting class for various traffic volumes on both separated and non-separated carriageways (Norwegian Public Roads Administration 2011). Norway actively supports the use of adaptive lighting systems where it will be effective even if costly (E-Street Initiative 2008). The lighting performance measures for Norway are shown in Table A8.

Table A7 Recommended Roadway Lighting Classes in Norway

ADT	<1500	1500 – 4000	4000 – 8000	8000 – 12000	>12000
Separated carriageways		MEW3	MEW3	MEW3	MEW3
Non-separated carriageways	MEW4	MEW3	MEW2	MEW2	MEW2

(Source: Norwegian Public Roads Administration 2011)

Table A8 Recommended Lighting Levels for Equivalent CE Lighting Classes in Norway

Average luminance (cd/m^2)		2	1.5	1	0.75	0.5			
Class	CE0	MEW1 CE1	MEW2 CE2	MEW3 CE3 S1	MEW4 CE4 S2	MEW5 CE5 S3	S4	S5	S6
Average illuminance (lux)	50	30	20	15	10	7.5	5	3	2

(Source: Norwegian Public Roads Administration 2011)

Poland

Poland has had virtually no road illumination standard since it went from a centrally commanded to a liberal market economy (E-Street Initiative 2008). For now, policy and guidelines are given by the Polish Committee of Illumination and the Association of Polish Electricians on a case-by-case basis.

Slovenia

The Slovene road authorities use the part 1 of the EN as warrant for roundabout illumination. Parts 2, 3 and 4 of the EN are used as standard for lighting performance requirements (E-Street Initiative 2008).

The decision to illuminate rural roundabouts is left to the discretion of municipalities (Bizjak 2012; E-Street Initiative 2008). Slovenia has developed a strong practice of adaptive illumination for roundabouts that dims lighting level at low traffic times of the night (Bizjak 2012; Black Sea Regional Energy Centre 2006).

Spain

In Spain the Royal Decree 1890/2008 of November 14, (Complementary Technical Instructions), is used as Instrucciones técnicas complementarias EA-01 a 07 both a warrant and a standard for roundabout illumination. The document states that illumination of a roundabout must be at least 50% more than the highest lighting level of its adjacent legs. Also, if a roundabout is to be illuminated, its minimum average luminance level must be 40 lux. Furthermore, the roundabout must maintain its luminance level for 200m in every direction (Ministerio de Fomento 2012).

Sweden

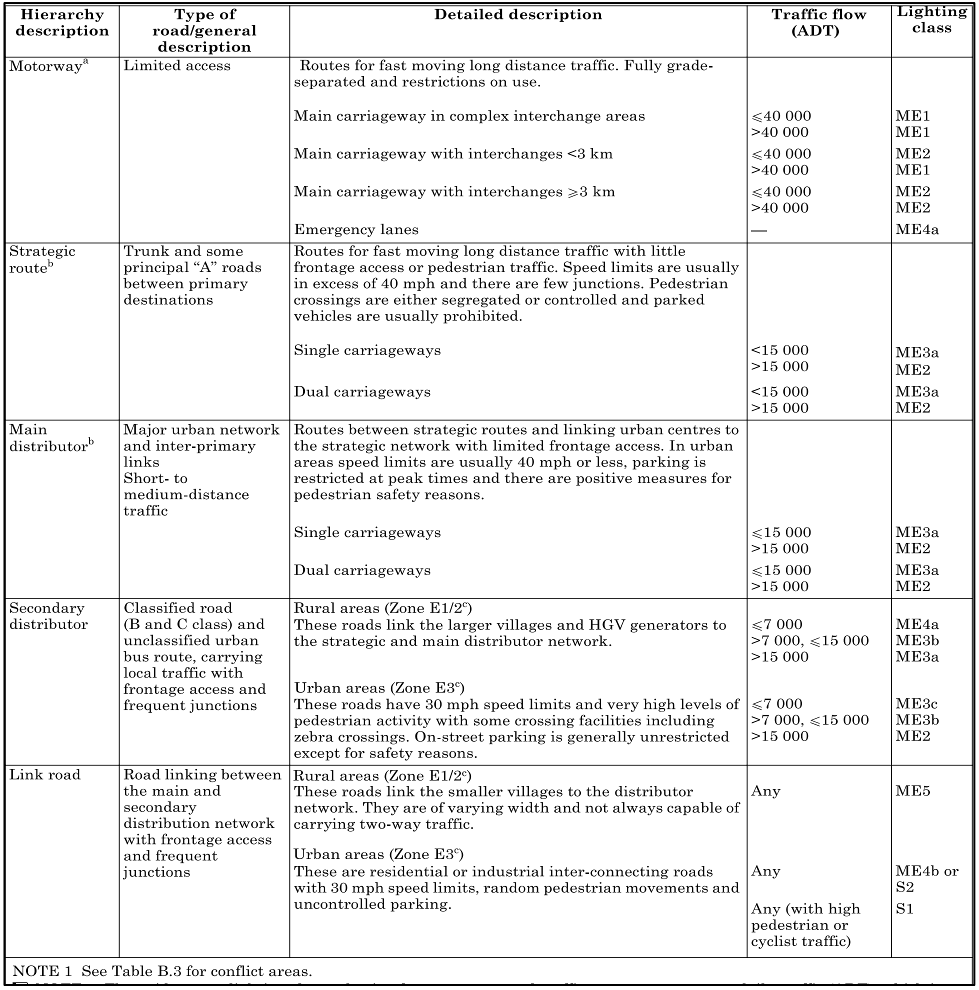
The document VGU (VV Publication 2004:80) (Vagverket et al. 2004) acts as both a warrant and a standard for roadway illumination in Sweden (E-Street Initiative 2008). It gives recommendations for the choosing of lighting classes and assigns the corresponding illumination levels. The document provides for the adaptive lighting of roadway sections, this is done extensively in Sweden. The standard component is based on the EN (E-Street Initiative 2008). The federal and local authorities have the responsibility to decide whether to illuminate public and local roads respectively (E-Street Initiative 2008).

Switzerland

The Swiss Standard for lighting public roads is based on the EN. However, the Swiss Association of Lighting has published additional recommendations to the standard (CEDR's TG Road Safety 2009). There is no central control over rural roundabout (including other roadways) illumination. The application of the standard is the responsibility of the Cantons, Cities, and Municipalities. However, most roundabouts in urban areas are well lit.

United Kingdom

In England, the British Standard BS 5489-1:2003 (British Standards 2003) is used as a warrant to determine the lighting class of road sections (12). This is done according to the recommendations in Figure A1. The warrant states that if none of the adjacent legs to a roundabout are lit but a decision is made to illuminate it, the CE lighting class should be chosen as the equivalent to the prevailing ME/MEW class corresponding to the traffic demands and general environment of the roundabout. Once the lighting class has been determined, parts 2, 3, and 4 of the EN are used to assign the appropriate minimum average illuminance level and overall uniformity (Parry 2012) There is no mandatory requirement to provide lighting (CEDR's TG Road Safety 2009), however; the vast majority of British rural roundabouts are illuminated (Parry 2012).



Hierarchy description	Type of road/general description	Detailed description	Traffic flow (ADT)	Lighting class
Motorway^{a}	Limited access	Routes for fast moving long distance traffic. Fully grade-separated and restrictions on use.		
		Main carriageway in complex interchange areas	⩽40 000 >40 000	ME1 ME1
		Main carriageway with interchanges <3 km	⩽40 000 >40 000	ME2 ME1
		Main carriageway with interchanges ⩾3 km	⩽40 000 >40 000	ME2 ME2
		Emergency lanes	—	ME4a
Strategic route^{b}	Trunk and some principal “A” roads between primary destinations	Routes for fast moving long distance traffic with little frontage access or pedestrian traffic. Speed limits are usually in excess of 40 mph and there are few junctions. Pedestrian crossings are either segregated or controlled and parked vehicles are usually prohibited.		
		Single carriageways	<15 000 >15 000	ME3a ME2
		Dual carriageways	<15 000 >15 000	ME3a ME2
Main distributor^{b}	Major urban network and inter-primary links Short- to medium-distance traffic	Routes between strategic routes and linking urban centres to the strategic network with limited frontage access. In urban areas speed limits are usually 40 mph or less, parking is restricted at peak times and there are positive measures for pedestrian safety reasons.		
		Single carriageways	⩽15 000 >15 000	ME3a ME2
		Dual carriageways	⩽15 000 >15 000	ME3a ME2
Secondary distributor	Classified road (B and C class) and unclassified urban bus route, carrying local traffic with frontage access and frequent junctions	Rural areas (Zone E1/2^{c}) These roads link the larger villages and HGV generators to the strategic and main distributor network.	⩽7 000 >7 000, ⩽15 000 >15 000	ME4a ME3b ME3a
		Urban areas (Zone E3^{c}) These roads have 30 mph speed limits and very high levels of pedestrian activity with some crossing facilities including zebra crossings. On-street parking is generally unrestricted except for safety reasons.	⩽7 000 >7 000, ⩽15 000 >15 000	ME3c ME3b ME2
Link road	Road linking between the main and secondary distribution network with frontage access and frequent junctions	Rural areas (Zone E1/2^{c}) These roads link the smaller villages to the distributor network. They are of varying width and not always capable of carrying two-way traffic.	Any	ME5
		Urban areas (Zone E3^{c}) These are residential or industrial inter-connecting roads with 30 mph speed limits, random pedestrian movements and uncontrolled parking.	Any Any (with high pedestrian or cyclist traffic)	ME4b or S2 S1

NOTE 1 See Table B.3 for conflict areas.

(Source: BS 5489-1:2003)

Figure A1 UK Recommended Lighting Classes for Motorways and Traffic Routes

ASIA

Unlike Europe there is currently no uniform roadway illumination warrant or standard across Asia. Existing practice is uncoordinated among countries. However, the Association of South East Asian Nations is discussing the possibility of a uniform warrant and standard. Several Asian countries have adopted illumination practices modeled on the EN, the British Standard 5489, or the AASHTO Design Manual. Others have also developed their own illumination standards. Regarding roundabout illumination, Australia and New Zealand are currently the only Asian nations that have a common document

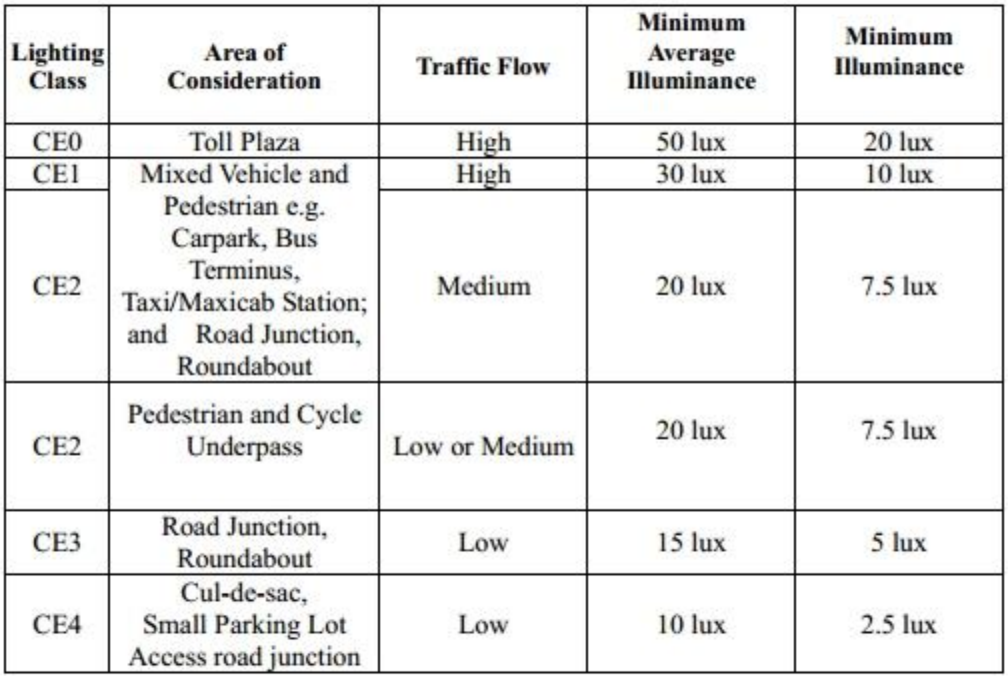
Australia

There is no unified warrant for roadway illumination across Australia. Each territory is responsible for defining its own warrant. The AS/NZS1158.1.1: 2005 (Lighting for Roads and Public Spaces) is a joint New Zealand-Australia standard (Joint Technical Committee 2005) which provides clear guidelines on roundabout illumination. It includes minimum lighting level requirement and geometric design guidance for each lighting class. Roundabouts fall into category V lighting (motorized traffic and road safety) or category P (pedestrian movement and personal security). In South New Wales there is systematic illumination of roundabouts.

Hong Kong

In Hong Kong, the Public Lighting Design Manual-2006 is used to warrant roundabout illumination (Lighting Division 2006). The document references the British Standard 5489 (British Standards 2003). The warrant selects lighting classes according to functional class, traffic density, traffic complexity, traffic segregation, pedestrian volume, and ambient brightness (Lighting Division 2006). The standard includes the provision that maintained average illuminance on the road surface of a roundabout shall be higher than on the approach roads. Additionally, the document provides for the use of high mast lighting at roundabouts where “higher than normal level of illuminance is considered desirable or the large number of conventional lighting columns would confuse the motorists with patterns of lanterns at different levels and impair the aesthetics.” In Hong Kong, roundabouts can be illuminated as class CE2 or CE3 depending on traffic flow as shown in Table A9.

Table A9 Hong Kong Lighting Levels for Conflict Areas



Lighting Class	Area of Consideration	Traffic Flow	Minimum Average Illuminance	Minimum Illuminance
CE0	Toll Plaza	High	50 lux	20 lux
CE1	Mixed Vehicle and Pedestrian e.g. Carpark, Bus Terminus, Taxi/Maxicab Station; and Road Junction, Roundabout	High	30 lux	10 lux
CE2		Medium	20 lux	7.5 lux
CE2	Pedestrian and Cycle Underpass	Low or Medium	20 lux	7.5 lux
CE3	Road Junction, Roundabout	Low	15 lux	5 lux
CE4	Cul-de-sac, Small Parking Lot Access road junction	Low	10 lux	2.5 lux

(Source: Lighting Division 2006)

India

The standard for roadway lighting in India is the IS1944-1970 (Bureau of India Standards 1970). The lighting level and class assigned to roadways is primarily based on traffic.

Roundabouts must meet general illumination criteria for junctions and must have minimum lighting levels of 50 lux and distance between lighting poles must be less than 70% of adjacent roads. For small roundabouts with central island less than 18 meters, the code allows the location of a single luminaire pole in the center of island (Bureau of India Standards 1970).

Israel

In 2010, Israel adopted the EN. Part 1 of the EN is used as the warrant roundabout illumination while parts 2, 3, and 4 are applied as the lighting standard to determine the levels for various lighting classes. Also, the decision of whether or not to illuminate a roundabout is done on a case-by-case basis.

Kazakhstan

СН РК В.2.5-18-2003 (Instructions for designing outdoor electric lighting for cities, towns and villages) is both the warrant and the standard. It does not provide information specifically on roundabouts, but it gives guidelines regarding junctions. In general, if there is a pedestrian crossing at a roundabout, illumination is obligatory (Ministry of Engery, Industry and Trade 2001).

Korea

The Installation and Maintenance Guidelines for Roadway Safety Facilities (Ministry of Land Transport and Maritime Affairs 2012) is used as both a warrant and a standard for roadway illumination in Korea. The Korean Roundabout Design Manual (Ministry of Land Transport and Maritime Affairs 2010) stipulates that in unusual circumstances such as the presences of pedestrians, lighting should follow the basic concept of the Installation and Maintenance Guidelines for Roadway Safety Facilities. Otherwise, lighting can be modified according to local conditions.

Malaysia

There is no warrant for roadway illumination in Malaysia. The Jaban Kerja Raya (National Road Authority) decides whether to illuminate a roundabout on a case-by-case basis. The Guide to the Design of At-Grade Intersections (Jalan et al. 2009) recommends that channelized intersections should have lighting provided even if it is not warranted and if lighting is not available, the islands should be equipped with pavement reflectors. Roundabouts are channelized intersections so they should be illuminated.

New Zealand

In New Zealand there is no uniform illumination warrant for roundabouts. Road authorities in each region independently decide whether or not to illuminate. Also, similar to the Australian standard they must also decide whether a roundabout is category V lighting (motorized traffic and road safety) or category P (pedestrian movement and personal security).The joint New Zealand-Australian standard (Joint Technical Committee 2005) provides clear guidelines on roundabout illumination including required lighting level tables and geometric design guidance per lighting class.

Philippines

The Philippine road authorities addressed the need for safe and efficient lighting systems for the first time in the Roadway Lighting Guidelines-2008 (Department of Energy 2008). The Philippine road lighting policies are still at an experimental stage. The document does not specifically mention the roundabout but provides directives for at-grade junction illumination.

Russia

The Russian Agency of Technical Regulation and Meteorology adopted the EN in 2005 (Russian Federal Agency for Technical Regulation and Metrology). Part 1 of the EN is used to pick lighting classes at roundabouts. Illumination requirements of the roadway classes are then prescribed with parts 2, 3 and 4.

Turkey

The Turkish road lighting standard is based on the CIE Publication No: 12-1977 (Recommendations for the Lighting of Roads for Motorized Traffic). Supplemental guidelines are provided in the Yol Tasarımının Esasları ve Uygulamaları (Turkish General Directorate of Highways 2005) which is modeled after the AASHTO Standard (AASHTO 2005).

AMERICAS

Countries in the Americas have their own individual policies on how to illuminate roundabouts. Most of these policies are modeled after the International Committee for Illumination guideline CIE 115:2010 (International Commission on Illumination 2010).

Argentina

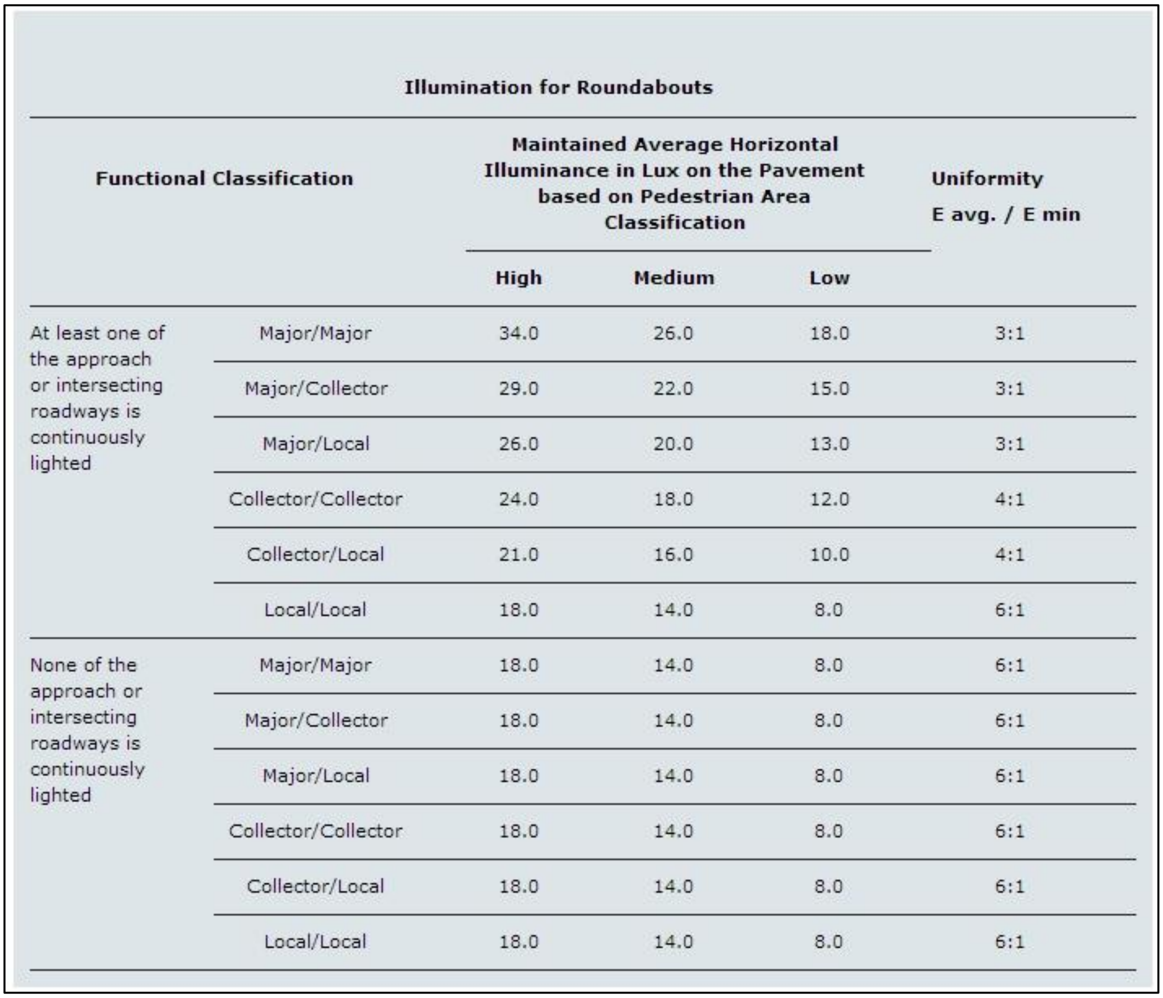
In Argentina, municipalities have the responsibility for deciding whether or not to illuminate the roundabouts within their jurisdiction. When a decision is made to illuminate a roundabout, there are three Argentine standards that can be used jointly to determine the required illumination (Asociacion Argentina de Luminoteca 2001). The AADL J IRAM-2022 Street lighting 21 (Classification of roads and recommended levels) is used to determine the lighting class. This same document is then used to find the appropriate illumination level. AADL J IRAM-2020 Street lighting 23 (Design features) provides geometric guidelines for roadway illumination and AADL J IRAM-2021 Street lighting 67 (Testing requirements) gives a procedure to test whether road portions satisfy safety lighting requirements. All three standards are based on the CIE 115:2010 (International Commission on Illumination 2010).

Brazil

Under Brazilian legislation, public lighting is the responsibility of municipalities (Rosito 2009). They decide whether or not to illuminate roundabouts. The most recent Brazilian Standard, NBR 5101 (Road Lighting Procedure), was published in 2012 and it serves as both a warrant and a standard for roadway illumination (Brazillian Standards 2012) The Brazilian Standard is based on the CIE 115:2010 (International Commission on Illumination 2010).

Canada

In Canada, each province produces its own policies. In Quebec and Ontario, illumination is recommended for almost all roundabouts (Ministère des Transports du Québec 2002; Ontario Ministry of Transportation 2012). Less densely populated provinces, where power supply is not readily available on rural roadways have less strict policies. However, all roundabouts under provincial jurisdiction must comply with the warrants listed in the "Ministry Policy for Roundabout Illumination" (Ontario Ministry of Transportation 2012). This document provides a standard for the required illumination levels and the geometric design and it is based on the Illumination Engineering Society of North America (IESNA) Design Guide for Roundabout Lighting (DG-19) (Illuminating Engineering Society 2008). In general all roundabouts under provincial jurisdiction are to be lighted. The Canadian Guide for the Design of Roadway Lighting can also serve as a standard because it incorporates the recommendations of the IESNA standard. The required illumination levels are determined according to the type of crossroads and the pedestrian area classification. The recommended lighting levels in Lux as well as the Uniformity ratios for various types of crossroads are presented in Figure A2.



Illumination for Roundabouts

Functional Classification		Maintained Average Horizontal Illuminance in Lux on the Pavement based on Pedestrian Area Classification			Uniformity E avg. / E min
		High	Medium	Low	
At least one of the approach or intersecting roadways is continuously lighted	Major/Major	34.0	26.0	18.0	3:1
	Major/Collector	29.0	22.0	15.0	3:1
	Major/Local	26.0	20.0	13.0	3:1
	Collector/Collector	24.0	18.0	12.0	4:1
	Collector/Local	21.0	16.0	10.0	4:1
	Local/Local	18.0	14.0	8.0	6:1
None of the approach or intersecting roadways is continuously lighted	Major/Major	18.0	14.0	8.0	6:1
	Major/Collector	18.0	14.0	8.0	6:1
	Major/Local	18.0	14.0	8.0	6:1
	Collector/Collector	18.0	14.0	8.0	6:1
	Collector/Local	18.0	14.0	8.0	6:1
	Local/Local	18.0	14.0	8.0	6:1

(Source: Ontario Ministry of Transportation 2012)

Figure A2 Canadian Lighting Levels at Roundabouts

Chile

The Reglamento de Alumbrado Pùblico de Vìas de Tràfico vehicular serves as both a warrant and a standard (Empresa de Energia del Pacifico 2000). The warrant stipulates that conflict areas including roundabout must always be illuminated. A roundabout must at least be illuminated to the highest lighting level of its legs. If none of the legs (Ministro de Obras Publicas 2012; Republica De Chile Ministerio De Economía 2008) are illuminated, the roundabout must be lit to the highest prescribed level of illumination of the adjacent intersection legs. The guidelines are aligned with the CIE 115: 2010 (International Commission on Illumination 2010) requirements.

Columbia

In Columbia, both the warrant and standard for roundabout illumination is contained in the Reglamento Técnico de Iluminaciòn y Alumbrado Pùblico (Ministerio de Minas y Energia 2012; Ministerio de Transportes y Comunicacion 2001). Unlike the Chilean standard, Columbia's standard does not recommend illumination for roundabouts when none of the legs is illuminated. The standard explains how to calculate minimum light levels but does not give geometric requirements. The guidelines are aligned with the CIE 115:2010 (International Commission on Illumination 2010) requirements.

Mexico

There is no uniform illumination warrant and standard in use across Mexico. Individual states decide whether or not to illuminate roundabouts. Some states have well documented roadway illumination policies. Chihuahua for example establishes clear policies in Decreto No. 850/95 XVIII (Secretaria de Servicios Juridico Legislativos 2008). Generally, it is recommended that at the least, roundabouts should be illuminated to the minimum level of the legs.

Nicaragua

The geometric design guide, Guia de Diseno Geometrico, also serves as the Nicaraguan standard. It includes a section on roundabouts and requires that all roundabouts in Nicaragua must be illuminated. However, because rural roundabouts may be located far from energy sources, this is not always the case in practice.

Peru

The decision of whether or not to illuminate a rural roundabout is made at the administrative divisions. N° 013-2003-EM/DM. - Norma Técnica de Alumbrado de Vías Públicas (technical standard for public road lighting) (Ministerio de Energia y Minas 2003) is used as the warrant and it defines the applicable lighting classes. This document must be used in conjunction with the standard - CIE 115:2010 (International Commission on Illumination 2010). Additionally, the warrant requires that a roundabout must at least be illuminated to the minimum illumination level of its legs.

Venezuela

The central government is responsible for the illumination of roundabouts. The Resumen NVF 3290: 2008 establishes technical guidelines for roadways including transition zones (Comite de electricidad 2008).

AFRICA

Africa does not have a uniform roadway illumination warrant and standard. Most countries also do not have an official illumination warrant and/or standard.

Ghana

In Ghana, the Metropolitan, Municipal, and District Assemblies (MMDAs) are responsible for the development, installation, ownership and maintenance of streetlights within their jurisdictions (Ghana Energy Commission 2011). Ghana does not have a national road lighting standard.

South Africa

In South Africa, the modern roundabouts are called traffic circles and they are not as widespread as mini-roundabouts. The current warrant and standard document is made up of two parts; *SANS 10098-1 Public Lighting - Part 1: The Lighting of Public Thoroughfares for Lighting Public Roads and SANS 10098-2 Public Lighting – Part 2: The Lighting of Certain Specific Areas of Streets and Highways.* It is unclear whether these documents address roundabouts specifically.

SUMMARY OF RURAL ROUNDABOUT LIGHTING PRACTICES

Table 10 and Table 11 present a summary of systematic rural roundabout lighting practices among the surveyed countries. The results in these table show 59 percent of all the countries scanned do not have a systematic policy to light rural roundabouts. These include countries with comparable transportation systems such as Germany, France, Holland, Canada, and New Zealand. The results further show that while warrants exist there in these countries, there is underlying trend to leave the ultimate decision to light a roundabout to local authorities. Also, the results highlight some key factors which affect the illumination of rural roundabouts in these countries. These key factors include:

- The presence of pedestrian volumes at the roundabout.
- The presence of illumination in the immediate vicinity of the roundabout.
- At least one approach street is illuminated.
- The availability of power.

Next, while a few countries, 16 percent of surveyed countries, do attempt to illuminate all roundabouts it is more common to find a requirement to light all urban roundabouts. Also, it was not possible to determine the nature of rural roundabout illumination requirement at about 25 percent of the countries surveyed. The survey results also show that adaptive lighting practices are not common with respect to roundabout illumination among the scanned countries. Figure A3 presents a map of all the surveyed countries.

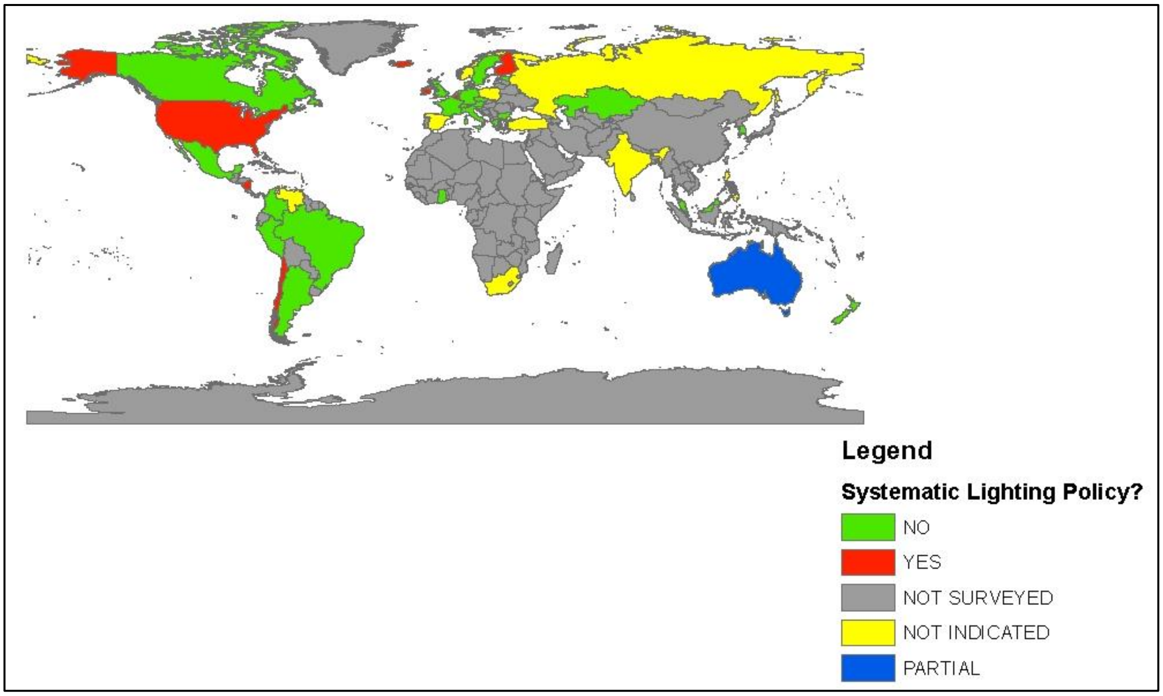


Figure A3 Systematic Roundabout Illumination Policies around the World

Table A10 Summary of Systematic Lighting Practices at Rural Roundabouts

Country	**Warrant & Standard**	**Roundabout Lighting in Rural Areas**		**Illuminance Range (Lux)**	**Known to Use Adaptive Lighting**
		Systematic?	**Comment**		
Austria	EN	No		7.5 - 50	
Belgium	EN with supplements to warrants	Yes		30	
Bulgaria	EN	No		7.5 - 50	
Czech	EN with modifications	No	Illuminate if an adjacent leg is illuminated.	7.5 - 50	Yes, but not applicable in high crime areas
Denmark	EN in collaboration with original Danish recommendations	No		7.5 - 50[1]	
Estonia	EN	No	Except if adjacent legs are illuminated or pedestrian crossing is present	7.5 - 50	
Finland	EN with modifications	Yes		7.5 - 50	Yes
France		No	Except if adjacent legs are illuminated or pedestrian crossing is present		
Germany	EN (Translated version)	No		7.5 - 50	Yes
Greece	EN	No	Unless those on national network	7.5 - 50	
Holland	EN with modifications (Translated)	No		7.5 - 50	Yes
Iceland	EN	Yes		7.5 - 50	
Ireland	BS for warrant, EN for	Yes		7.5 - 50	

Country	Warrant & Standard	Roundabout Lighting in Rural Areas		Illuminance Range (Lux)	Known to Use Adaptive Lighting
		Systematic?	Comment		
	standard				
Italy	EN with modification (Translated)	No	Unless it is grade separated or split level maneuvers	7.5 - 50	
Luxemburg	EN	Not Indicated		7.5 - 50	
Norway	EN with modification	Not Indicated		7.5 - 50	Yes
Poland	None[2]	Not Indicated			
Slovenia	EN	No		7.5 - 50	Yes
Spain	Unique	Not Indicated		40+	
Sweden	EN	No		7.5 -40	Yes
Switzerland	EN with additional recommendations	No			
United Kingdom	BS for warrant, EN for standard	No	Can be lighted if one adjacent leg is illuminated	7.5 - 50	
Australia	No uniform warrant, standard is *AS/NZS1158*	Only in territory		?	
Hong Kong	Warrant based on BS, Standard based on EN	Not Indicated		15 - 20	
India	Unique	Not indicated		50	
Israel	EN	No		7.5 - 50	
Kazakhstan	Unique	No	Unless pedestrian crossing is present	?	
Korea	Unique	No	Unless pedestrian crossing is present	?	
Malaysia	Unique	Yes	All channelized intersections must be lighted	?	

Country	Warrant & Standard	Roundabout Lighting in Rural Areas		Illuminance Range (Lux)	Known to Use Adaptive Lighting
		Systematic?	Comment		
New Zealand	No uniform warrant, standard is *AS/NZS1158*	No		?	
Philippines	Unique	Not Indicated		?	
Russia	EN	Not Indicated		7.5 - 50	
Turkey	Based on CIE 12-1977 and AASHTO	Not Indicated		?	
Argentina	No uniform warrant, Standard based on CIE 115:2010	No		?	
Brazil	Based on CIE 115:2010	No		?	
Canada	Unique warrant, standard based on IESNA DG-19	No	Unless in Quebec and Ontario or under provincial jurisdiction	8 - 34	
Chile	Based on CIE 115:2010	Yes		?	
Columbia	Based on CIE 115:2010	No		?	
Mexico	No uniform warrant or standard across Mexico	No	Unless one of the legs is illuminated in Chihuahua State	?	
Nicaragua	Unique warrant and standard[3]	Yes	But most are not because of distance from power sources	?	
Peru	Unique warrant used in collaboration with CIE 115:2010	No		?	
Venezuela	Unique warrant and standard[3]	Not Indicated		?	
Ghana	No known warrant or	No		?	

Country	Warrant & Standard	Roundabout Lighting in Rural Areas		Illuminance Range (Lux)	Known to Use Adaptive Lighting
		Systematic?	Comment		
	standard				
South Africa	Unique	Not Indicated		?	

1. Based on the EN. The local Danish recommendation was not available for comparison with the EN in terms of illumination levels.
2. A version based on the EN is being drafted.
3. It was not possible to determine if it is based on any of the major lighting standards; IESNA, EN, BS

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APPENDIX B

LIST OF CONVENTIONAL INTERSECTIONS AND ROUNDABOUTS SELECTED FOR THE CASE STUDY

This appendix presents the list of the original roundabouts and conventional intersections selected for the study. The list of conventional intersections presented in three tables representing the layout of luminaires around the intersection. Each table also contains two average AADT groupings of “High” (for locations with at least 4000 average entering AADT) and “Low” (for locations with average entering AADT less than 4000).

Table B1 Selected Conventional Intersections with No Dedicated Illumination

ID	Area	Illumination Scheme	6 Year AADT	Latitude	Longitude
1	Atlanta	None	12020	33.610942	-84.164771
2	Atlanta	None	12040	33.328946	-84.506553
3	Atlanta	None	8866	33.460053	-85.128609
4	Dalton	None	9979	34.369142	-85.003718
5	Cochran	None	18155	32.551695	-83.610783
6	Dalton	None	9124	34.688607	-84.466841
7	Dalton	None	6377	34.9748	-85.403825
8	Dalton	None	5736	34.4693954	-85.3867744
9	Dalton	None	7740	34.640838	-84.507932
10	Cochran	None	4501	32.1810091	-84.134394
11	Atlanta	None	2471	33.409001	-83.760712
12	Cochran	None	1980	31.692196	-83.113783
13	Cochran	None	1256	31.752663	-83.677117
14	Cochran	None	2447	32.431813	-84.002947
15	Cochran	None	612	32.412943	-83.933468
16	Dalton	None	2112	34.927671	-85.5869896
17	Dalton	None	3938	34.9765363	-85.3667792
18	Cochran	None	3986	31.942601	-83.738504
19	Cochran	None	837	32.123434	-82.863377
20	Cochran	None	2647	32.27341	-82.710022

Table B2 Selected Conventional Intersections with Partial Illumination

ID	Area	Illumination Scheme	6 Year AADT	Latitude	Longitude
21	Atlanta	Partial	8145	33.510852	-84.439024
22	Dalton	Partial	7512	34.8936246	-85.1848787
23	Brunswick	Partial	4327	31.743804	-81.439981
24	Dalton	Partial	4079	34.484807	-85.479902
25	Dalton	Partial	9206	34.684957	-84.474753
26	Dalton	Partial	5468	34.8706584	-85.2287353
27	Dalton	Partial	11418	34.9283653	-85.2109702
28	Dalton	Partial	5389	34.977439	-85.415864
29	Cochran	Partial	11042	32.495781	-83.607992
30	Cochran	Partial	6529	32.859922	-83.347219
31	Brunswick	Partial	1630	31.633891	-81.396489
32	Dalton	Partial	1235	34.49462	-84.452927
33	Dalton	Partial	1792	34.978912	-85.433719
34	Dalton	Partial	3676	34.8073337	-85.3892644
35	Dalton	Partial	3441	34.7938924	-85.334694
36	Cochran	Partial	1085	32.204694	-82.668616
37	Cochran	Partial	2630	32.2589	-82.700656
38	Cochran	Partial	1822	32.806965	-82.913333
39	Cochran	Partial	2913	32.810497	-82.757167
40	Cochran	Partial	3480	31.944808	-83.54261

Table B3 Selected Conventional Intersections with Full Illumination

ID	Area	Illumination Scheme	6 Year AADT	Latitude	Longitude
41	Dalton	Full	5934	34.69849	-84.481714
42	Cochran	Full	5559	32.541576	-82.903634
43	Dalton	Full	8483	34.694238	-84.481535
44	Dalton	Full	5697	34.689081	-85.30046
45	Dalton	Full	7982	34.69774	-84.481912
46	Atlanta	Full	12176	33.565767	-85.045059
47	Atlanta	Full	16192	31.85	-81.595833
48	Atlanta	Full	15019	33.441022	-84.457578
49	Brunswick	Full	8866	33.46	-85.128611
50	Atlanta	Full	15430	33.368122	-84.779261
51	Dalton	Full	2767	34.696972	-84.480126
52	Cochran	Full	1324	31.807311	-83.487729
53	Cochran	Full	1978	31.948536	-83.456307
54	Cochran	Full	2156	31.949674	-83.454632
55	Cochran	Full	1695	31.946251	-83.456309
56	Cochran	Full	921	32.18756	-82.566154
57	Cochran	Full	1378	32.53928	-82.90251
58	Cochran	Full	1037	31.809023	-83.490021
59	Cochran	Full	2084	31.949702	-83.45626
60	Atlanta	Full	1566	33.791296	-83.596102

Table B4 Selected Roundabouts

ID	City	6 Year AADT	Latitude	Longitude
22R	Brookhaven	22R	33.872842	-84.3347
15R	Lawrenceville	15R	34.017206	-84.075889
14R	Suwanee	14R	33.902144	-84.050561
37R	Sandy Springs	37R	33.92663	-84.371615
36R	Sandy Springs	36R	33.947204	-84.364817
24R	Druid Hills/Emory Village	24R	33.7883333	-84.325833
34R	Dunwoody	34R	33.950407	-84.349524
23R	Druid Hills/Emory Village	23R	33.787392	-84.329167
87R	Sandy Springs	87R	33.9692417	-84.328008
93R	Suwanee	93R	34.0636111	-84.103056
35R	Roswell	35R	34.02617	-84.34475
85R	Alpharetta	85R	34.0628889	-84.289097
25R	Lithonia	25R	33.675992	-84.114903
30R	Alpharetta	30R	34.076474	-84.206831
39R	Conyers	39R	33.6643056	-84.019722
89R	College Park	89R	33.6677778	-84.514722
90R	College Park	90R	33.6627778	-84.515
8R	Woodstock	8R	34.108419	-84.517583
18R	Acworth-Kennesaw	18R	33.92704	-84.63778
44R	Fayetteville	44R	33.441022	-84.457578
13R	Dawsonville	13R	34.354339	-84.051697
95R	Locust Grove	95R	33.3508333	-84.095556
94R	Locust Grove	94R	33.3480556	-84.095556
28R	Douglasville	28R	33.652762	-84.768535
84R	Newnan	84R	33.3861111	-84.741944
29R	Douglasville	29R	33.6136	-84.836881
1R	Carrollton	1R	33.565767	-85.045059
9R	Rome	9R	34.281063	-85.1657
42R	Newnan	42R	33.368122	-84.779261
45R	Culloden	45R	32.879497	-84.090189
82R	Evans	82R	33.5755556	-82.163611
83R	Evans	83R	33.5758333	-82.167778

Table B5 Selected Roundabouts cont'd

ID	City	6 Year AADT	Latitude	Longitude
53R	Statesboro	1821	32.422583	-81.775444
96R	Hinesville	1027	31.8513889	-81.653333
56R	Hinesville	16192	31.85	-81.595833
54R	St. Simon's Island	21198	31.159613	-81.388569
55R	St. Simon's Island	7739	31.216497	-81.375515
86R	Decatur	3932	33.8019444	-84.364444
31R	Atlanta	2490	33.736256	-84.352692
88R	Fairburn	2948	33.6405556	-84.637778
3R	Whitesburg	12080	33.491411	-84.912458
2R	Roopville	8867	33.46	-85.128611
92R	St. Simon's	3208	31.1816667	-81.379722
91R	St. Simons's	2891	31.1816667	-81.381806

APPENDIX C

FIELD DEPLOYMENT DOCUMENT FOR USE IN PHOTOGRAPHIC AUDITING OF ROADWAY LIGHTING

Photographic Audit of Street Roadway Lighting at Intersections

Field Deployment Document

March 2015

1. OVERVIEW

Street lighting is a proven nighttime crash countermeasure which serves to augment nighttime visibility for road users. The established protocol for auditing the adequacy of street lighting at intersections involves very tedious spot measurements of incident light levels (illuminance) from points on an imaginary grid of 6ft by 6ft over the intersection area. This protocol makes it difficult to:

- Perform audits efficiently
- Reproduce/verify previous measurements
- Obtain consistent luminance readings during measurements due to changes in luminance caused by voltage fluctuations in the AC systems that power street lights.

The photographic auditing method offers an alternative auditing approach and a remedy for the prior-mentioned challenges of gridded spot measurements. It uses image analysis techniques to link pixel intensity in an image to scene luminance (pavement brightness perceived by road users).

Please note that in this manual important instructions are emphasized by using bold italicized text.

2. EQUIPMENT REQUIRED FOR FIELD SURVEYS

The following pieces of equipment would be required for successful luminance measurement on roads.

- Canon EOS Rebel T3 SLR digital camera.
- Two fully charged batteries for digital camera.
- Two 4GB SD cards for storing images of intersections and scanned copies of filled data recording forms.
- An Extech-HD450 illuminance meter.
- One extra 9V battery for illuminance meter.
- Traffic safety vests for all team members.
- Two traffic cones.
- A 165 feet or 50 meters long measuring tape.
- Metered wheel.
- Compass.
- GPS device.
- Flash light.
- Intersection Identification Cards.
- An external time device such as a digital wrist watch or a mobile phone device.

- A Tripod with capability to mount a camera. ***Tripod should be tall enough to allow the top surface of the tripod to be 1.24 m (49 in) above the ground (measured at the center of the three legs) when tripod is fully set up.***

3. HOW TO SETUP THE TRIPOD

1. Tripod height must always be ***set such that the top surface of the tripod is at 1.24 m (49 in) above the ground (measured at the center of the three legs) when tripod is fully set up.*** Figure C1 shows a correctly setup tripod.
2. The mounting piece on the tripod must be balanced horizontally so that the digital camera will also be balanced in the horizontal plane when it is mounted

Figure C1 Correct Tripod Setup

4. SETTING UP THE CAMERA

Inserting/Removing Batteries and SD Card

To insert the battery and/or SD card please follow the steps below.

1. Slide the lever as shown by the arrows and open the cover. Be careful not to push the cover further back otherwise the hinge might break.
2. Insert the battery end with the contacts. Push gently until the battery locks in place.

3. Insert the SD card with the labeled face toward the back of the camera. Push it gently all the way.
4. Closer the cover by pressing until it snaps shut. Figure C2 shows pictures of the four steps above.

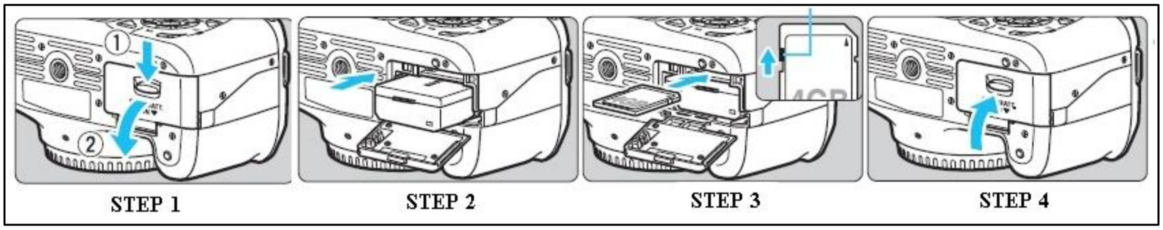


Figure C2 Inserting Batteries and SD Card into the Camera

To remove the battery/card make sure the power switch is in the <OFF> position before opening the cover. If "Recording…" is displayed on the LCD screen, close the cover.

5. Press the battery release lever as shown by the arrow and remove the battery.
6. Gently push in the card and let go. The card will stick out then pull the card.
7. Close the cover until it snaps shut. Figure C3 shows pictures that further explain Step 5 and Step 6 above.

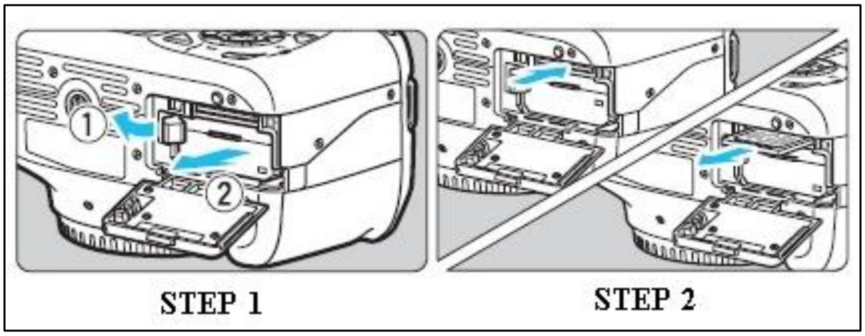


Figure C3 Removing Battery and SD Card from Camera

Turning the Camera On and Off

Turn the power switch to the <ON> position as shown in **Error! Reference source not ound.** F4. To save battery power, the camera turns off automatically after about 30 seconds of non-operation. To turn on the camera again, just press the shutter button halfway

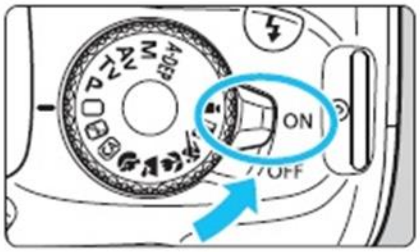
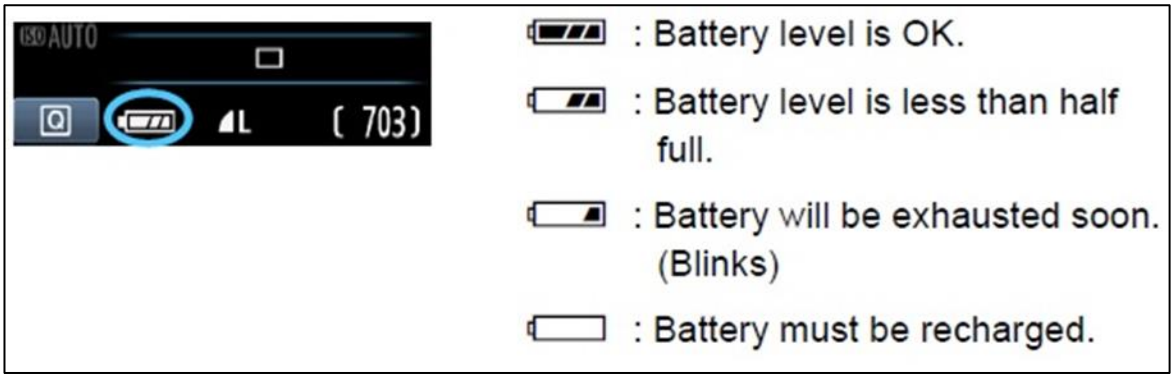


Figure C4 Turning the Power Switch to the On Position

Checking the Battery Level
Turn the power switch to the <ON> position. The battery level will be indicated in one of four levels on the LCD screen as shown in Figure C5



: Battery level is OK.

: Battery level is less than half full.

: Battery will be exhausted soon. (Blinks)

: Battery must be recharged.

Figure C5 Battery Charge Indicator Levels

5. SETTING THE IMAGE SHOOTING FUNCTIONS

Shooting Mode

Set the mode dial to <M> as shown in Figure C6 This is the manual shooting mode

Figure C6 Setting the Mode Dial to Manual

Accessing the Quick Control Screen

1. Turn the power switch to the <ON> position or if in live shooting mode (LCD screen view) tap the camera icon above the <Q> button to escape out of the live shooting mode.

2. Press the <Q> button shown in Figure C7 for the quick control screen to appear

Figure C7 The Quick Access Button

3. Press the cross keys (Up, Down, Right, Left) to select the function to be set. Then turn the main dial over the shutter button to change the setting. Figure C8 presents a labeled diagram of the quick control screen under the manual shooting mode. Items with * cannot be controlled from this screen.

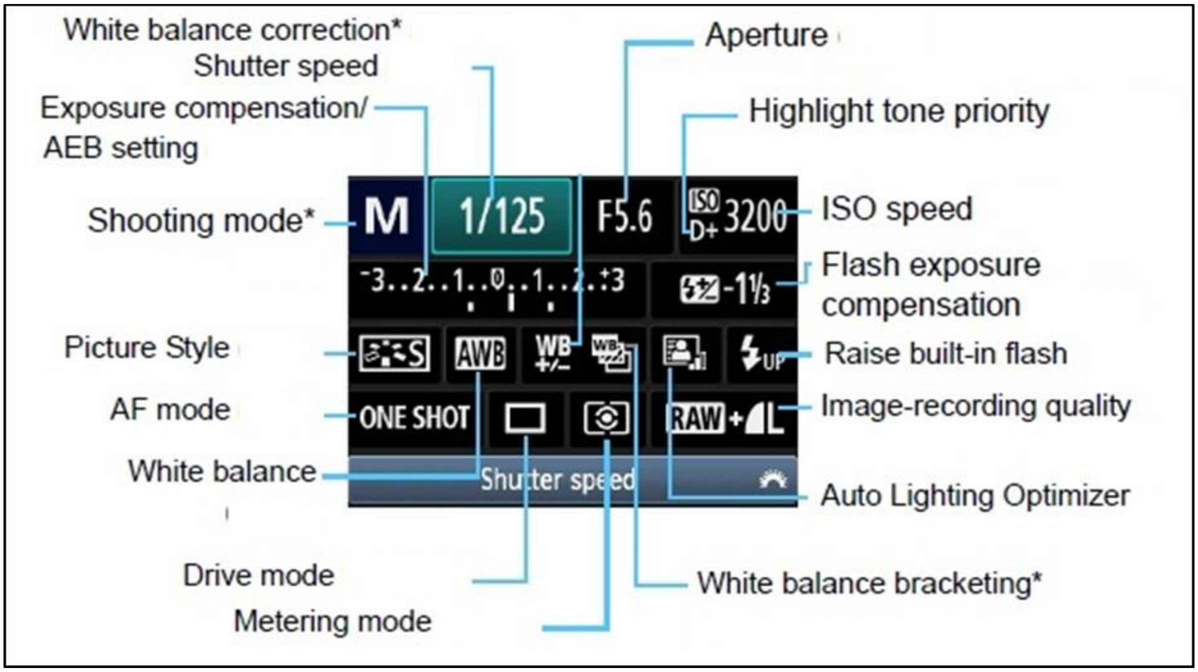


Figure C8 Quick Control Screen.

Correct Settings for the Image Shooting Functions

1. ***Shooting Mode: <M> (Manual)***
2. Shutter Speed: This setting will vary based on the exposure level setting. Note: Exposure level setting is discussed in a later section.

3. Aperture: ***two aperture settings*** from ***<F5.0>, <F4.50> , <F4.0> and <F3.5>*** can be used in the field. F3.5 and F4.0 work best for unlit intersections.
4. ISO: the ***ISO setting*** should be maintained ***at <3200> always.***
5. ***Exposure Compensation/AEB Setting***: this should be ***set to OFF***, i.e., no indicators on the scale
6. ***Flash Exposure Compensation***: should be ***maintained at Zero (±0) always***
7. ***Picture Style***: this setting should be kept at ***<Monochrome 0, 0, N, N>*** always. It is important that the monochrome settings always read 0, 0, N, N.
8. ***White Balance***: this should be ***set to <AWB> always***. This is the auto white balance setting.
9. ***Auto Lighting Optimizer***: this should be ***set to <OFF> always***.
10. Raise Built-in Flash: The built-in flash light should never be raised during shooting.
11. ***AF Mode***: This should be ***set to <ONE SHOT> always***
12. ***Self-timer***: This should be ***set to 2 seconds***.
13. ***Metering Mode***: This should always be ***set to <Evaluative metering> always***.
14. ***Image Recording Quality***: This should be ***set to <RAW> always***.

Figure C9 shows the quick control screen with correct settings of shooting functions

Figure C9 Quick Control Screen Showing Correctly Set Shooting Functions

6. SHOOTING IMAGES IN THE FIELD

Please follow the following steps to shoot images in the field. Please note that all field images shall be taken based on a predetermined combination of aperture and exposure level explained in this section.

Field Precautions

1. An intersection survey must be carried out by ***at least two people***.
2. Survey crew must wear a ***traffic safety vest*** at all times. The vest must be on before they set off from their base to the intersection site(s). The vest must be worn on top of all other clothing. No one must work at any of the intersection sites without a safety vest.
3. ***The survey crew must keep off the active travel lanes at all times.***
4. One team member must always serve as a lookout to inform other members of impending hazard. The lookout can also be the one that takes the illuminance readings (discussed later). ***The job of the lookout is not to control traffic.***
5. Survey vehicle must be parked off the road at any available free parking spot close to the intersection such as a gas station or store front. Turn off all lights including headlights and emergency lights if the free parking spot is within 60 meters of intersection.
6. If it is necessary to park vehicle on road shoulder then it should be parked ***at least 60 meters*** away from the intersection to avoid being in the camera's view. ***The emergency/hazard lights must be turned on***.
7. ***All the headlights (high beam and low beam) of the crew's vehicle must be turned off.***
8. Use the ***two traffic cones*** to provide additional visibility of surveyors by placing them behind the tripod in the direction of on-coming vehicles at intervals of 50 ft.
9. ***No surveys will be carried out on wet pavement.*** Allow sufficient time for pavements to be fully dried after rains before performing any surveys. Any water on the pavement surface will affect the photographic luminance readings.
10. Also, pictures must only be taken when there are ***no approaching vehicles/headlights*** towards the intersections from any of the legs.

All state-specific safety guidelines should be followed including those outlined in the GDOT Automated Survey Manual. The GDOT Automated Survey Manual can be downloaded at the web address below.
http://www.dot.ga.gov/doingbusiness/policiesmanuals/roads/surveymanual/surveymanual.pdf

Supplemental safety guidelines can be obtained from the ‘Survey Safety Handbook of the Florida DOT and the ‘Caltrans Survey Manual’ of the California DOT. The links to these two documents are given below.
http://www.dot.state.fl.us/surveyingandmapping/documentsandpubs/safety.pdf
http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/02_Surveys.pdf

Camera and Tripod Positions

For each of the survey intersections, images of will be captured from all of the intersection legs. Therefore, the steps below will be repeated for each intersection leg.

1. Starting from the stop line, measure a distance of 38 meters or 125 feet in the direction of in-coming traffic (away from the intersection) along the road edge.
2. Make a mark on the road shoulder and setup the tripod over this position. Thus, the tripod shall be positioned at a distance of 38 meters or 125 feet from the stop line on the approach.
3. Where the stop line is not marked, the corner of the intersecting roads can be fairly assumed as the stop line. However, if the corner position is used as the start line on one leg of the intersection, then it must be used on all the other legs for consistency.
4. Setup the tripod over a level surface. Steep slopes on road shoulder must be avoided.
5. Mount the digital SLR camera on the tripod with the camera’s view facing the intersection. The intersection must be centered in the view.
6. For each leg of the intersection, ***the mounted camera and tripod must not be moved or shifted until all the pictures for that leg have been taken***. It is very important that the set of pictures from one leg covers the same shooting area for automated image analysis algorithm to work effectively. Ensure that the camera is firmly screwed onto the tripod to avoid shifts in the camera’s view area during shooting.

Live View Shooting

1. Press the <Camera> button on the right side of the LCD screen to see the live view image on the LCD screen. The camera button is shown in Figure C10.

Figure C10 The Camera Button for Accessing Live View Shooting Mode

2. Press the <Shutter> button halfway to see where the AF points are focusing in the image. If necessary adjust the camera's direction by using the appropriate adjusting screw on the tripod's headpiece.
3. Press the <Shutter> button completely. The picture will be taken after two seconds and the captured image will be displayed on the LCD screen until image review ends. Then the camera will return to Live View shooting automatically.
4. To exit live view shooting press the Camera Button again.

Choosing the Aperture

As mentioned prior, two aperture settings from F3.5, F4.0, F4.5, and F5.0 can be used to capture images in the field. To change or choose any of these aperture settings;

1. Escape from Live View Shooting Mode by pressing the <Camera> button
2. Press the <Q> button to access the quick control screen.
3. Use the cross keys to select the aperture function.
4. Turn the <Main Dial> above the shutter button to choose the desired aperture setting.

Sometimes, depending on the focus setting on the lens it will not be possible to choose a desired aperture setting. If that happens follow the steps below

5. Turn the focusing ring on the lens a little in either clockwise or anticlockwise direction. Then turn the <Main Dial> above the shutter button again. It you still can't choose the desired aperture turn the focusing ring again and repeat the process. If you are turning the focusing ring in the wrong direction you will realize when you turn the <Main Dial> above the shutter that the available aperture settings are moving away from the desired. This shows that you should be turning the focusing ring in the opposite direction.

Choosing the Exposure Level

Images will be taken at four exposure levels which can be assessed from the exposure level indicator on the LCD screen. The exposure levels are +2.00, +1.00, -2.00, and -3.00. For each intersection leg, images will be taken at these exposure levels for both for the two chosen apertures. Thus, eight images will be taken from each leg of the intersection. To choose the exposure level you must first choose the desired aperture from the quick control screen as described in the previous section. Next, follow the steps below.

1. Press the <Camera> button to go into Live Shooting Mode. The LCD screen will show the view of the intersection.
2. The ***exposure level scale*** will be displayed in the middle of the screen at bottom. It is a graduated number scale with a positive axis (1 to 3) to the right, zero (0) in the middle, and a negative axis (1 to 3) to the left.

3. Press the shutter button halfway and release it. The current exposure level will be indicated by a white bar below the scale. Turn the <Main Dial> above the shutter button to move the indicator bar to the desired exposure level. If the indicator bar display turns off you can bring it back by pressing the shutter button halfway.
4. ***Please note that the camera is setup to use 1/3-stops on the exposure level scale***. This means that there are three scale points between the labeled exposure levels on the scale. For example, transition from 0 to -1 will require that three turns of the <Main Dial> corresponding to -1/3, -2/3, and -1.

Order of Shots

At every intersection the following order should be followed in taking the pictures. Step 1 to Step 3 will be done just once for each intersection.

1. Take a picture of the intersection’s identification card. The card could be held up by one team member or could be placed on the sidewalk for the picture to be taken. The intersection identification card is a piece of square cut paper or card with the number corresponding to the ID written on it.
2. Take a picture of the external time device (digital wrist watch or mobile phone) with the time displayed on it.
3. Take a picture of the crossroad names on sign post if one is available. This will usually be at one corner of the intersection.

Step 4 to Step 7 would be repeated on each intersection leg after the camera and tripod have been correctly positioned and have been made ready to shooting.

4. Set the camera’s aperture to F4.0
    a. Adjust the shutter speed to set the exposure level indicator to +2.00 and take the picture of the intersection. Record the shutter speed for the current aperture and exposure level
    b. Adjust the shutter speed to set the exposure level indicator to -2.00 and take the picture of the intersection. Record the shutter speed for the current aperture and exposure level
    c. Adjust the shutter speed to set the exposure level indicator to -3.00 and take the picture of the intersection. Record the shutter speed for the current aperture and exposure level
5. Set the camera’s aperture to F5.0
    a. Adjust the shutter speed to set the exposure level indicator to +2.00 and take the picture of the intersection. Record the shutter speed for the current aperture and exposure level
    b. Adjust the shutter speed to set the exposure level indicator to -2.00 and take the picture of the intersection. Record the shutter speed for the current aperture and exposure level

    c. Adjust the shutter speed to set the exposure level indicator to -3.00 and take the picture of the intersection. Record the shutter speed for the current aperture and exposure level
6. Move the tripod and camera to the next leg of the intersection and repeat Step 4 and Step 5 after the equipment is properly set up.
7. For each intersection surveyed check the observed lighting conditions in the appropriate column of the data recording form. Ambient lighting refers to lighting from surrounding properties (such as gas station, stores, houses etc.) that give some level of brightness to the intersection. The options on the form are
    a. Purpose-built lighting (NO) and Ambient lighting (NO)
    b. Purpose-built lighting (NO) and Ambient lighting (YES)
    c. Purpose-built lighting (YES) and Ambient lighting (YES)
    d. Purpose-built lighting (YES) and Ambient lighting (NO)
    e. Flashing amber (YES)
    f. Flashing amber (NO)
    g. Traffic Signal (YES)
    h. Traffic Signal (NO)

7. HOW TO USE THE ILLUMINANCE METER

An EXTECH-HD450® illuminance meter will be used to record illuminance at a fixed location at each intersection. The chosen location should be such that the recorder does not block the incident light to the sensor. This could preferably be a corner of the intersection where the second recorder can also watch out for approaching vehicles at the same time. ***The Light sensor, cable, and the reader must be on the ground during measurement***. Do not hold the sensor in your hands. Figure C11 shows a picture of the HD450 EXTECH illuminance meter.

The illuminance meter has already been set up and no additional setup is required by the survey team. Please follow the steps below to properly operate the illuminance meter

1. The measurement units must always be set to Lux. Pressing the <UNITS> button will toggle the measurement units between Lux and FC (foot candles).
2. The illuminance range must always be set to ‘400 Lux’. There are four illuminance ranges and pressing the “RANGE APO’ button will toggle the range between these. The other ranges are ‘4k Lux’, ‘40k kLux’, and ‘400k kLux’.

Figure C11 Picture of the EXTECH HD 450® Illuminance meter

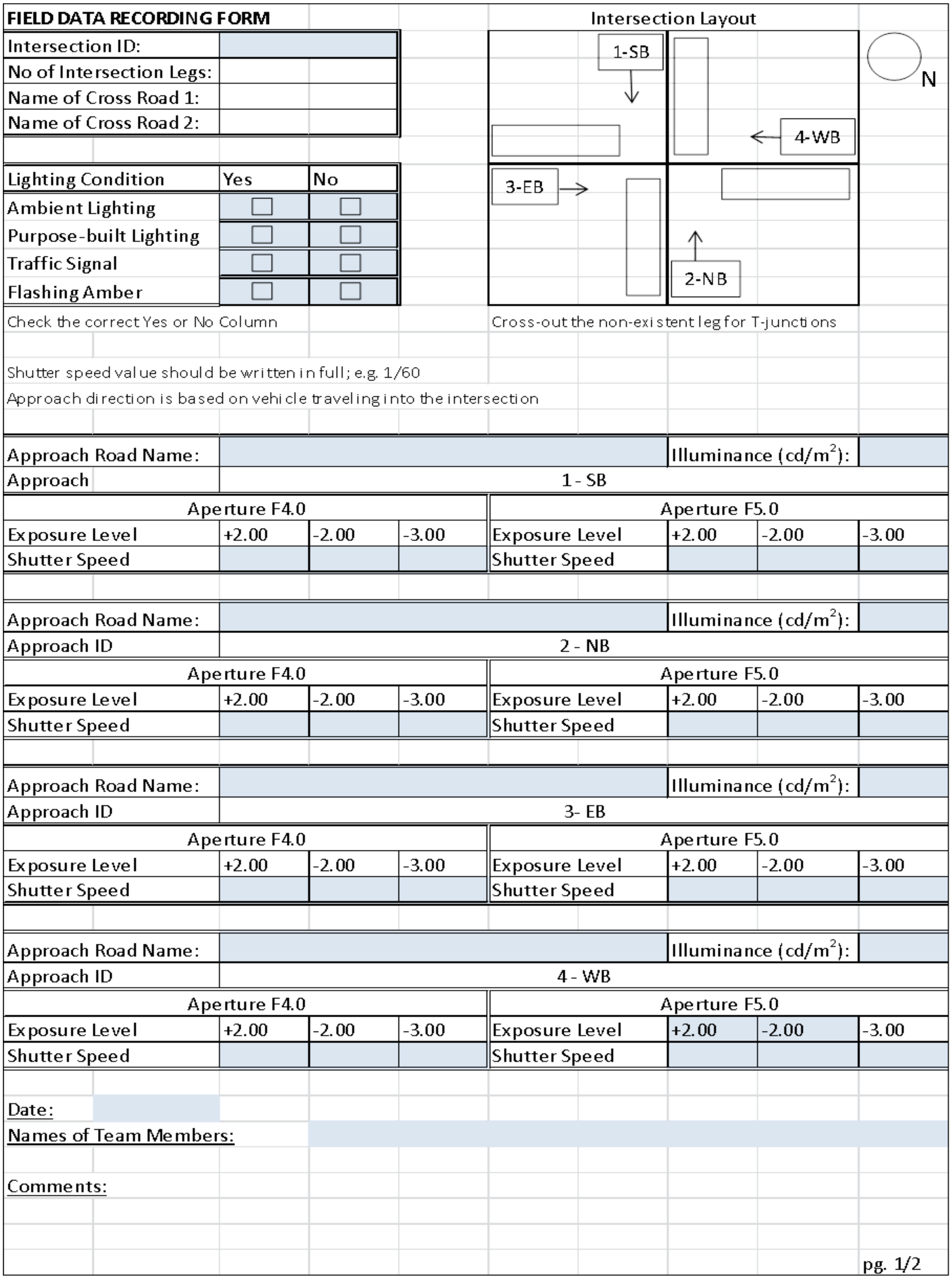
3. Do not use the recording function. Attempting to manually trigger it can cast a shadow of the recorder over the light sensor.
4. The sensor's cable should be stretched out so that the recorder can read the displayed values from a distance without blocking incident light on the sensor.
5. Press the power for the meter to start reading the incident light value continuously.

Record one illuminance reading per intersection leg just before the intersection pictures are taken for the leg. Therefore, the number of recordings will be equal to the number of intersection legs.

8. FIELD DATA RECORDING AND CHECKLIST FORMS

The field data reporting form and a checklist for required equipment and field data are given below. The sketched intersection layout on the data recording form should be modified for a "T" or three leg intersection by crossing out the non-existent leg. Also, care should be taken when assigning the intersection leg directions. ***The directions are based on vehicle traveling into the intersection***. Therefore, a Northbound (NB) designation should be given to the leg on which vehicles entering the intersection are traveling north rather than the leg on which vehicles exiting the intersection are traveling north. Also the directions are general; a Northeast direction from the compass can be taken as Northbound.

The shaded cells on the form represent cells were data is required for correct analysis. Any form with an empty shaded cell cannot be considered as complete (use "NA" to fill cells if no data is available for the cell). The list at the back of the form serve as check list for quality assurance purposes and must have a check mark placed at the end of each row to confirm completion. Figure C13 shows the data recording form while Figure C14 shows the checklist form.



FIELD DATA RECORDING FORM

Intersection ID:
No of Intersection Legs:
Name of Cross Road 1:
Name of Cross Road 2:

Lighting Condition	Yes	No
Ambient Lighting	☐	☐
Purpose-built Lighting	☐	☐
Traffic Signal	☐	☐
Flashing Amber	☐	☐

Check the correct Yes or No Column

Cross-out the non-existent leg for T-junctions

Shutter speed value should be written in full; e.g. 1/60

Approach direction is based on vehicle traveling into the intersection

Approach Road Name:					Illuminance (cd/m^2):		
Approach	1 - SB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed				Shutter Speed			

Approach Road Name:					Illuminance (cd/m^2):		
Approach ID	2 - NB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed				Shutter Speed			

Approach Road Name:					Illuminance (cd/m^2):		
Approach ID	3- EB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed				Shutter Speed			

Approach Road Name:					Illuminance (cd/m^2):		
Approach ID	4 - WB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed				Shutter Speed			

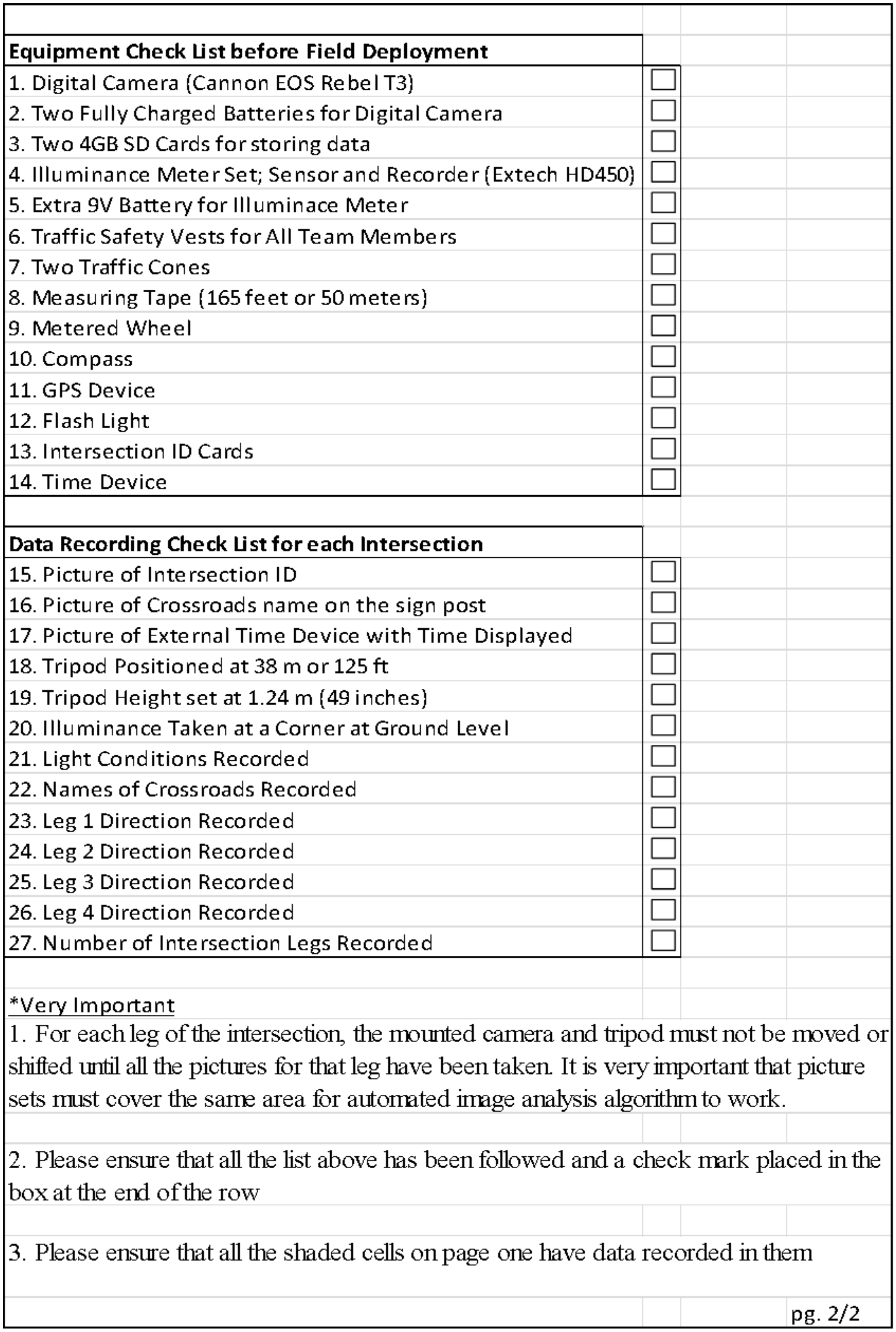
Date:

Names of Team Members:

Comments:

pg. 1/2

Figure F13 Data Recording Form



Equipment Check List before Field Deployment

1. Digital Camera (Cannon EOS Rebel T3) ☐
2. Two Fully Charged Batteries for Digital Camera ☐
3. Two 4GB SD Cards for storing data ☐
4. Illuminance Meter Set; Sensor and Recorder (Extech HD450) ☐
5. Extra 9V Battery for Illuminace Meter ☐
6. Traffic Safety Vests for All Team Members ☐
7. Two Traffic Cones ☐
8. Measuring Tape (165 feet or 50 meters) ☐
9. Metered Wheel ☐
10. Compass ☐
11. GPS Device ☐
12. Flash Light ☐
13. Intersection ID Cards ☐
14. Time Device ☐

Data Recording Check List for each Intersection

15. Picture of Intersection ID ☐
16. Picture of Crossroads name on the sign post ☐
17. Picture of External Time Device with Time Displayed ☐
18. Tripod Positioned at 38 m or 125 ft ☐
19. Tripod Height set at 1.24 m (49 inches) ☐
20. Illuminance Taken at a Corner at Ground Level ☐
21. Light Conditions Recorded ☐
22. Names of Crossroads Recorded ☐
23. Leg 1 Direction Recorded ☐
24. Leg 2 Direction Recorded ☐
25. Leg 3 Direction Recorded ☐
26. Leg 4 Direction Recorded ☐
27. Number of Intersection Legs Recorded ☐

*Very Important

1. For each leg of the intersection, the mounted camera and tripod must not be moved or shifted until all the pictures for that leg have been taken. It is very important that picture sets must cover the same area for automated image analysis algorithm to work.

2. Please ensure that all the list above has been followed and a check mark placed in the box at the end of the row

3. Please ensure that all the shaded cells on page one have data recorded in them

pg. 2/2

Figure F14 Check List Form

9. SUMMARY INSTRUCTIONS

Below is a summary of the instructions that should be followed.

1. Before starting out, go through the equipment check list at the back of the data recording form and make sure all the equipment have been packed into the vehicle for the field trip
2. Park the vehicle off the road and turn off the headlights and emergency lights if it is within 60 m of the intersection.
3. If vehicle can't be parked off road then park the vehicle at least 60 m (200 ft.) from intersection and away from the travel lanes, put on the traffic safety vest before coming out of the vehicle and turn on the emergency hazard lights of the vehicle. Turn off the vehicle headlights so that the light from the vehicle does not compromise the data that will be collected.
4. Insert the battery and SD card into the camera. Take a picture of the intersection ID, the external time device, and crossroad names sign.
5. Set up the tripod at a distance of 38 m (125 ft.) from the stop line (intersection corner if stop line is not marked)
6. Set up the tripod such that the top surface of the tripod is at 1.24 m (49 in) above the ground (measured at the center of the three legs) when tripod is fully set up.
7. Check to ensure that the camera is in the correct shooting mode.
8. Mount the camera on the tripod and orient it so that the view through the lens faces the intersection.
9. Turn on the camera and set the aperture from the quick control screen
10. Use the shutter speed to set the exposure level.
11. Take an illuminance reading before you start taking the set of pictures on an intersection leg.
12. Take a picture of the intersection at each of these exposure levels to +2.00, -2.00, and -3.00
13. If the intersection is too dark and the camera is unable to autofocus then have a team member throw a high flashlight beam on the intersection to help the camera focus. When autofocus is achieved, keep finger on the trigger to maintain the autofocus, turn off the flashlight beam, and take the image.
14. Do not move or shift the mounted camera and tripod until all the pictures have been taken for each intersection leg. Then move the tripod and camera and set up on another intersection leg.
15. Repeat Step 5 through Step 14 for each intersection leg.
16. All the shaded cells on the data form are required data fields. Go through the data recording check list and ensure that all the required data has been collected.

Data Retrieval and Storage

1. All the field data (digital images and scanned copies of the data recording forms) shall be forwarded within 24 hours of field work to the Georgia Tech team for analysis and feedback (if necessary)
2. The survey team must also archive a copy of the digital images and scanned copies of the field data on the supplied 4TB external hard drive

10. PARTS OF THE CAMERA

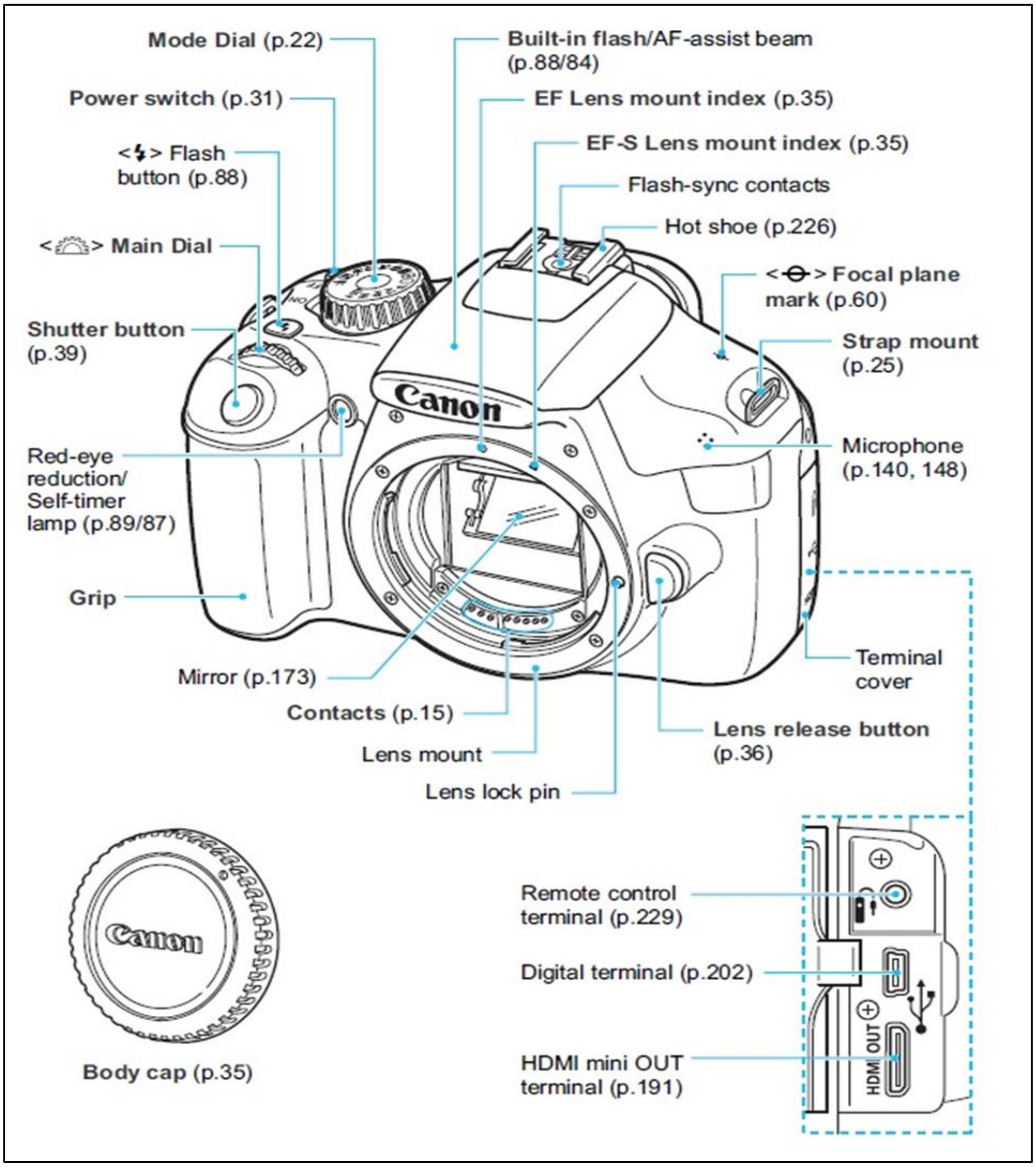


Figure C15 Parts of the Camera

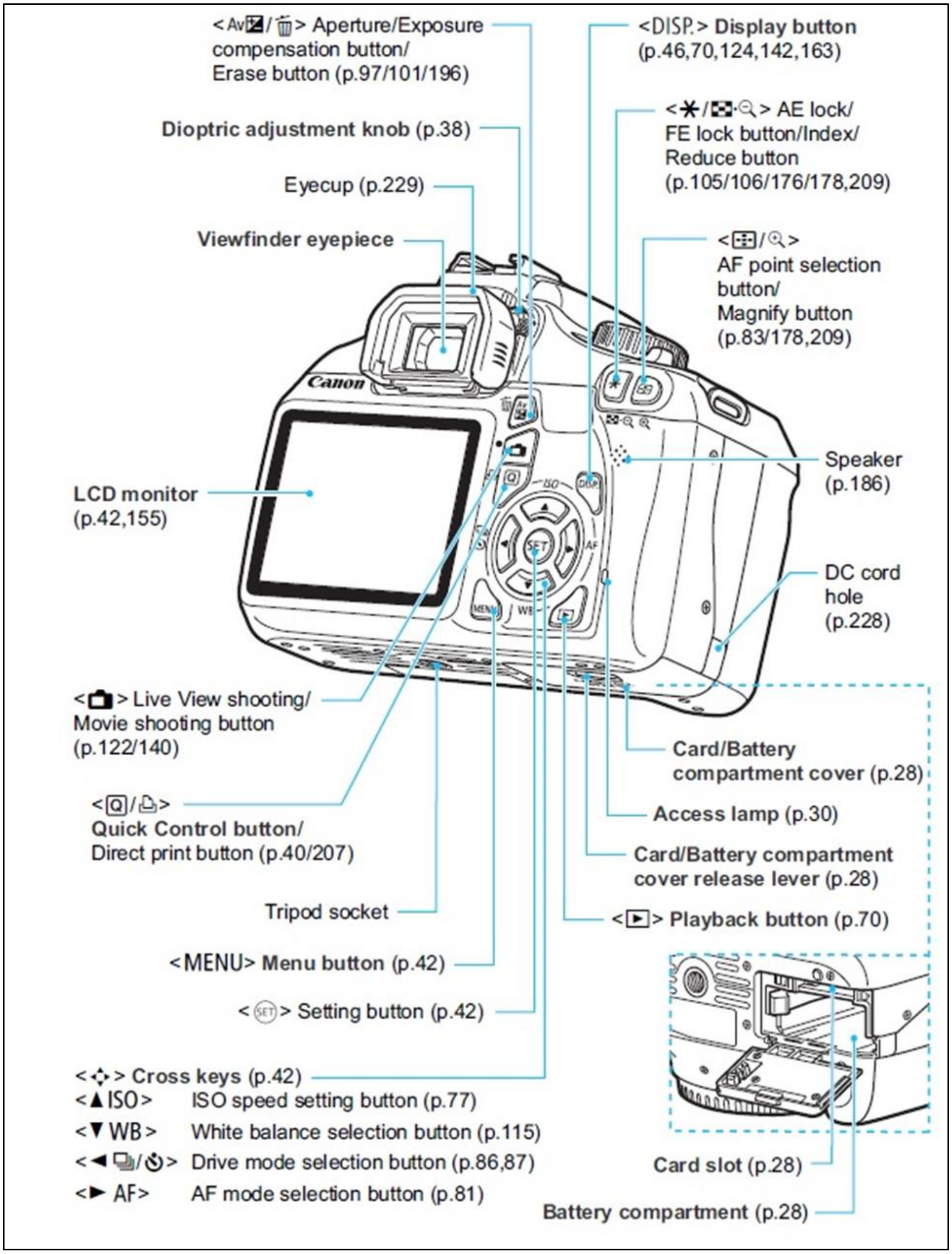
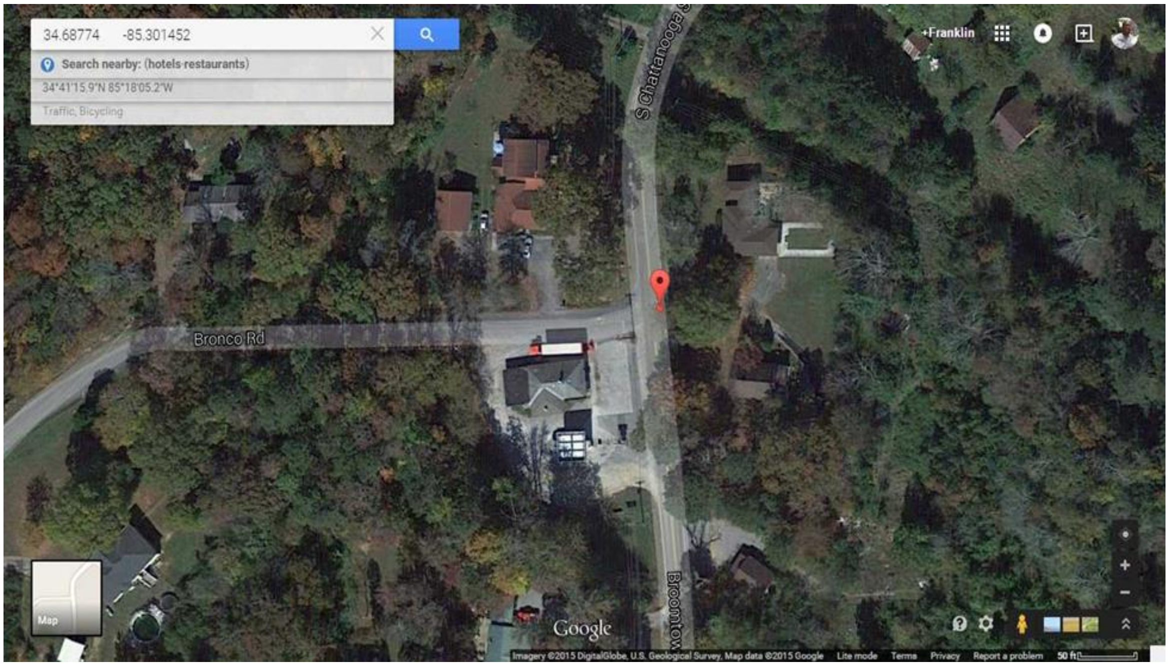


Figure C15 Parts of the Camera. Cont'd

11. CAMERA HANDLING PRECAUTIONS

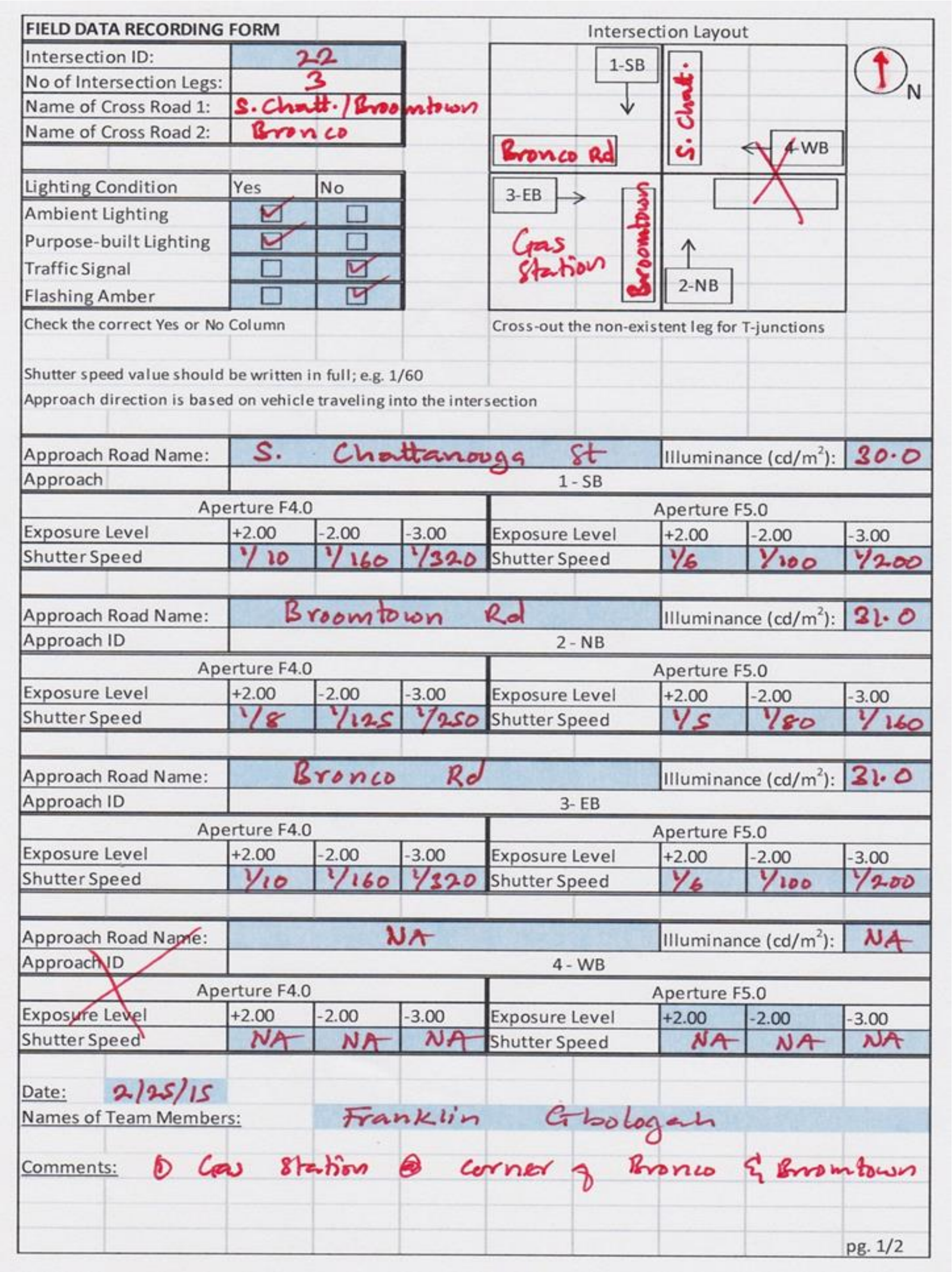
- The Canon Rebel T3 camera is a precision instrument. Do not drop it or subject it to physical shock
- The camera is not waterproof. Avoid any kind of contact with water and avoid storage in a high humidity environment.
- Never leave the camera near anything having a strong magnetic field such as magnet or electric motor.
- Avoid using or leaving the camera near anything emitting strong radio waves such as large antenna.
- Do not leave the camera in excessive heat such as in a car in direct sunlight. High temperatures can cause the camera to malfunction
- Use a blower to blow away dust on the lens, viewfinder, reflex mirror, and focusing screen. Do not use cleaners that container organic solvents to clean the camera body or lens
- Do not touch the camera's contacts with your fingers to avoid corroding them.
- If the camera is suddenly brought in from the cold into a warm room, condensation may form on the internal parts. To avoid condensation, first put the camera in a sealed plastic bag or its packaging and box and let it adjust to the warmer temperature before taking it out of the bag.
- If condensation forms do not use the camera. Remove the lens, card and battery from the camera, and wait until the condensation has evaporated before using the camera.
- Avoid storing the camera where there are corrosive chemicals such as a darkroom or chemical lab

12. EXAMPLE INTERSECTION WITH COMPLETED LUMINANCE DATA RECORDING FORMS



34.68774 -85.301452

Figure C16 Satellite Image of Example Intersection



FIELD DATA RECORDING FORM

Intersection ID:	22
No of Intersection Legs:	3
Name of Cross Road 1:	S. Chatt./Broomtown
Name of Cross Road 2:	Bronco

Lighting Condition	Yes	No
Ambient Lighting	☑	☐
Purpose-built Lighting	☑	☐
Traffic Signal	☐	☑
Flashing Amber	☐	☑

Check the correct Yes or No Column

Shutter speed value should be written in full; e.g. 1/60

Approach direction is based on vehicle traveling into the intersection

Approach Road Name:	S. Chattanooga St			Illuminance (cd/m²):	30.0		
Approach	1 - SB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed	1/10	1/160	1/320	Shutter Speed	1/6	1/100	1/200

Approach Road Name:	Broomtown Rd			Illuminance (cd/m²):	31.0		
Approach ID	2 - NB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed	1/8	1/125	1/250	Shutter Speed	1/5	1/80	1/160

Approach Road Name:	Bronco Rd			Illuminance (cd/m²):	31.0		
Approach ID	3- EB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed	1/10	1/160	1/320	Shutter Speed	1/6	1/100	1/200

Approach Road Name:	NA			Illuminance (cd/m²):	NA		
Approach ID	4 - WB						
Aperture F4.0				Aperture F5.0			
Exposure Level	+2.00	-2.00	-3.00	Exposure Level	+2.00	-2.00	-3.00
Shutter Speed	NA	NA	NA	Shutter Speed	NA	NA	NA

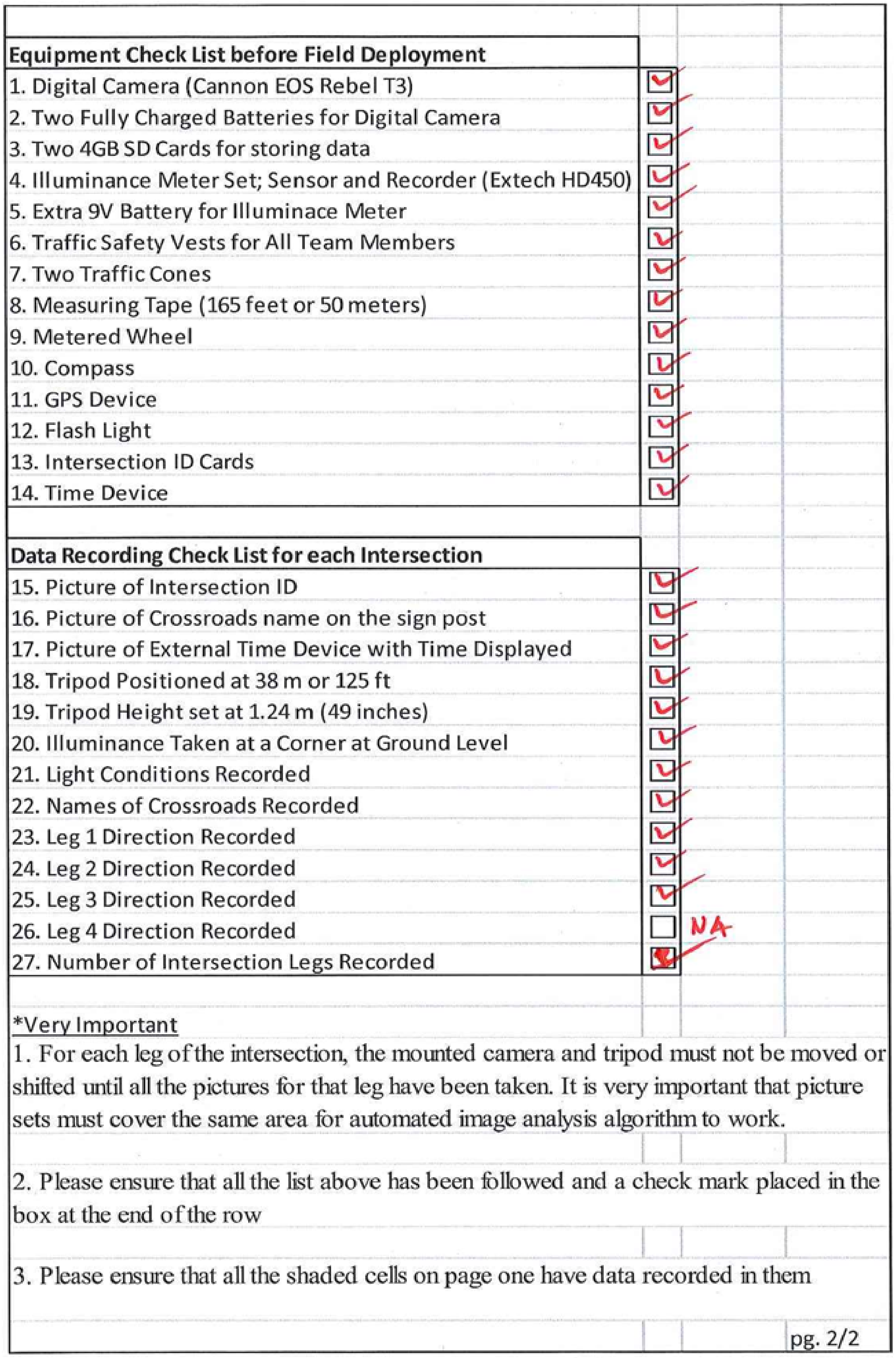
Date: 2/25/15

Names of Team Members: Franklin Gbologah

Comments: ① Gas station @ corner of Bronco & Broomtown

pg. 1/2

Figure C17 Filled Data Recording Form for Example Intersection



Equipment Check List before Field Deployment	
1. Digital Camera (Cannon EOS Rebel T3)	☑
2. Two Fully Charged Batteries for Digital Camera	☑
3. Two 4GB SD Cards for storing data	☑
4. Illuminance Meter Set; Sensor and Recorder (Extech HD450)	☑
5. Extra 9V Battery for Illuminace Meter	☑
6. Traffic Safety Vests for All Team Members	☑
7. Two Traffic Cones	☑
8. Measuring Tape (165 feet or 50 meters)	☑
9. Metered Wheel	☑
10. Compass	☑
11. GPS Device	☑
12. Flash Light	☑
13. Intersection ID Cards	☑
14. Time Device	☑
Data Recording Check List for each Intersection	
15. Picture of Intersection ID	☑
16. Picture of Crossroads name on the sign post	☑
17. Picture of External Time Device with Time Displayed	☑
18. Tripod Positioned at 38 m or 125 ft	☑
19. Tripod Height set at 1.24 m (49 inches)	☑
20. Illuminance Taken at a Corner at Ground Level	☑
21. Light Conditions Recorded	☑
22. Names of Crossroads Recorded	☑
23. Leg 1 Direction Recorded	☑
24. Leg 2 Direction Recorded	☑
25. Leg 3 Direction Recorded	☑
26. Leg 4 Direction Recorded	☐ NA
27. Number of Intersection Legs Recorded	☑

*Very Important

1. For each leg of the intersection, the mounted camera and tripod must not be moved or shifted until all the pictures for that leg have been taken. It is very important that picture sets must cover the same area for automated image analysis algorithm to work.

2. Please ensure that all the list above has been followed and a check mark placed in the box at the end of the row

3. Please ensure that all the shaded cells on page one have data recorded in them

pg. 2/2

Figure C18 Filled Check List Form for Example Intersection

APPENDIX D

CIVIL SURVEY MANUAL FOR INVENTORYING FEATURES THAT INFLUENCING INTERSECTION SAFETY

EVALUATION OF THE COST EFFECTIVENESS OF ILLUMINATION
AS A SAFETY TREATMENT AT RURAL INTERSECTIONS

Civil Survey Manual for Inventorying Features that Influence Intersection Safety

MARCH, 2015

1. OVERVIEW – DETERMINING THE SAFETY INFLUENCE AREA OF AN INTERSECTION

The selection of intersection related crashes for analysis requires a systematic way to determine an intersection's safety influence area. The length of this so called influence area depends on the geometric design, traffic control, and operating features (Abdel-Aty et al. 2009; North Carolina Department of Transportation 1999). Some states use a distance of 250 feet from the center of the intersection to determine if the crash is within this influence area while other states also determine this area by considering the effect of left turning lanes (Abdel-Aty et al. 2009). Table D1 shows the distances used by different states.

There have been a lot of inconsistencies in the length of the safety influence area used in previous studies. Lyon et al. (2005) used a distance of 65.6ft from the center of the intersection to identify intersection related crashes for their study of intersections in Toronto. A distance of 150ft has also been used by Persaud et al. (2005) to identify rear-end collisions related to intersections. Next, Hardwood et al. (2003), Mittra et al. (2007), and Donnell et al. (2010) all used a safety influence distance of 250ft to identify intersection related crashes. Cottrell and Mu (2005) also identified intersection related crashes in Utah based on the stopping sight distance. Initially they applied a distance of 500ft for an average approach speed of 40 mph. However, they realized that a 100ft distance was applicable to most of their intersections and only two intersections needed the 500ft distance as influence area. Another study (Joksch and Kostyniuk 1998) of intersections from three different states applied varying influence area distances ranging from 350ft to 7ft.

Abdel-Aty et al. (2009) argue that the main challenge in determining intersection related crashes is deciding the safety influence area upstream of the approach. The authors performed a study to investigate how the size of the intersection, left-turn lane length, through and left turning traffic volumes, skewness and other intersection features affect the safety influence area upstream of approach. The study analyzed crash data from 177 regular four-legged intersections in Florida from 2000 to 2005. The results show that the approach upstream safety influence area is influenced by the through volume, approach speed, number of right lanes and left turn protection. The authors concluded that since the approaches to an intersection can have different attributes, it may be advantageous to define the safety influence area of each approach separately.

Table D1 Default Distances Used by Different States to Identify Intersection Safety Area

State	**Length of Intersection Influence area from center of Intersection**
Alaska	200 feet
California	250 feet
Colorado	264 feet upstream of approach
Connecticut	50 feet from stop bar
Delaware	528 feet
Florida [a]	At Intersection: less than 50 feet Intersection related: 50 to 250 feet
Hawaii [b]	75 feet, more if crash occurred in left turn lane
Iowa	Urban: 75 feet Rural: 150 feet Expressways: 300 feet High speed road: up to 1320 feet
Kansas	150 feet, more if intersection is large
Maryland	250 feet
Mississippi	500 feet of upstream only
Missouri	132 feet
Utah	138 feet, more if intersection is large
Vermont	Determined by stopping sight distance, e.g. 275 feet for 40 mph
Virgin Islands	100 feet
Note: [a] Crash reports show that police officers usually measure from stop bar and not center of intersection [b] Not stated in report if distance is from the center or edge	

2. REQUIRED FIELD EQUIPMENT

- Compass
- GPS device
- Traffic safety vest for each team member
- Survey-crew-ahead signs
- Two traffic cones
- Metered wheel
- 25 feet tape measure
- Laser distance meter (Bosch GLM 50)
- Laser target card

- Laser enhancement glasses

3. SAFETY PRECAUTIONS

Survey crew must wear a traffic safety vest at all times. The vest must be on before they set off from their base to the intersection site(s). The vest must be worn on top of all other clothing. No one must work at any of the intersection sites without a safety vest. The survey must be carried out by at least two surveyors; one can serve as a lookout to warn of impending hazard while the other does the main survey work. ***Crew members should not enter the active travel lane at any time***. There is no required measurement that will require crew members to be in the active travel lane.

All state-specific safety guidelines should be followed including those outlined in the GDOT Automated Survey Manual. The GDOT Automated Survey Manual can be downloaded at the web address below.
http://www.dot.ga.gov/doingbusiness/policiesmanuals/roads/surveymanual/surveymanual.pdf

Supplemental safety guidelines can be obtained from the 'Survey Safety Handbook of the Florida DOT and the 'Caltrans Survey Manual' of the California DOT. The links to these two documents are given below.
http://www.dot.state.fl.us/surveyingandmapping/documentsandpubs/safety.pdf
http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/02_Surveys.pdf

4. DATA COLLECTION BOUNDARY

Data shall be collected within a boundary of 400 feet from the entry/exit point of each intersection leg. The stop lines should be used to delineate exit and entry points. See Figure D1. In situations where the 400 feet point from a survey intersections is closer to an adjacent intersection (less than 400 feet from the stop line of the adjacent intersections), the boundary on that leg should be set at the half-way mid-block point.

5. GEOCODING OF INTERSECTIONS

The latitude and longitude of each intersection surveyed shall be recorded. The reference location point shall be a point within 100ft of the intersection's center. The latitude and longitude values should be recorded as decimal degrees.

6. SELECTION OF INTERSECTIONS

The civil survey shall be performed at 60 selected rural intersections. The intersections have been selected within 50 mile buffer zones of Cochran, Atlanta, Brunswick, and Dalton in Georgia.

The intersections were selected by a stratified-random process. Stratification involved grouping a larger set of about 153 intersections into three illumination categories and two AADT groupings per illumination category. The three illumination categories are "None", "Partial", and "Full". The AADT categories are "Low" and "High". High AADT group consist of sites with a 5-Year (2009 – 2013) AADT not less than 4000 cars per day. Thus, there are 6 stratified selection bins. Next, 10 intersections were randomly selected from each bin using a discrete random number generator.

7. MEASURING THE WIDTH OF TRAVEL LANES

In order to avoid crew members entering the active travel lanes to measure the widths, the survey team has been furnished with a Bosh GLM 50 laser distance meter, a laser target card, and laser enhancement glasses to be worn during daytime to enhance the ability to see the red beam laser in sunlight. ***Please measure the lane width on the intersection boundary on the leg (see the Data Collection Boundary session discuss prior)***

<u>To measure the lane width on a two-way road</u>

- Use the laser meter and the laser target card to measure the entire road width from one edge of the pavement to the other.
- One crew member should have the laser meter on one edge while another crew member holds the laser target card at the other end. **WARNING:** ***In order to avoid eye damage, crew member holding the card should never look at the laser meter while he is holding the card.***
- Beam the laser across the travel lanes to hit the target. Note the width of the two-way road as displayed on the screen of the meter.
- Divide the measured distance by the number of lanes to obtain the width of each lane.

<u>To measure lane width on a divided highway (With wide median island)</u>

- Measure the edge to edge road width for only the in-coming approach lanes.
- One crew member should hold the laser meter on the edge of pavement closer to the shoulder while the target card is held at the edge of the pavement closer to the median with the crew member safely located on the median island.
- Beam the laser across the travel lanes to hit the target. Note the width of the two-way road as displayed on the screen of the meter.
- Divide the measured distance by the number of lanes to obtain the width of each lane.

WARNING: ***If the median island is not sufficiently wide or otherwise does not provide a safe refuge for the surveyor, the approach should be treated similar to a road with no median and the total width should be divided by the number of lanes across both oncoming and outgoing lanes.***

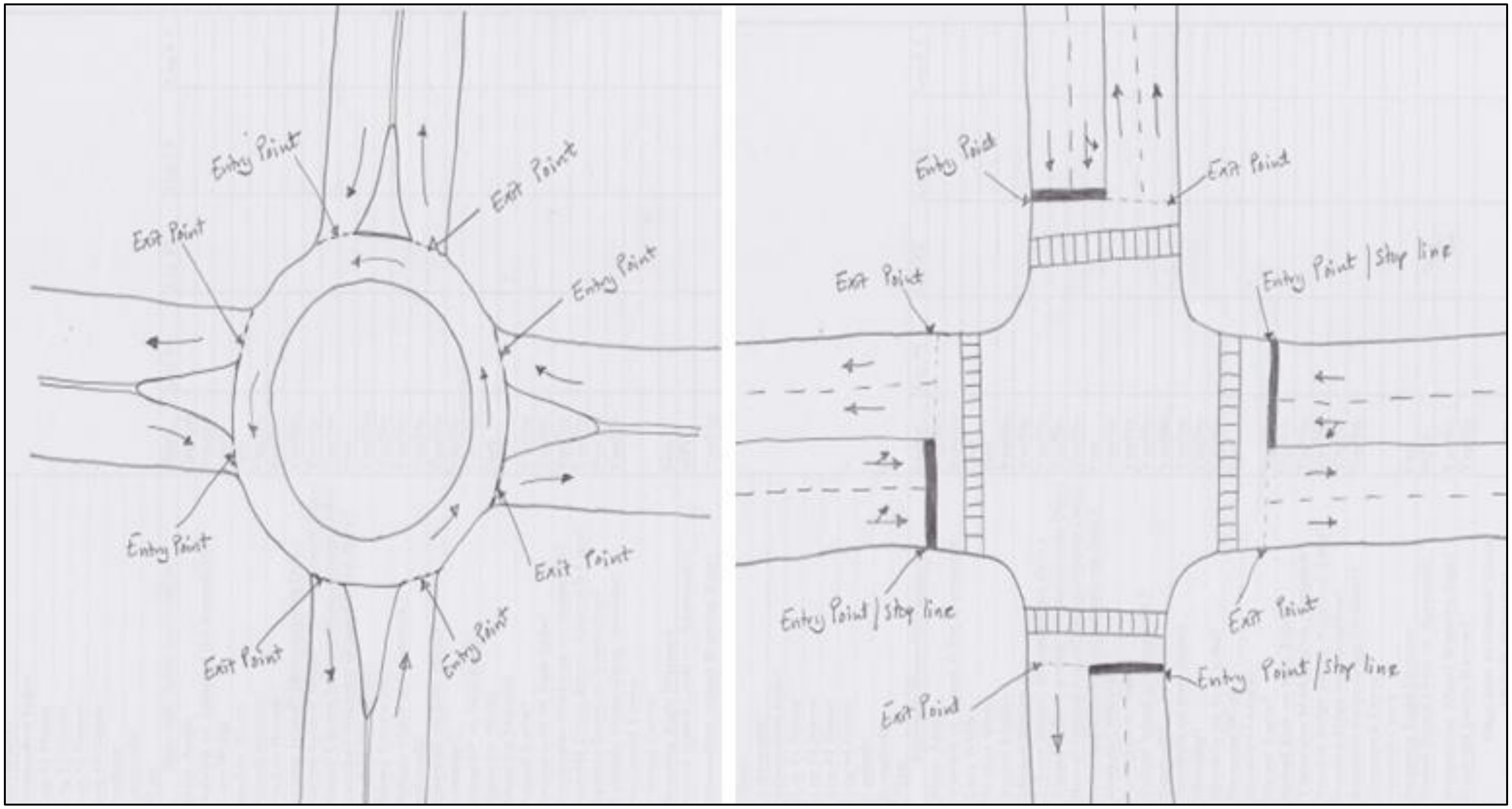


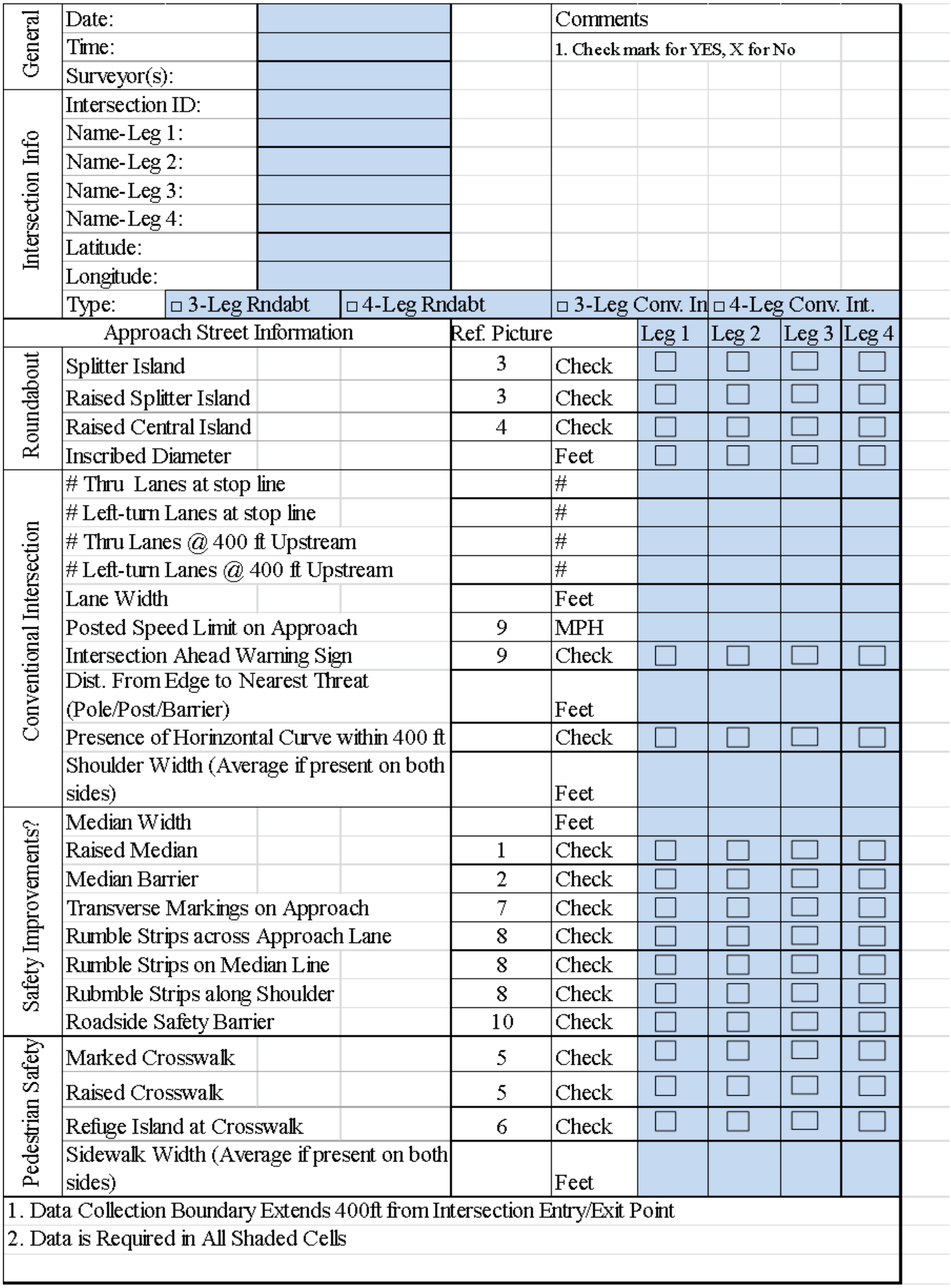
Figure D1 Location of Entry and Exit Points at Roundabouts and Conventional Intersections

8. DATA RECORDING

1. First, complete a sketch of the intersection layout. Choose the appropriate basic layout form shown in Figure D3 or Figure D4 depending on the intersection type. The basic layouts provided are for 4-leg intersections. Corresponding sketch for three-leg intersections should be made by crossing out one of the intersection legs.
2. Include, in the layout, a sketch of any abutting properties within 40 meters of the stop lines. ***WARNING: Surveyors should not trespass on any private property.***
3. Indicate the true North direction with a North Arrow on the intersection layouts
4. Assign intersection leg direction based on direction of vehicle traveling towards the intersection on the approach. For example, the Northbound (NB) approach is the one on which vehicles traveling towards the intersection are heading NB
5. Record the survey results on the Data Recording Form shown in Figure 3.
6. Record the presence of other possible lighting source(s) other than purposely built street lights at the intersection. For example, a Gas Station, Shop, or House.
7. The completed data forms must be scanned (including the sketch of the intersection layout) and emailed to the analysis team at Georgia Tech within 24 hours of any field survey.

Copies of the data must also be stored on the supplied 4TB external hard drive and returned to the Georgia Tech team after all data collection activities have been completed.

Data Reporting Forms



General	Date:			Comments			
	Time:			1. Check mark for YES, X for No			
	Surveyor(s):						
Intersection Info	Intersection ID:						
	Name-Leg 1:						
	Name-Leg 2:						
	Name-Leg 3:						
	Name-Leg 4:						
	Latitude:						
	Longitude:						
	Type:	☐ 3-Leg Rndabt	☐ 4-Leg Rndabt	☐ 3-Leg Conv. In	☐ 4-Leg Conv. Int.		
Approach Street Information		Ref. Picture		Leg 1	Leg 2	Leg 3	Leg 4
Roundabout	Splitter Island	3	Check	☐	☐	☐	☐
	Raised Splitter Island	3	Check	☐	☐	☐	☐
	Raised Central Island	4	Check	☐	☐	☐	☐
	Inscribed Diameter		Feet	☐	☐	☐	☐
Conventional Intersection	# Thru Lanes at stop line		#				
	# Left-turn Lanes at stop line		#				
	# Thru Lanes @ 400 ft Upstream		#				
	# Left-turn Lanes @ 400 ft Upstream		#				
	Lane Width		Feet				
	Posted Speed Limit on Approach	9	MPH				
	Intersection Ahead Warning Sign	9	Check	☐	☐	☐	☐
	Dist. From Edge to Nearest Threat (Pole/Post/Barrier)		Feet				
	Presence of Horinzontal Curve within 400 ft		Check	☐	☐	☐	☐
	Shoulder Width (Average if present on both sides)		Feet				
Safety Improvements?	Median Width		Feet				
	Raised Median	1	Check	☐	☐	☐	☐
	Median Barrier	2	Check	☐	☐	☐	☐
	Transverse Markings on Approach	7	Check	☐	☐	☐	☐
	Rumble Strips across Approach Lane	8	Check	☐	☐	☐	☐
	Rumble Strips on Median Line	8	Check	☐	☐	☐	☐
	Rubmble Strips along Shoulder	8	Check	☐	☐	☐	☐
	Roadside Safety Barrier	10	Check	☐	☐	☐	☐
Pedestrian Safety	Marked Crosswalk	5	Check	☐	☐	☐	☐
	Raised Crosswalk	5	Check	☐	☐	☐	☐
	Refuge Island at Crosswalk	6	Check	☐	☐	☐	☐
	Sidewalk Width (Average if present on both sides)		Feet				

1. Data Collection Boundary Extends 400ft from Intersection Entry/Exit Point
2. Data is Required in All Shaded Cells

Figure D2 Intersection Safety Feature Reporting Form

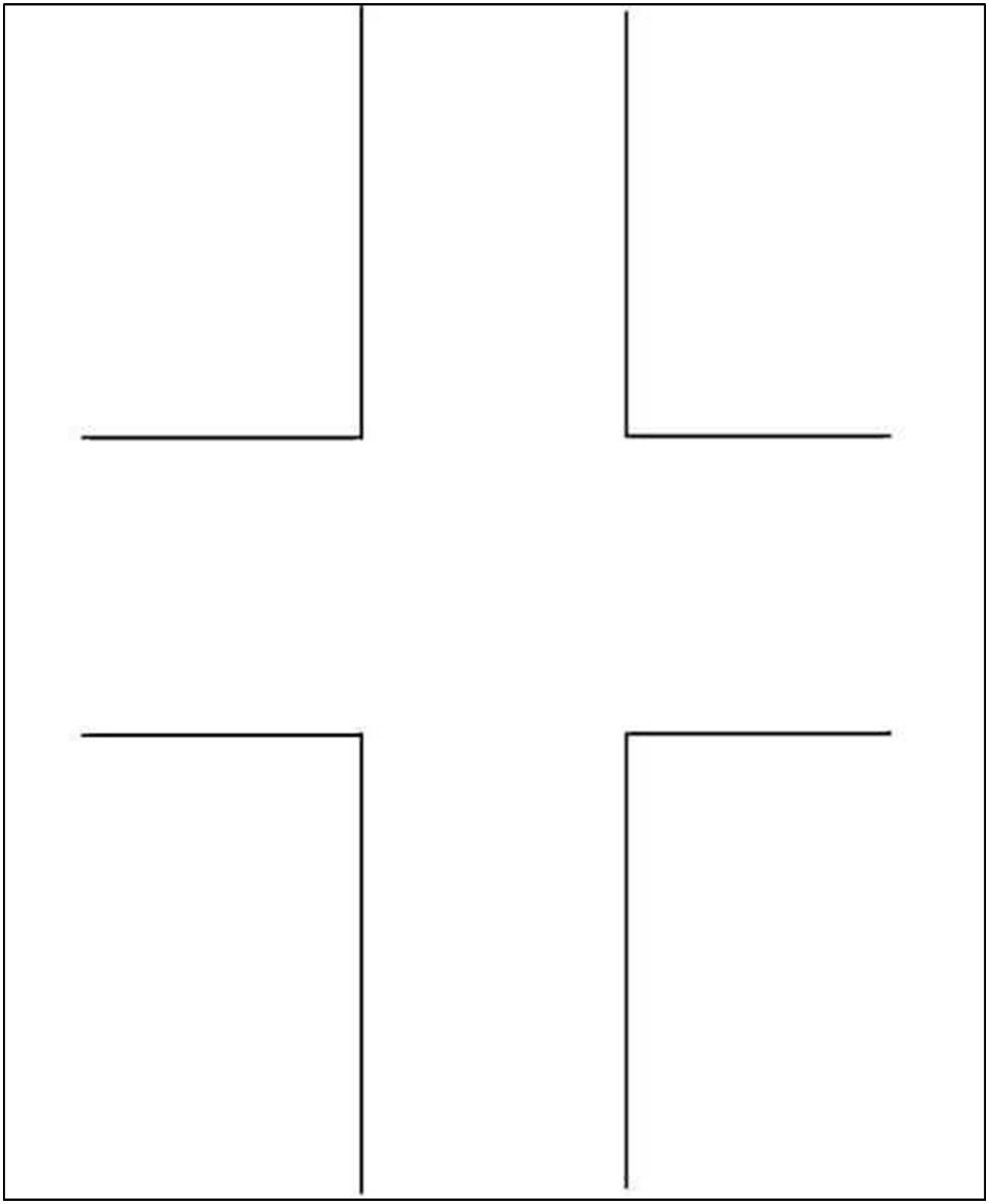


Figure D3 Basic Layout of a Conventional Intersection

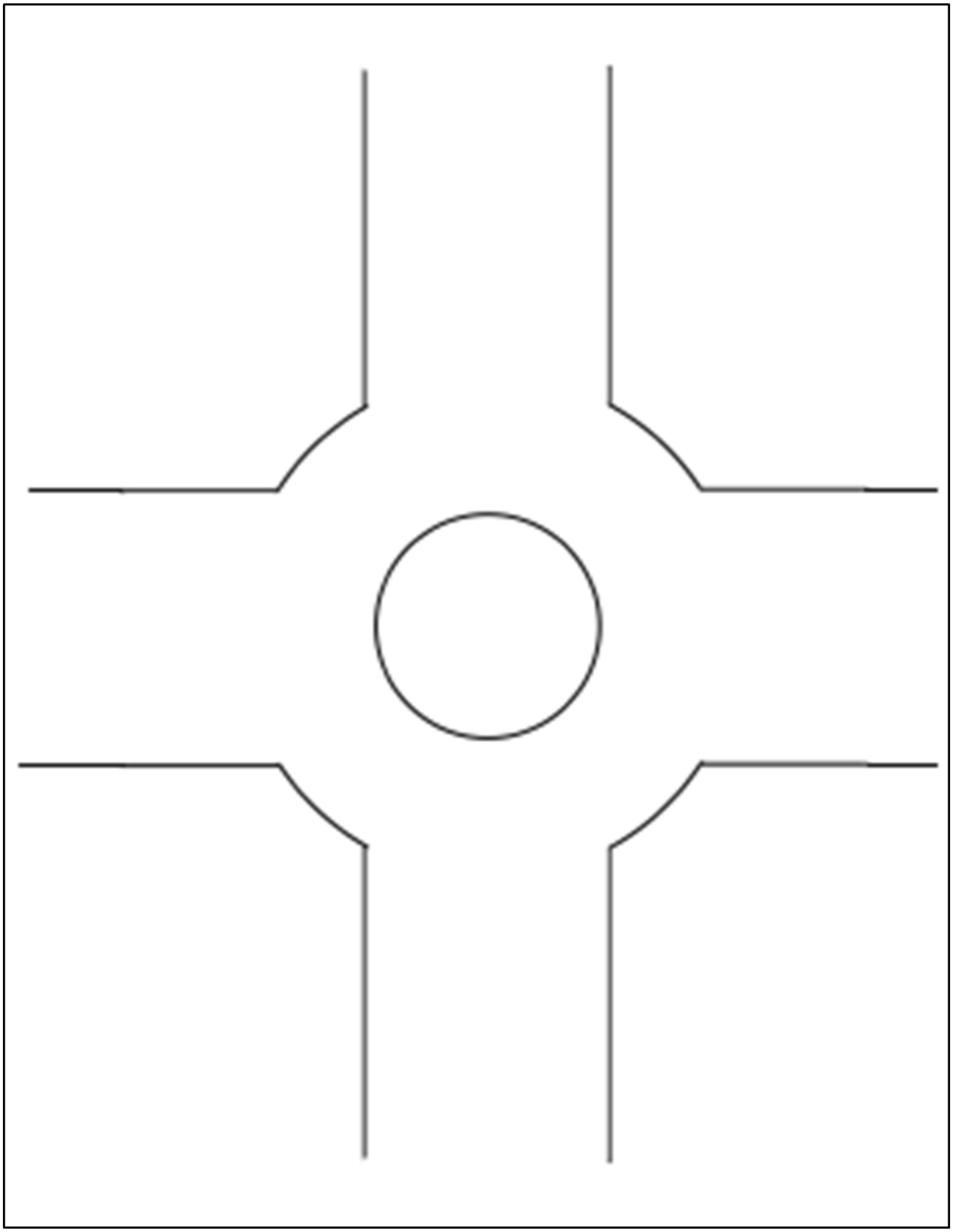


Figure D4 Basic Layout of a Roundabout

9. EXAMPLE INTERSECTION WITH COMPLETED INTERSECTION SAFETY FEATURE FORMS

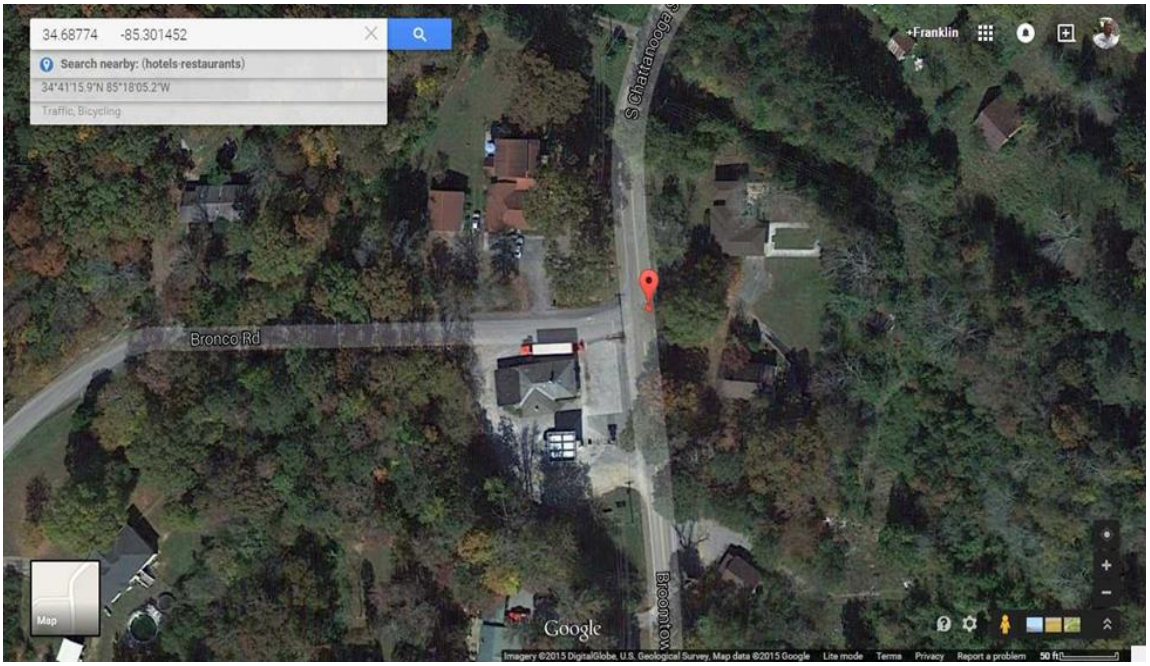


Figure D5 Satellite Image of Example Intersection

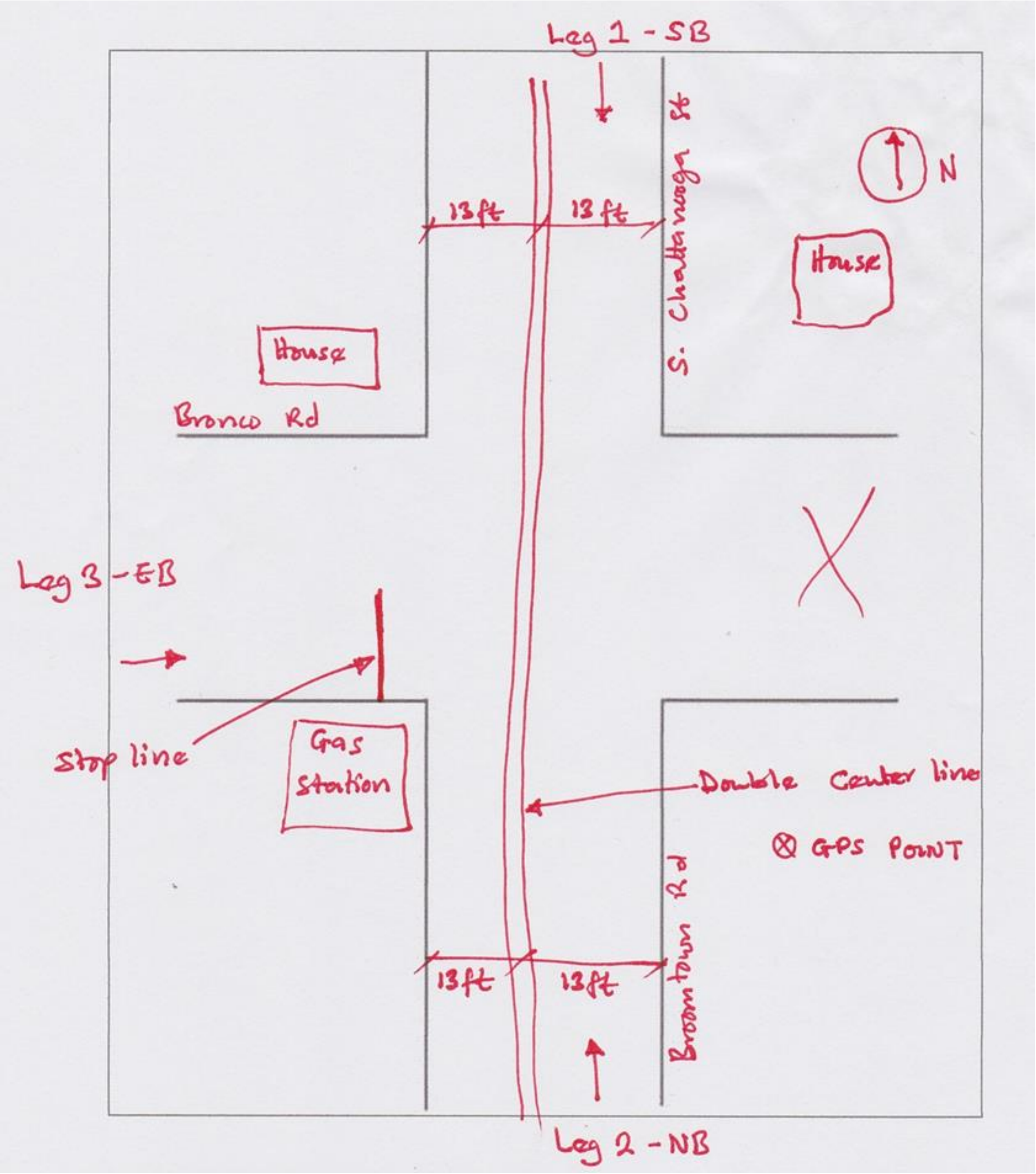
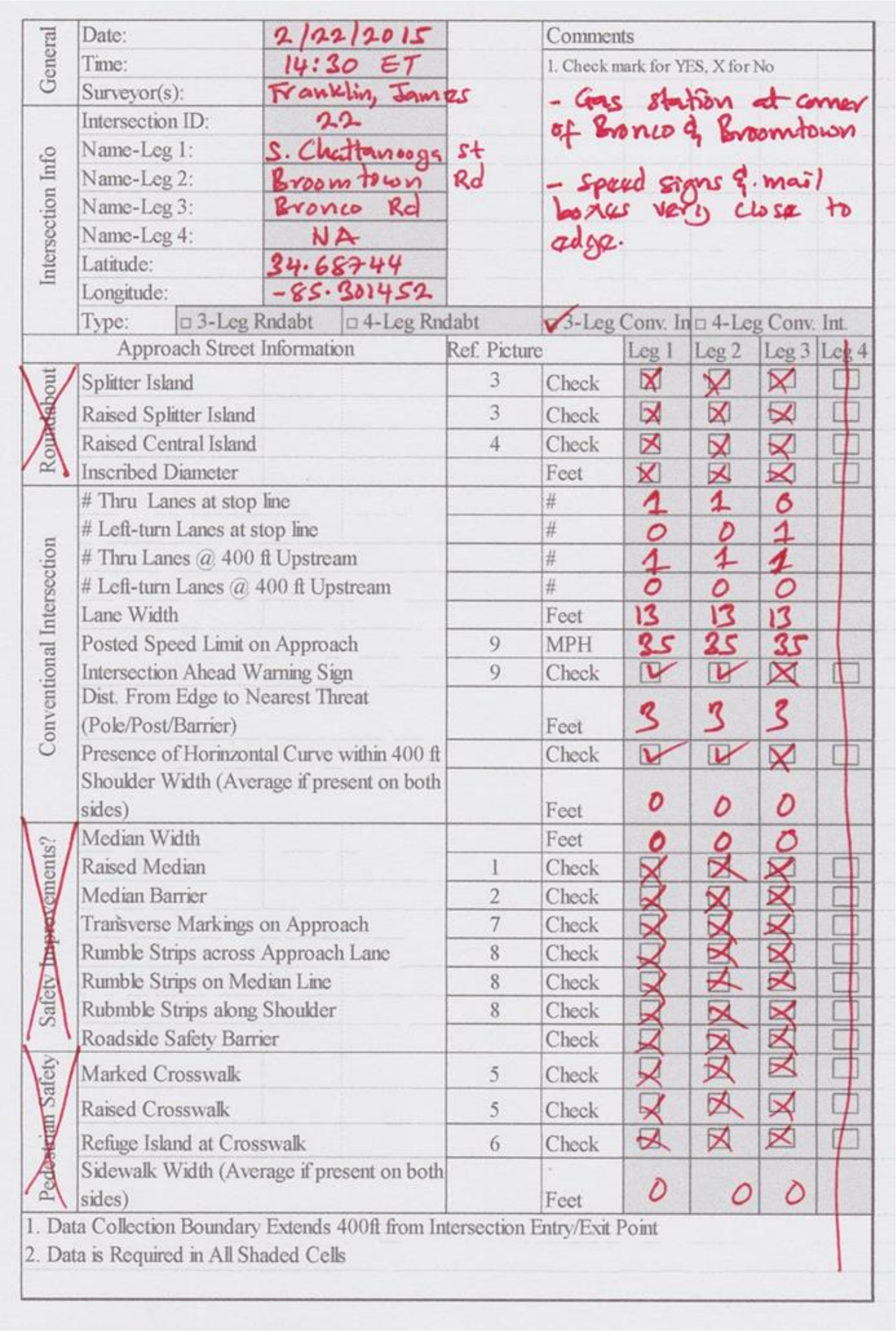


Figure D6 Intersection Layout Form with Notes



General	Date:	2/22/2015
	Time:	14:30 ET
	Surveyor(s):	Franklin, James
Intersection Info	Intersection ID:	22
	Name-Leg 1:	S. Chattanooga St
	Name-Leg 2:	Broomtown Rd
	Name-Leg 3:	Bronco Rd
	Name-Leg 4:	NA
	Latitude:	34.68744
	Longitude:	-85.301452
	Type:	☐ 3-Leg Rndabt ☐ 4-Leg Rndabt ☑ 3-Leg Conv. In ☐ 4-Leg Conv. Int.

Comments

1. Check mark for YES, X for No

- Gas station at corner of Bronco & Broomtown

- speed signs & mail boxes very close to edge.

	Approach Street Information	Ref. Picture		Leg 1	Leg 2	Leg 3	Leg 4
~~Roundabout~~	Splitter Island	3	Check	☒	☒	☒	☐
	Raised Splitter Island	3	Check	☒	☒	☒	☐
	Raised Central Island	4	Check	☒	☒	☒	☐
	Inscribed Diameter		Feet	☒	☒	☒	☐
Conventional Intersection	# Thru Lanes at stop line		#	1	1	0	
	# Left-turn Lanes at stop line		#	0	0	1	
	# Thru Lanes @ 400 ft Upstream		#	1	1	1	
	# Left-turn Lanes @ 400 ft Upstream		#	0	0	0	
	Lane Width		Feet	13	13	13	
	Posted Speed Limit on Approach	9	MPH	35	25	35	
	Intersection Ahead Warning Sign	9	Check	☑	☑	☒	☐
	Dist. From Edge to Nearest Threat (Pole/Post/Barrier)		Feet	3	3	3	
	Presence of Horinzontal Curve within 400 ft		Check	☑	☑	☒	☐
	Shoulder Width (Average if present on both sides)		Feet	0	0	0	
~~Safety Improvements?~~	Median Width		Feet	0	0	0	
	Raised Median	1	Check	☒	☒	☒	☐
	Median Barrier	2	Check	☒	☒	☒	☐
	Transverse Markings on Approach	7	Check	☒	☒	☒	☐
	Rumble Strips across Approach Lane	8	Check	☒	☒	☒	☐
	Rumble Strips on Median Line	8	Check	☒	☒	☒	☐
	Rubmble Strips along Shoulder	8	Check	☒	☒	☒	☐
	Roadside Safety Barrier		Check	☒	☒	☒	☐
~~Pedestrian Safety~~	Marked Crosswalk	5	Check	☒	☒	☒	☐
	Raised Crosswalk	5	Check	☒	☒	☒	☐
	Refuge Island at Crosswalk	6	Check	☒	☒	☒	☐
	Sidewalk Width (Average if present on both sides)		Feet	0	0	0	

1. Data Collection Boundary Extends 400ft from Intersection Entry/Exit Point
2. Data is Required in All Shaded Cells

Figure C7 Filled Intersection Safety Feature Reporting Form

10. IMAGES OF TYPICAL ROADWAY ELEMENTS

Michael Ronkin, Designing Streets for Pedestrians and Bicyclists

Figure D8 Example of a Raised Median

Figure D9 Examples of Median Barrier

Figure D10 Examples of Splitter Island

Figure D11 Examples of Central Island (Left: Raised, Right: Flat)

Figure D12 Examples of Crosswalk (Left: Marked, Center: Unmarked, Right: Raised)

Figure D13 Example of a Refuge Island

Figure D14 Example of a Transverse Lane Marking

Figure D15 Examples of Rumble Strips (Left: Centerline Rumble Strips, Middle: Lane Rumble Strips, Right: Shoulder Rumble Strips)

Figure D16 Examples of Intersection Ahead Signs

Figure D17 Examples of Roadside Barrier

11. LABELED DIAGRAMS OF TYPICAL INTERSECTIONS

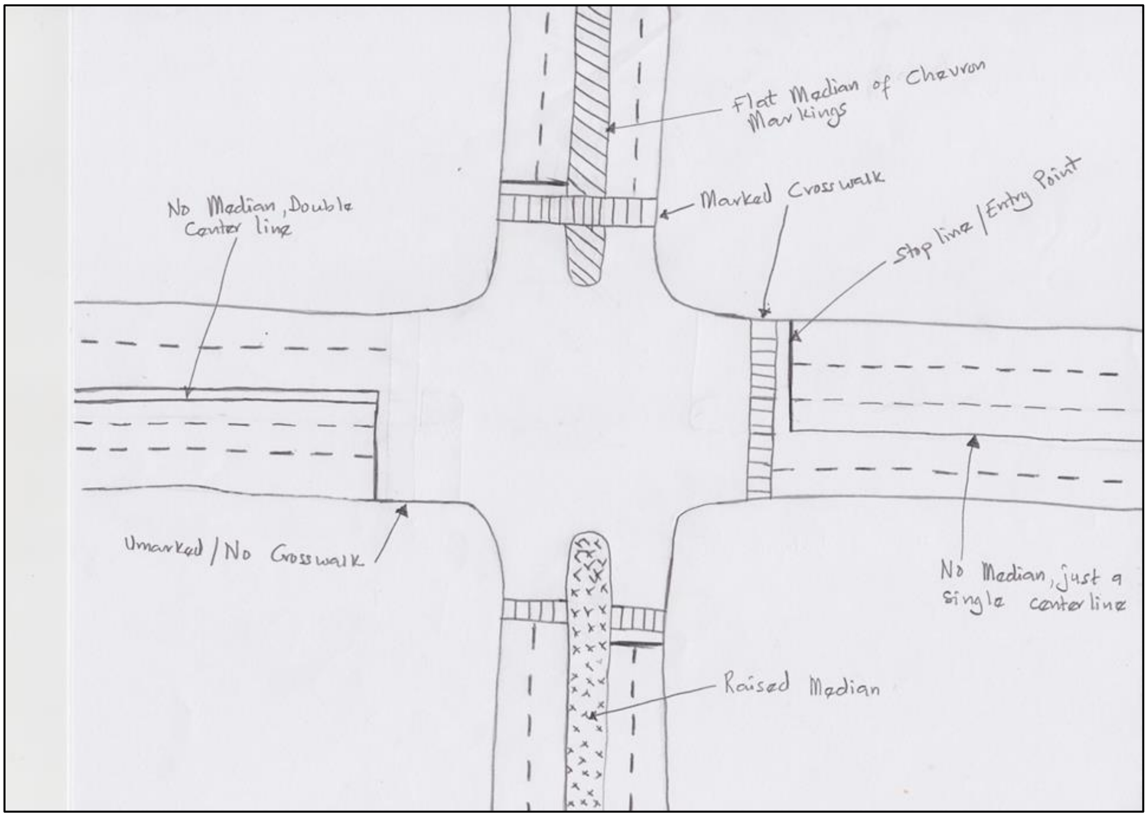


Figure D18 Labeled Diagram of Typical Conventional Intersection Layout

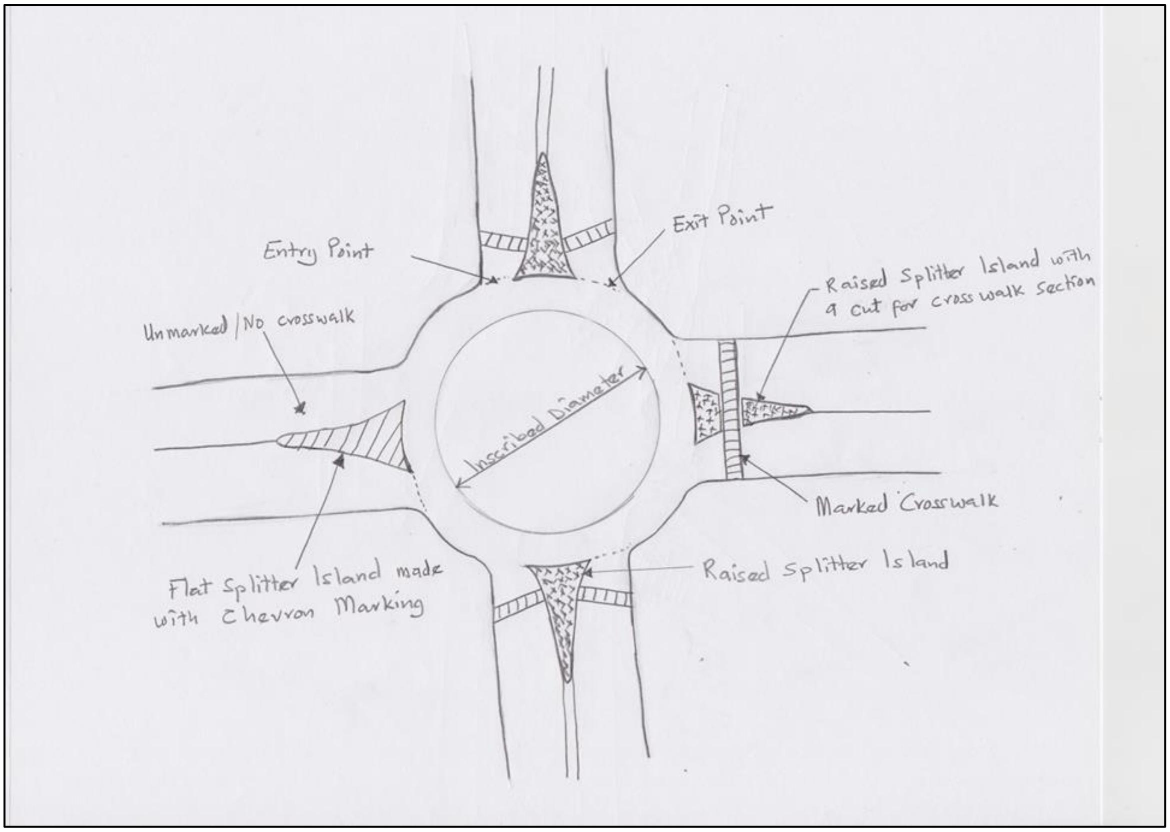


Figure D19 Labeled Diagram of Typical Roundabout Layout

12. REFERENCE

Abdel-Aty, M., X. Wang, and J. Santos. (2009). "Identifying Intersection-Related Traffic Crashes for Accurate Safety Representation." In Institute of Transportation Engineers. ITE Journal, No. 79(12), p.p 38-44.

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North Carolina Department of Transportation. (1999). "North Carolina Crash Report Instruction Manual."

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APPENDIX E

CALCULATING AVERAGE PIXEL INTENSITY FROM A SELECTED AREA OF AN IMAGE

This appendix shows a sample Perl® script used to calculate the average pixel intensity from a selected area of an image. The steps needed to use the script in ImageJ for automated analysis are as given below. The sample script can be found at the end of the numbered analysis steps shown below.

(a) Check the properties of the images that would be analyzed and identify the possible batch groups. A batch group is a set of images taken from the same position on an approach and with the same zoom/magnification/focus. This is necessary because the coordinates of features in such images will be the same. This is an important requirement to ensure that the coordinates of the intersection area identified from one image will apply to the whole set. Also, it is important that the images are numbered successively.

(b) Open ImageJ and then open the **macro recorder window** by following the following menu sequence; **Plugins→Macros→Record**

(c) Copy or type out the script supplied at the end of this appendix into a text editor such as notepad and save it.

(d) Open the saved script in the **macro window** with the following sequence of steps; **Plugins→Macros→Edit** and browse to the saved location of the script to open it.

(e) Open the first image in the set in ImageJ by sequentially clicking the following menus **File→Open** and browse to the image location to select it.

(f) Activate the Polygon tool by clicking on it. The Polygon tool is the third menu on the main menu bar (as shown in ImageJ 1.48v)

(g) Click the boundaries of the measurement area in on the image to demarcate it. Use as many clicks as possible to ensure that the polygon closely matches the area.

(h) Copy the coordinates of the measurement area from the **macro recorder window**. The coordinates can be found in parenthesis besides the “make polygon” command in the **macro recorder window**.

(i) Paste over or replace the coordinates in the script with the coordinates from the **macro recorder window**.

(j) Change the number of **iterations** in the script to **N – 1**, where N is the number of images being analyzed in the current batch group. For example, in the supplied script the number of images being analyzed is 5 so the N = 4.

(k) Run the script by following the following sequence of menus in the **macro window**; **Macros→Run Macro**. Alternatively, you can click on the **macro window** to make it the active window and then press **Ctrl+R**.

(l) The calculated mean pixel intensity over the measurement area for the images in the batch group will pop-up in the **results window**. The order of the results follows the image numbers (names).

SAMPLE SCRIPT

```
//This script will draw a polygon over the desired measurement area and estimate the
// average pixel intensity within the area.
run ("Measure");      // Estimate the average pixel intensity for the first image in the batch
for (i=1;i<=4;i++){     // Do for the next four images
run ("Open Next");  // Open the next image
run ("In [+]");                    // Zoom in
run ("In [+]");                    // Zoom in
run ("In [+]");                    // Zoom in
// Draw a polygon of the measurement area with the endpoints listed
makePolygon(2128,1452,2700,1412,2704,1456,2782,1474,3182,1518,2600,1620,1868,1506);
run ("Measure");      // Estimate the average pixel intensity
}
```

APPENDIX F

INTERSECTION LOCATION MAPS AND INTERSECTION LAYOUT IMAGES

This appendix presents maps showing the ID and locations of the studied conventional intersections and roundabouts.

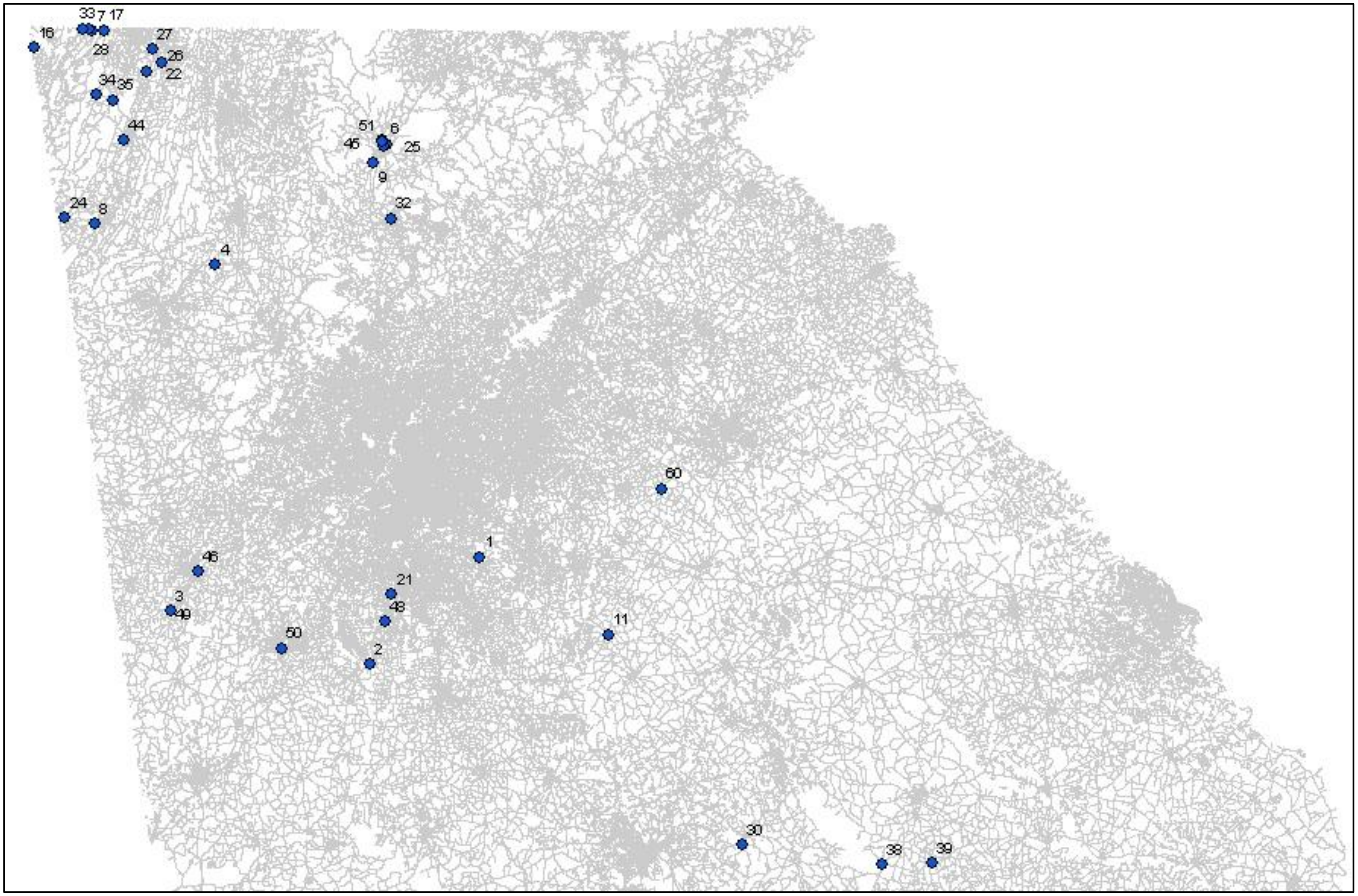

Figure F1 Studied Conventional Intersection Locations in the Upper Half of Georgia

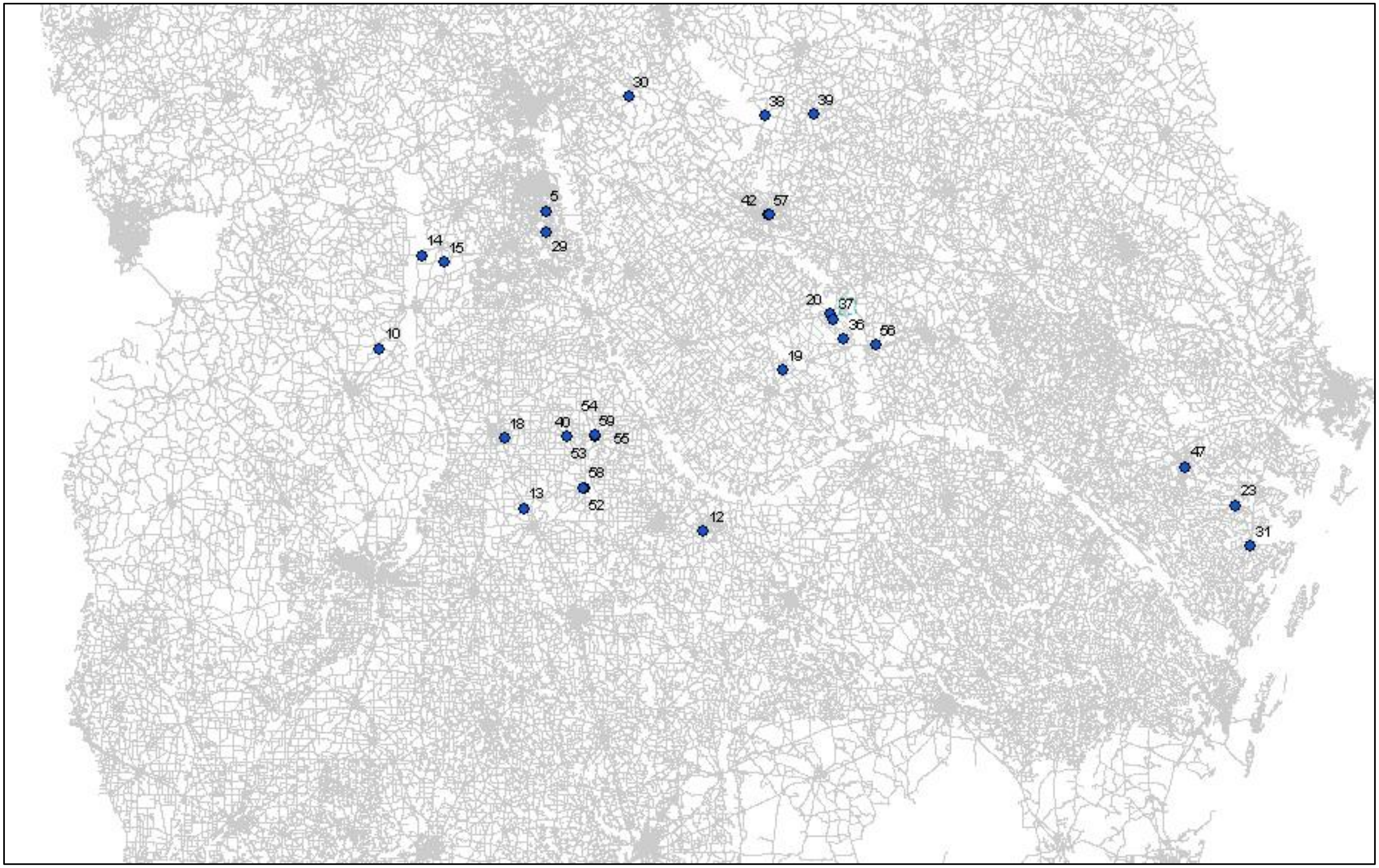

Figure F2 Studied Conventional Intersection Locations in the Lower Half of Georgia

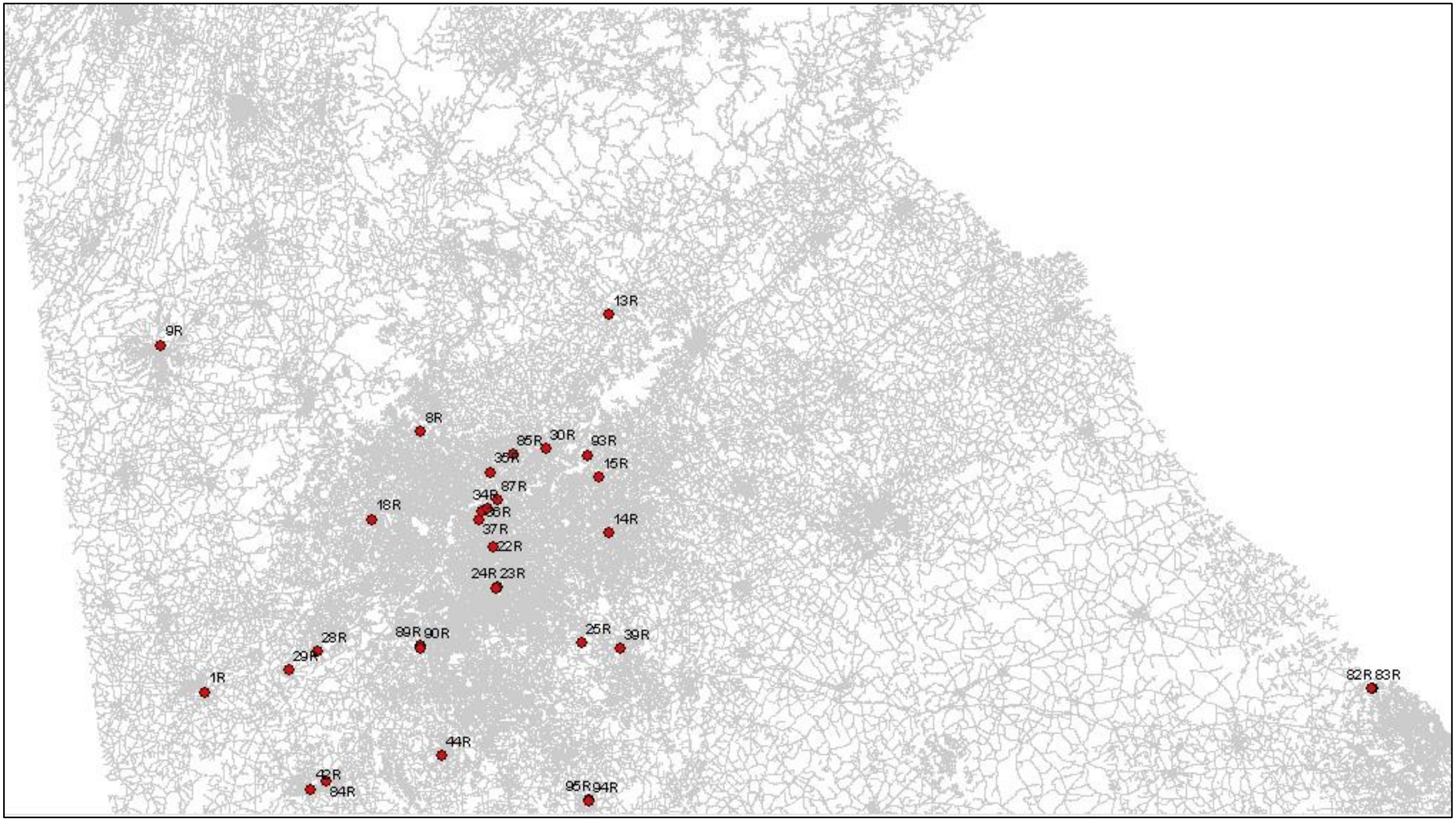

Figure F3 Studied Roundabout Locations in the Upper Half of Georgia

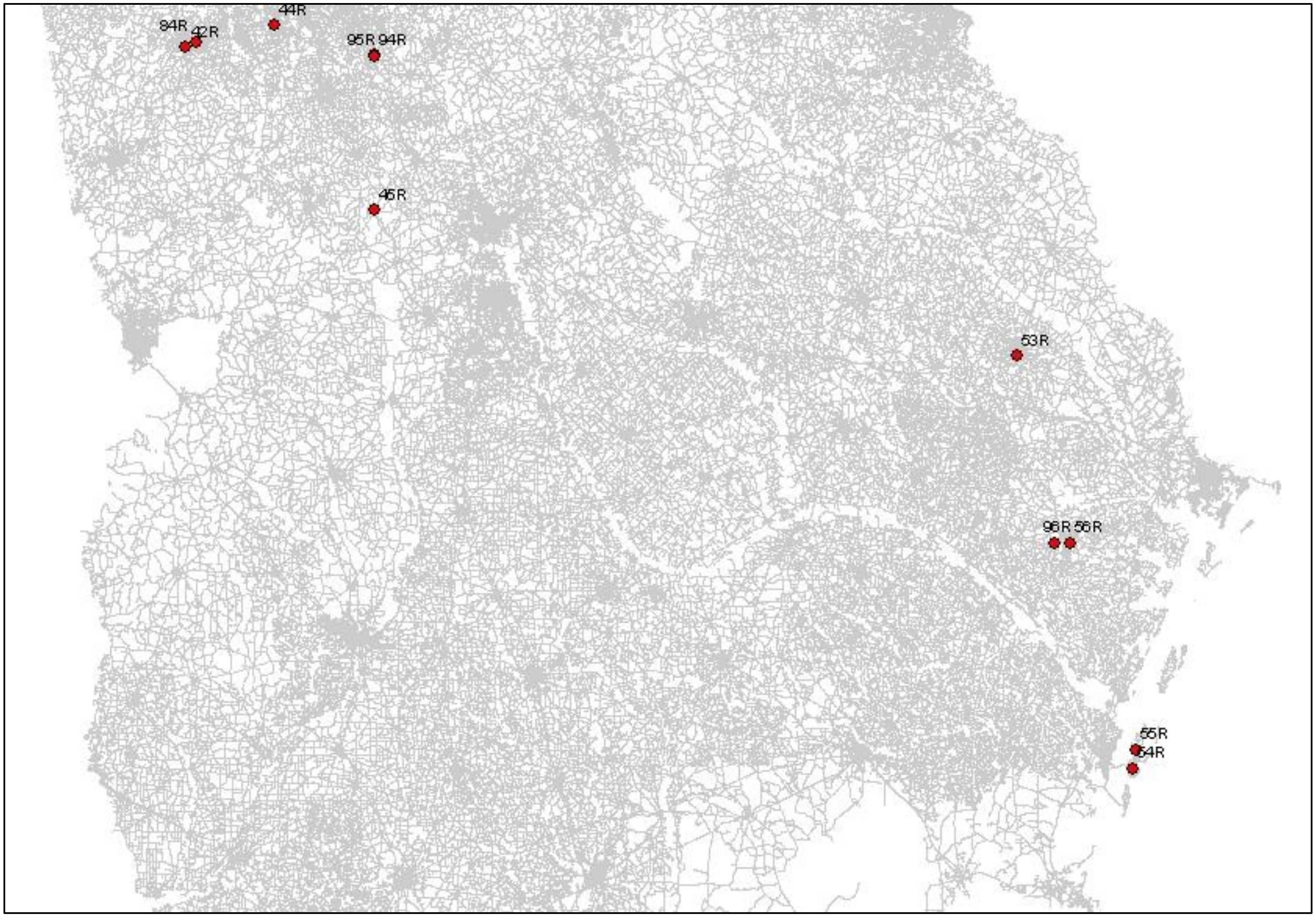

Figure F4 Studied Roundabout Locations in the Lower Half of Georgia

Intersection ID 98R

Roads: E Fairview Rd/ Fairview Rd/ Snapfinger Rd

Latitude: 33.610942 N

Longitude: 84.164771 W

Included in Analysis: YES

Figure F-1 Layout of Intersection #98R

Intersection ID 2

Roads: Georgia 85/ Highway 85 Connector

Latitude: 33.328946 N

Longitude: 84.506553 W

Included in Final Analysis: NO

Comment: One of only four conventional intersections with AADT > = 10000

Figure F-2 Layout of Intersection #2

Intersection ID 3

Roads: Georgia 5/ Georgia 5/ Old Highway 27 N/ Old Highway S

Latitude: 33.46005 N

Longitude: 85.128609 W

Included in Analysis? NO – not modern roundabout design; no raised central island and raised splitter island

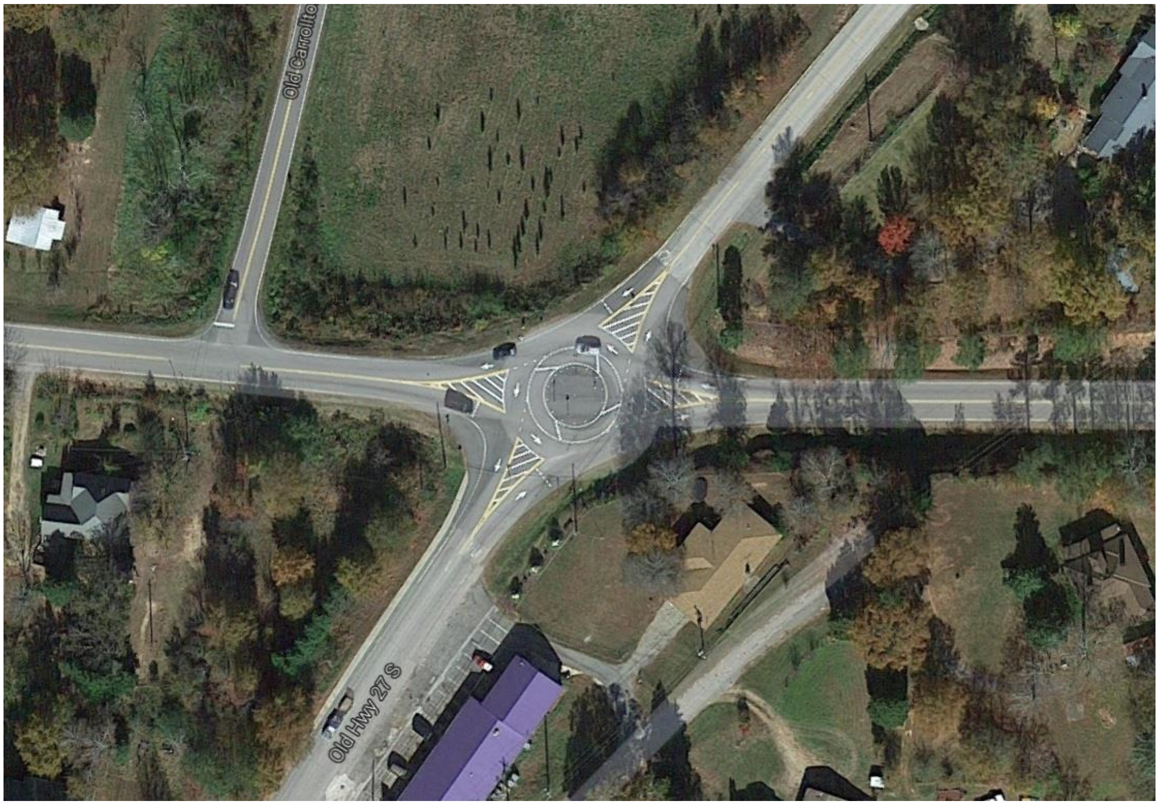

Figure F-3 Layout of Intersection #3

Intersection ID 4

Roads: Adairsville Rd NW/ W Oak Grove Rd NW

Latitude: 34.369142 N

Longitude: 85.003718 W

Included in Analysis: YES

Figure F-4 Layout of Intersection #4

Intersection ID 5

Roads: Georgia 96/ Oglethorpe Rd/ County Rd

Latitude: 32.551695 N

Longitude: 83.610783 W

Included in Final Analysis: NO

Comment: One of four only conventional intersections with AADT >= 10000

Figure F-5 Layout of Intersection #5

Intersection ID 6

Roads: Georgia 52/ Greenfield Rd

Latitude: 34.688607 N

Longitude: 84.466841 W

Included in Final Analysis: YES

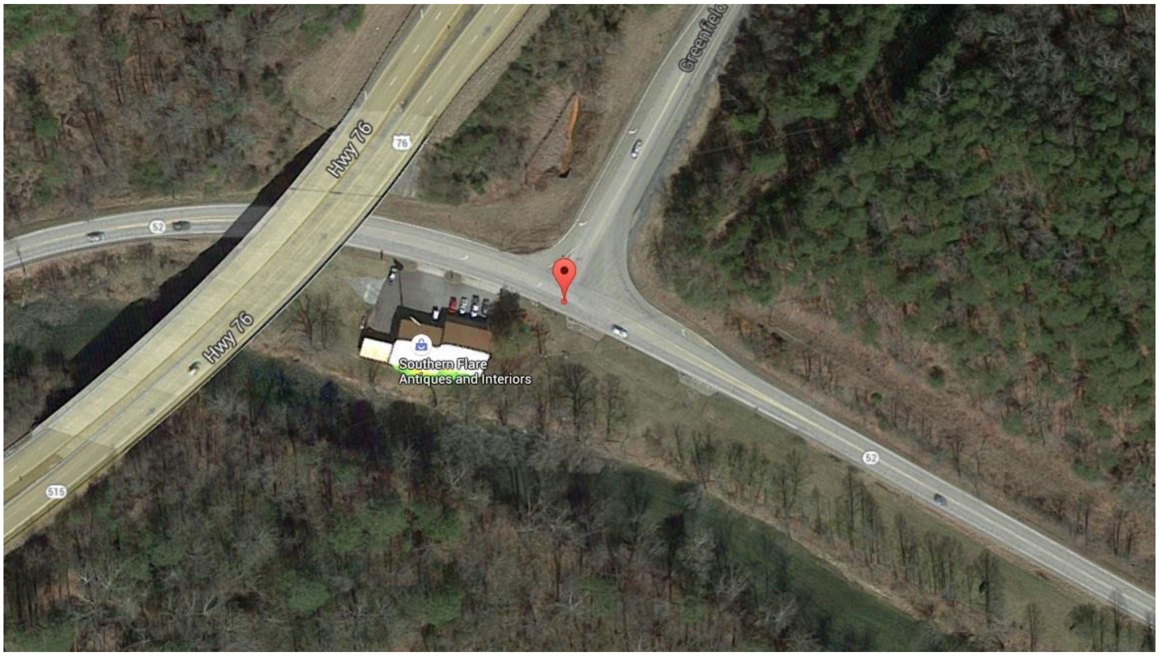

Figure F-6 Layout of Intersection #6

Intersection ID 7

Roads: Georgia 299/ Birmingham Pike

Latitude: 34.9748 N

Longitude: 85.403825 W

Included in Final Analysis: YES

Figure F-7 Layout of Intersection #7

Intersection ID 8

Roads: Georgia 48/ Mahan Rd/ Filter Plant Rd

Latitude: 34.4693954 N

Longitude: 85.386774 W

Included in Final Analysis: YES

Figure F-8 Layout of Intersection #8

Intersection ID 9

Roads: Georgia 382/ Old Highway 5 S

Latitude: 34.640838 N

Longitude: 84.507932 W

Included in Final Analysis: YES

Figure F-9 Layout of Intersection #9

Intersection ID 10

Roads: Georgia 195/ Georgia 49

Latitude: 32.1810091 N

Longitude: 84.134394 W

Included in Final Analysis: YES

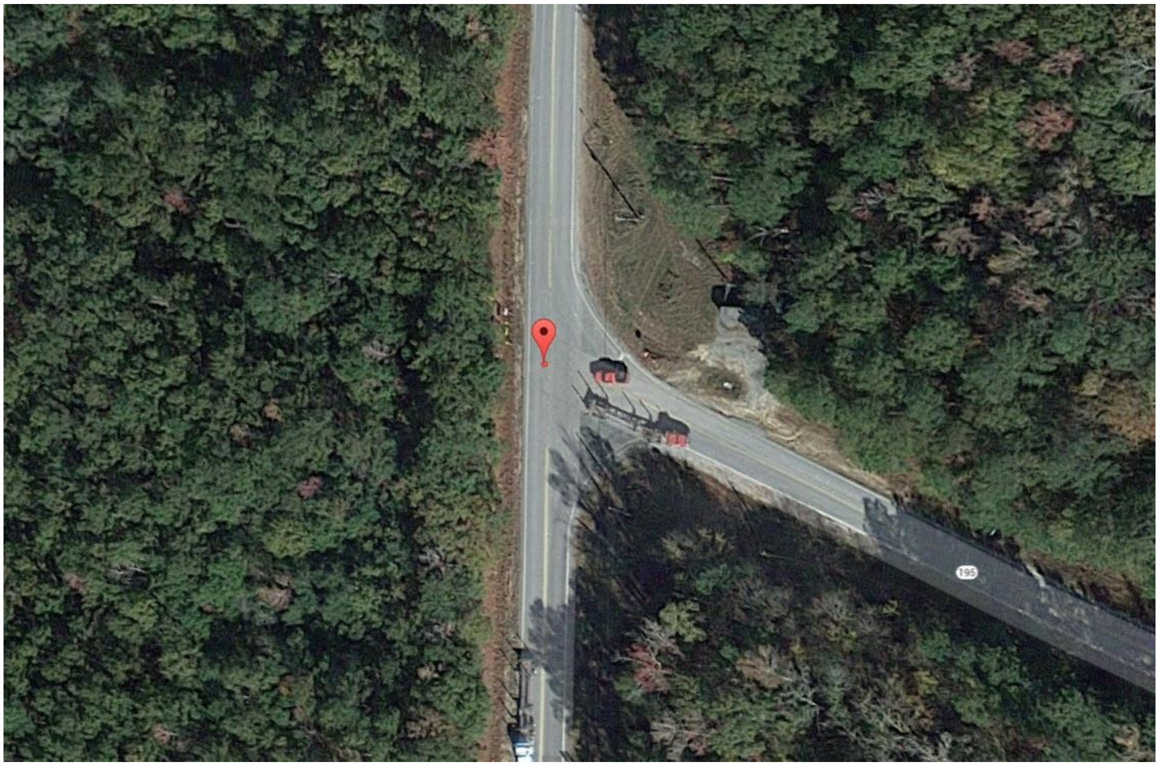

Figure F-10 Layout of Intersection #10

Intersection ID 11

Roads: Jackson Lake Rd/ Georgia 11/ Maddox St

Latitude: 33.409001 N

Longitude: 83.760712 W

Included in Final Analysis: YES

Figure F-11 Layout of Intersection #11

Intersection ID 12

Roads: Broxton Hwy/ Osier Field Rd

Latitude: 31.692196 N

Longitude: 83.113783 W

Included in Final Analysis: YES

Figure F-12 Layout of Intersection #12

Intersection ID 13

Roads: Ireland Rd/ U.S. 41

Latitude: 31.752663 N

Longitude: 83.677117 W

Included in Final Analysis: YES

Figure F-13 Layout of Intersection #13

Intersection ID 14

Roads: Georgia 127/ Georgia 127/ Georgia 29

Latitude: 32.431813 N

Longitude: 84.002947 W

Included in Final Analysis: YES

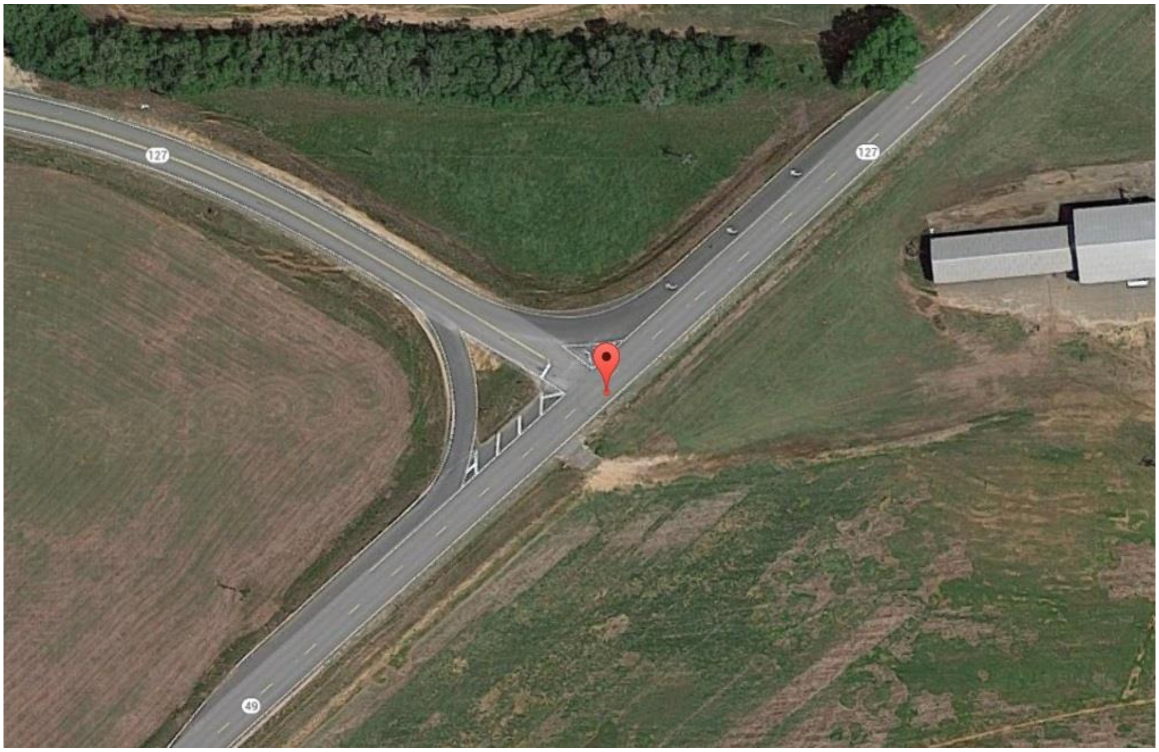

Figure F-14 Layout of Intersection #14

Intersection ID 15

Roads: Winchester Rd/ South St

Latitude: 32.412943 N

Longitude: 83.933468 W

Included in Final Analysis: YES

Figure F-15 Layout of Intersection #15

Intersection ID 16

Roads: Georgia 301/ Holder Rd/ Reeves Rd

Latitude: 34.927671 N

Longitude: 85.58699 W

Included in Final Analysis: YES

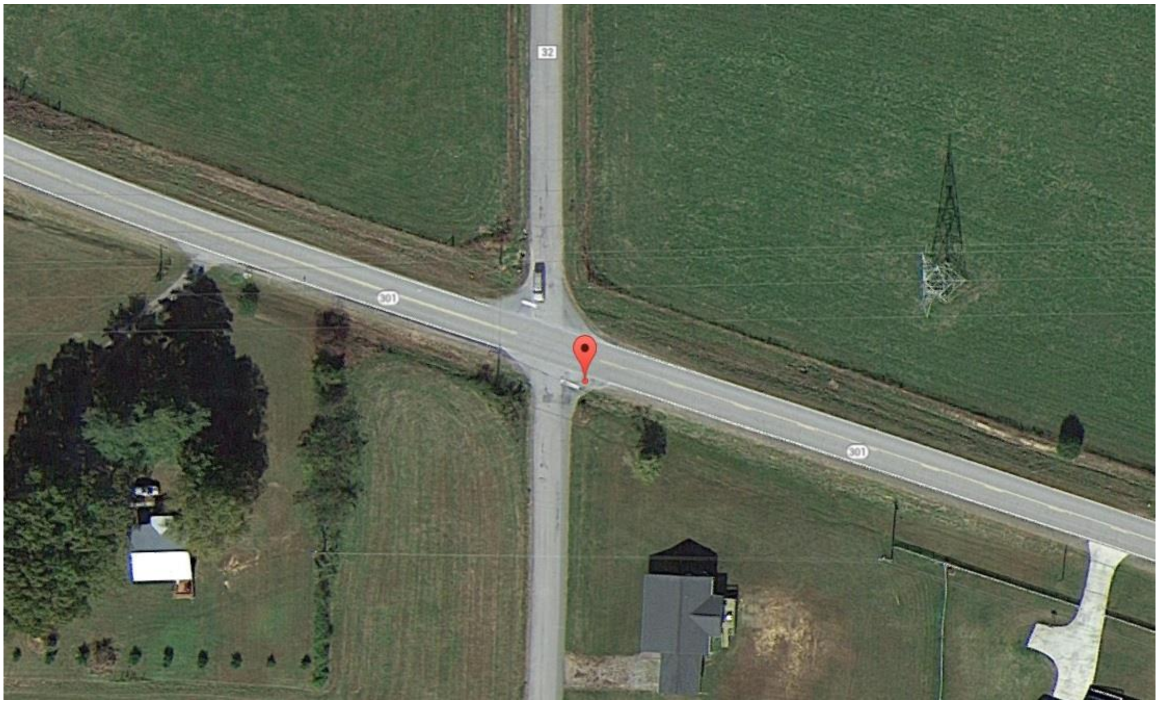

Figure F-16 Layout of Intersection #16

Intersection ID 17

Roads: Mc Farland Rd/ Scenic Hwy

Latitude: 34.9765363 N

Longitude: 85.366779 W

Included in Final Analysis: YES

Figure F-17 Layout of Intersection #17

Intersection ID 18

Roads: Georgia 300/ Georgia 90

Latitude: 31.942601 N

Longitude: 83.738504 W

Included in Final Analysis: YES

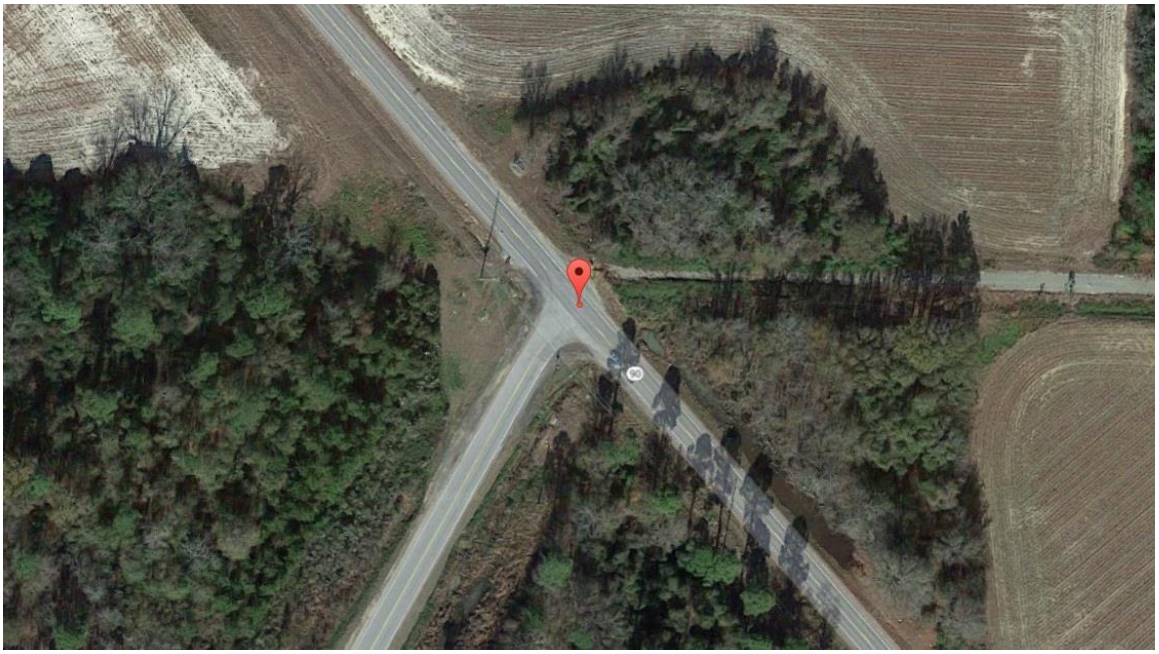

Figure F-18 Layout of Intersection #18

Intersection ID 19

Roads: County Road 136/ Little Rock Rd

Latitude: 32.123434 N

Longitude: 82.863377 W

Included in Final Analysis: YES

Figure F-19 Layout of Intersection #19

Intersection 20

Roads: Georgia 19/ Crossroad VFD Rd

Latitude: 32.27341 N

Longitude: 82.710022 W

Included in Final Analysis: YES

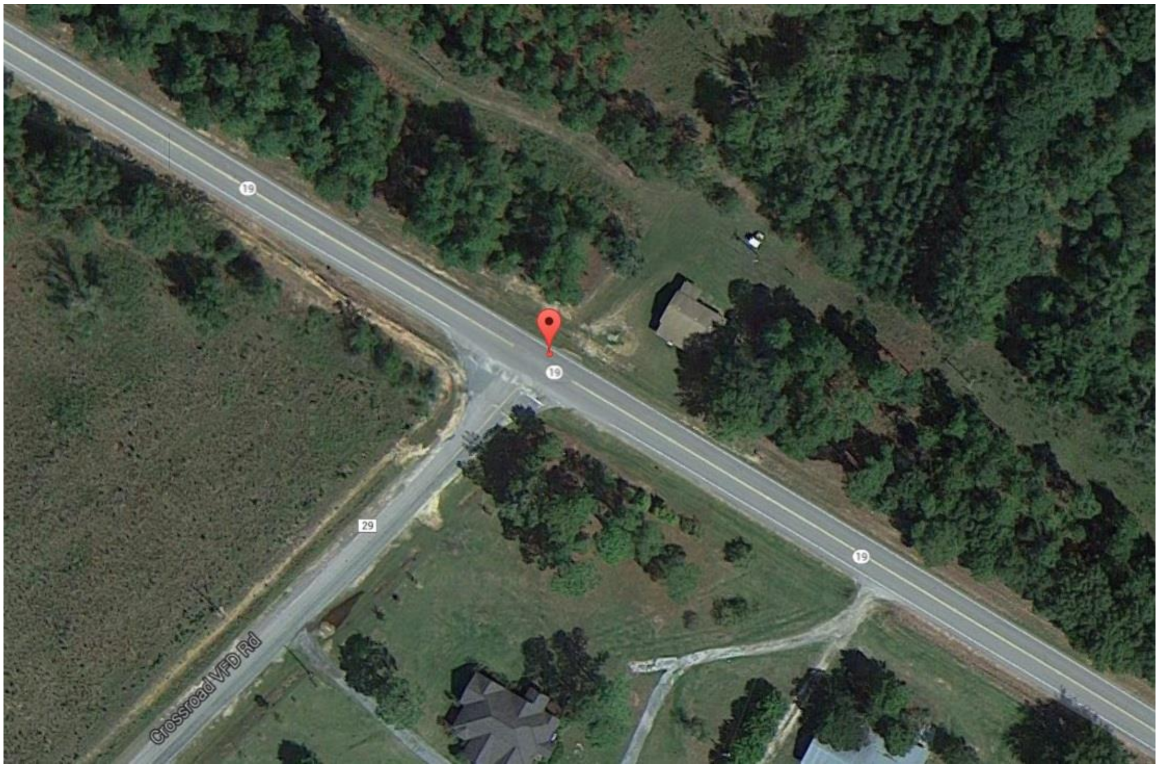

Figure F-20 Layout of Intersection #20

Intersection 21

Roads: Kenwood Rd/ Georgia 279

Latitude: 33.510852 N

Longitude: 84.439024 W

Included in Final Analysis: YES

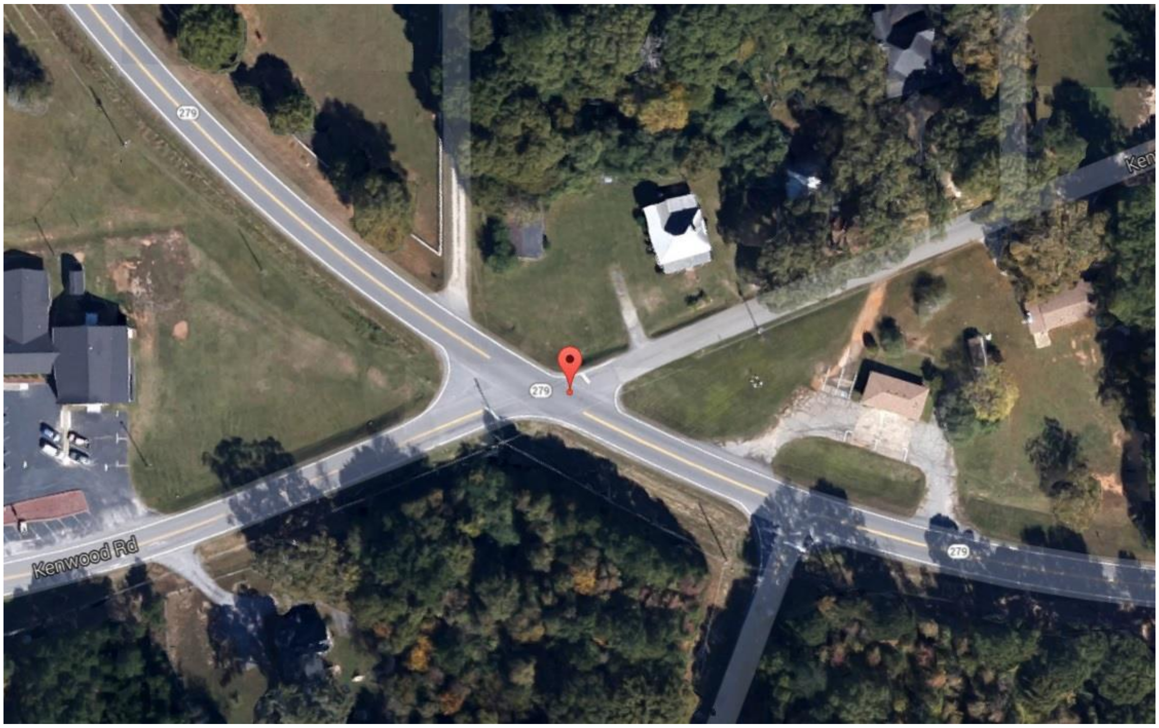

Figure F-21 Layout of Intersection #21

Intersection 22

Roads: Poplar Springs Rd/ Three Notch Rd

Latitude: 34.8936246 N

Longitude: 85.184879 W

Included in Final Analysis: YES

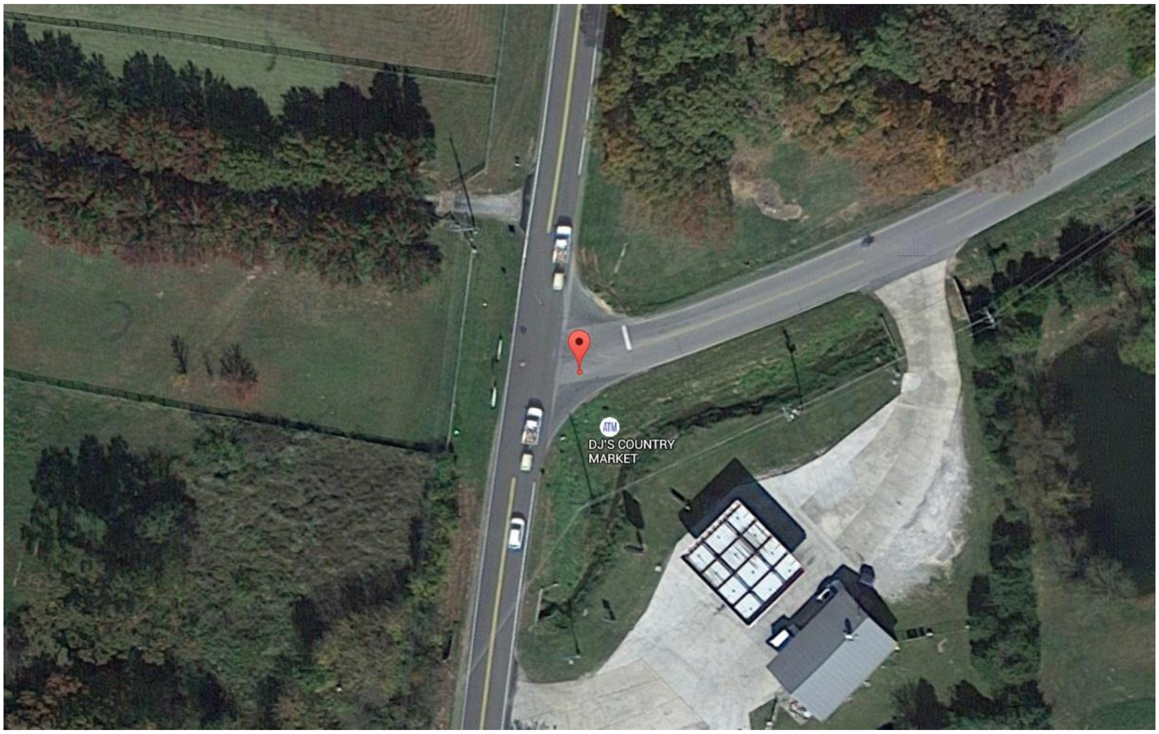

Figure F-22 Layout of Intersection #22

Intersection 23

Roads: E B Cooper Hwy/ S Coastal Hwy

Latitude: 31.743804 N

Longitude: 81.439981 W

Included in Final Analysis: YES

Figure F-23 Layout of Intersection #23

Intersection 24

Roads: Jamestown Rd/ Bell St/ Georgia 48

Latitude: 34.484807 N

Longitude: 85.479902 W

Included in Final Analysis: YES

Figure F-24 Layout of Intersection #24

Intersection 25

Roads: Industrial Blvd/ School St

Latitude: 34.684957 N

Longitude: 84.474753 W

Included in Final Analysis: YES

Figure F-25 Layout of Intersection #25

Intersection 26

Roads: Red Belt Rd/ Three Notch Rd/ Burning Bush Rd/ Long Hollow Rd

Latitude: 34.8706584 N

Longitude: 85.228735 W

Included in Final Analysis: YES

Figure F-26 Layout of Intersection #26

Intersection 27

Roads: Reeds Bridge Rd/ Boynton Dr/ Diets Rd/ Burning Bush Rd

Latitude: 34.9283653 N

Longitude: 85.21097 W

Included in Final Analysis: NO

Comment: One of only four conventional intersection with AADT >=10000

Figure F-27 Layout of Intersection #27

Intersection 28

Roads: Georgia 299/ Interstate 24

Latitude: 34.977439 N

Longitude: 85.415864 W

Included in Final Analysis: NO

Comment: Interchanges and Interchange terminal are omitted in this analysis

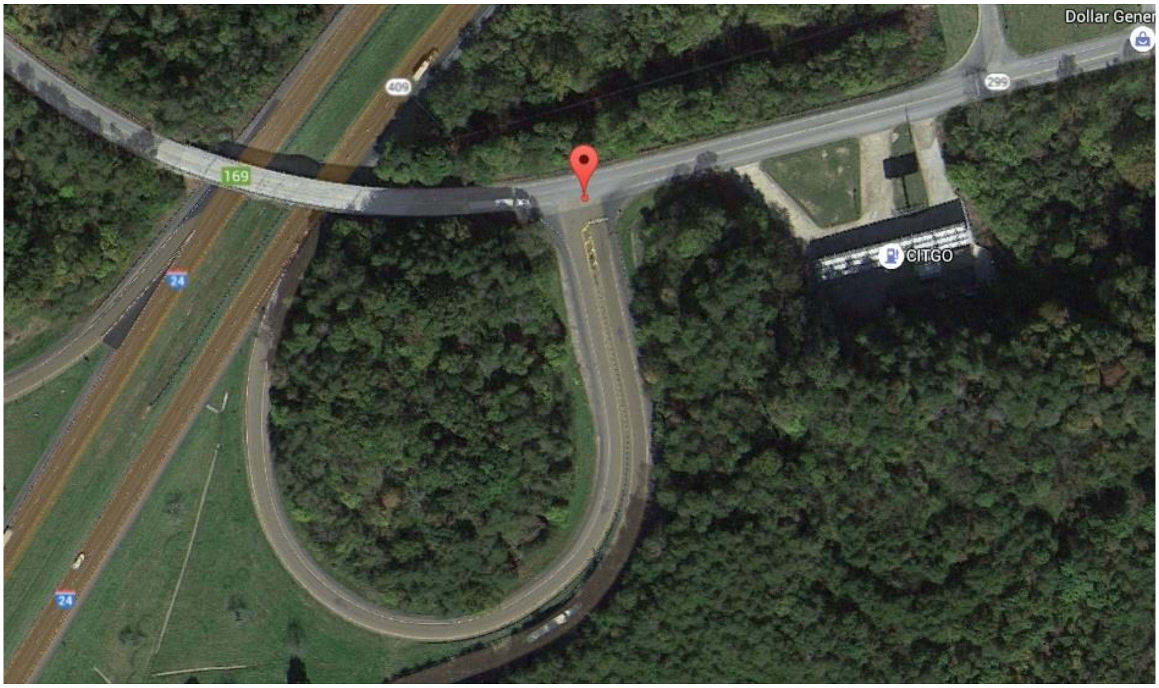

Figure F-28 Layout of Intersection #28

Intersection 29

Roads: Georgia 127/ Story Rd/ Georgia 247

Latitude: 32.495781 N

Longitude: 83.607992 W

Included in Final Analysis: NO

Comment: One of only four conventional intersections with AADT >= 10000

Figure F-29 Layout of Intersection #29

Intersection 99R

Roads: W Main St/ Georgia 18

Latitude: 32.859922 N

Longitude: 83.347219 W

Included in Final Analysis: YES

Comment: Site is actually a roundabout but google maps image does not show!

Figure F-30 Layout of Intersection #99R

Intersection 31

Roads: Jones Rd/ North Way

Latitude: 31.633891 N

Longitude: 81.396489 W

Included in Final Analysis: YES

Figure F-31 Layout of Intersection #31

Intersection 32

Roads: Twin Mountain Lake Dr/ Lumber Company Rd

Latitude: 34.49462 N

Longitude: 84.452927 W

Included in Final Analysis: NO – Nearest intersection is too close

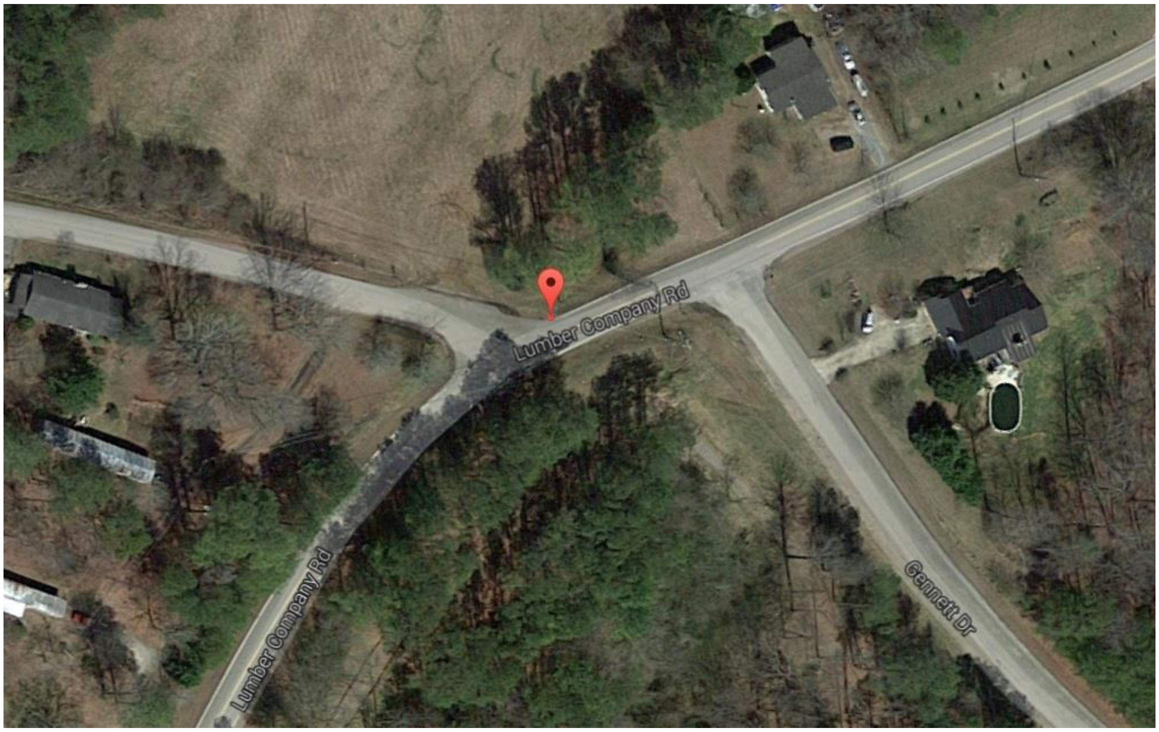

Figure F-32 Layout of Intersection #32

Intersection 33

Roads: Georgia 299/ Slygo Rd

Latitude: 34.978912 N

Longitude: 85.433719 W

Included in Final Analysis: YES

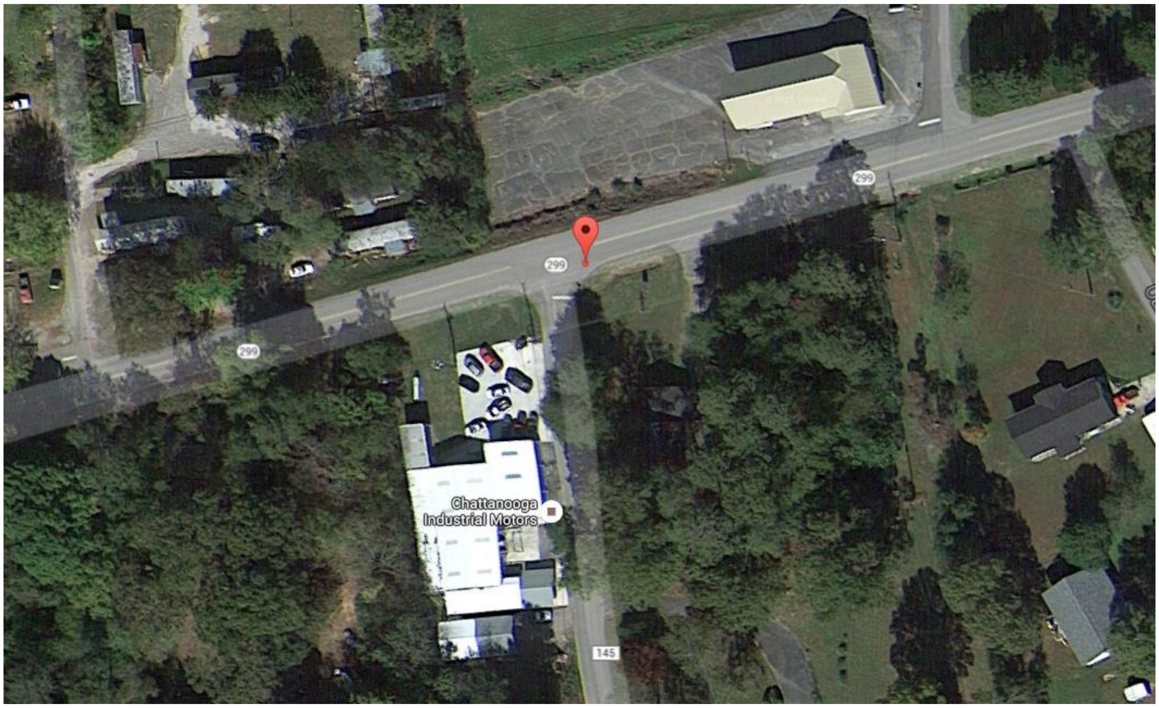

Figure F-33 Layout of Intersection #33

Intersection 34

Roads: Lookout Mountain Scenic Hwy/ Georgia 193

Latitude: 34.8073337 N

Longitude: 85.389264 W

Included in Final Analysis: NO – Flashing Amber Installed

Figure F-34 Layout of Intersection #34

Intersection 35

Roads: Cove Rd/ Georgia 341/ Georgia 136

Latitude: 34.7938924 N

Longitude: 85.334694 W

Included in Final Analysis: NO – Flashing Amber installed within analysis period

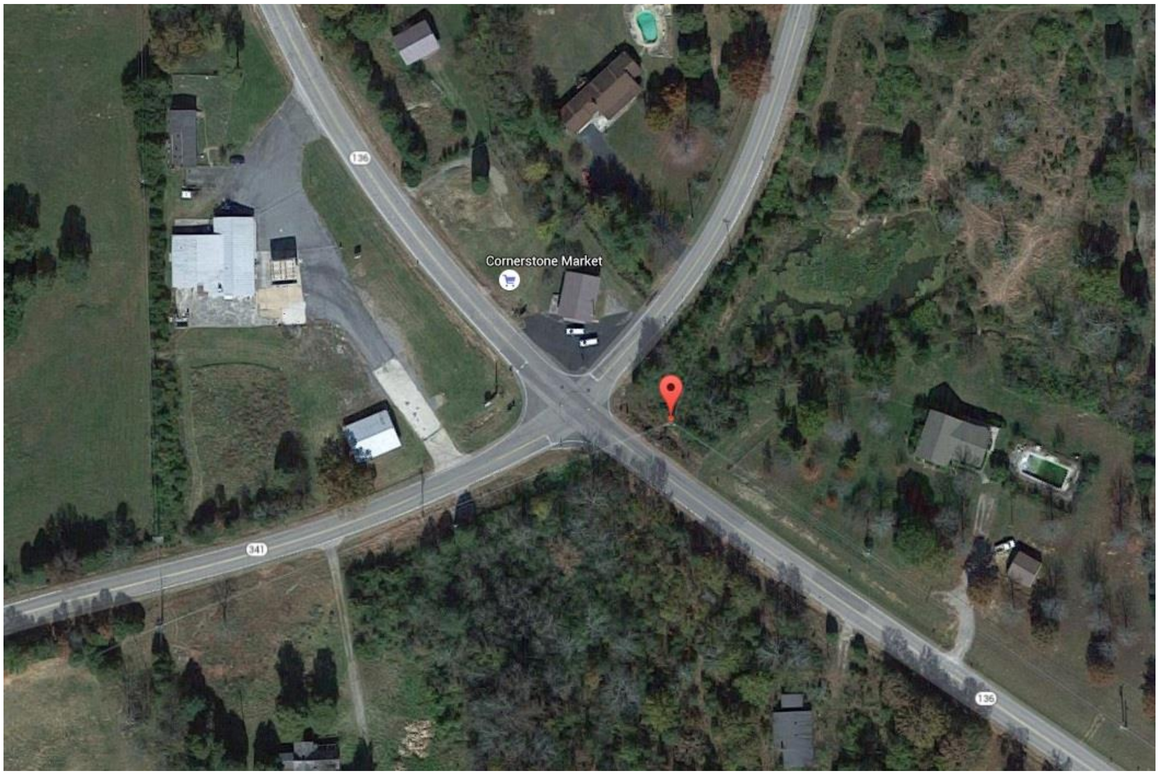

Figure F-35 Layout of Intersection #35

Intersection 36

Roads: County Road 12/ County Road 179/ County Road 12

Latitude: 32.204694 N

Longitude: 82.668616 W

Included in Final Analysis: YES

Figure F-36 Layout of Intersection #36

Intersection 37

Roads: County Road 13/ Georgia 19

Latitude: 32.2589 N

Longitude: 82.700656 W

Included in Final Analysis: YES

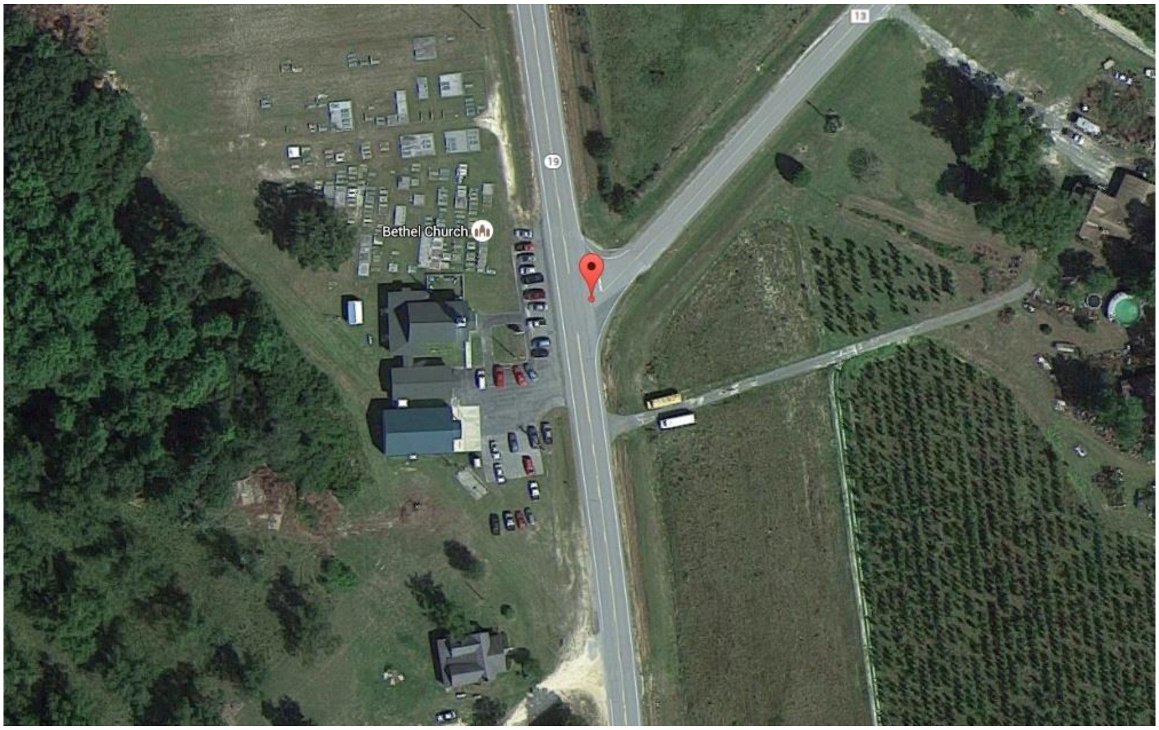

Figure F-37 Layout of Intersection #37

Intersection 38

Roads: Georgia 272/ Georgia 68

Latitude: 32.806965 N

Longitude: 82.913333 W

Included in Final Analysis: YES

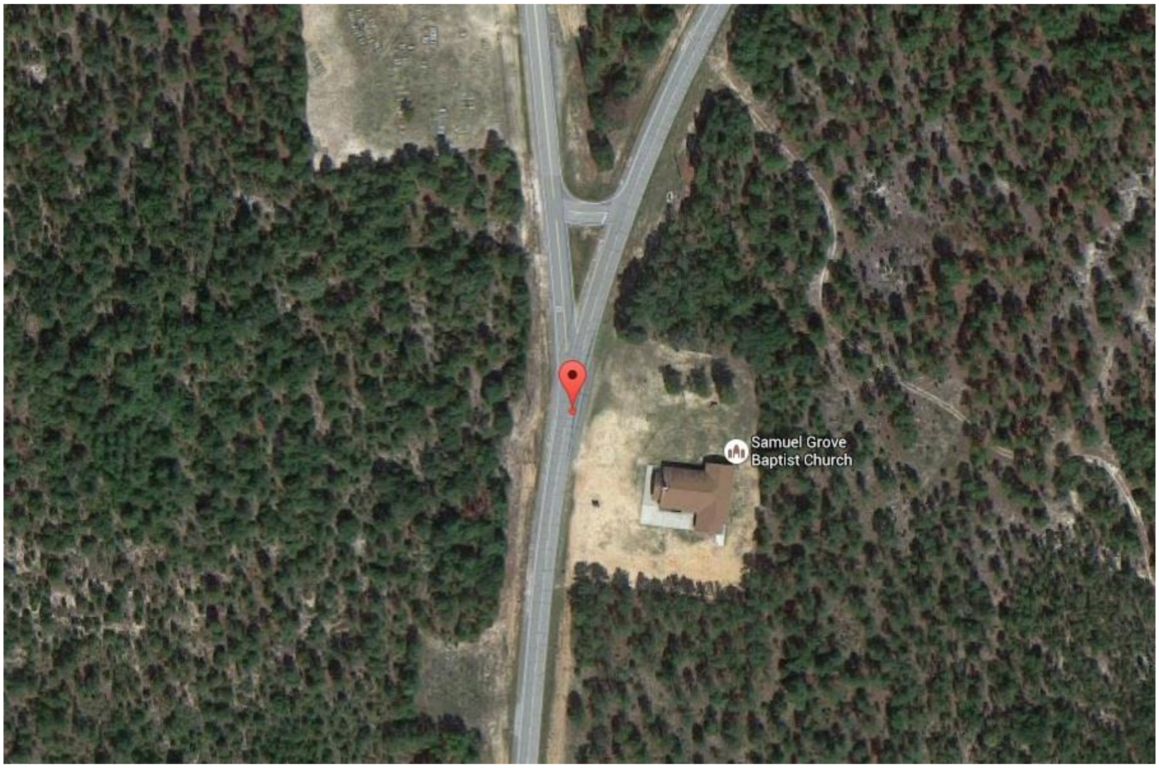

Figure F-38 Layout of Intersection #38

Intersection 39

Roads: Hartsford Rd/ Harrison-Riddleville Rd/ Georgia 15

Latitude: 32.810497 N

Longitude: 82.757167 W

Included in Final Analysis: NO – Staggered intersection

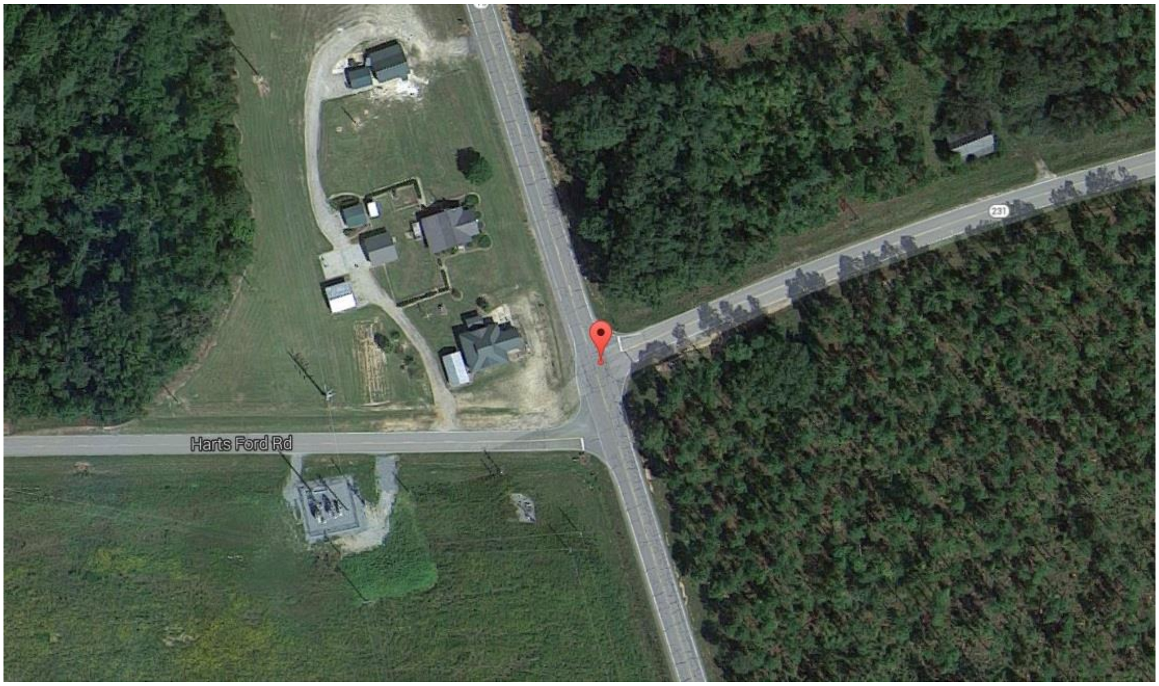

Figure F-39 Layout of Intersection #39

Intersection 40

Roads: 7th Ave W/ 10th St

Latitude: 31.944808 N

Longitude: 83.54261 W

Included in Final Analysis: YES

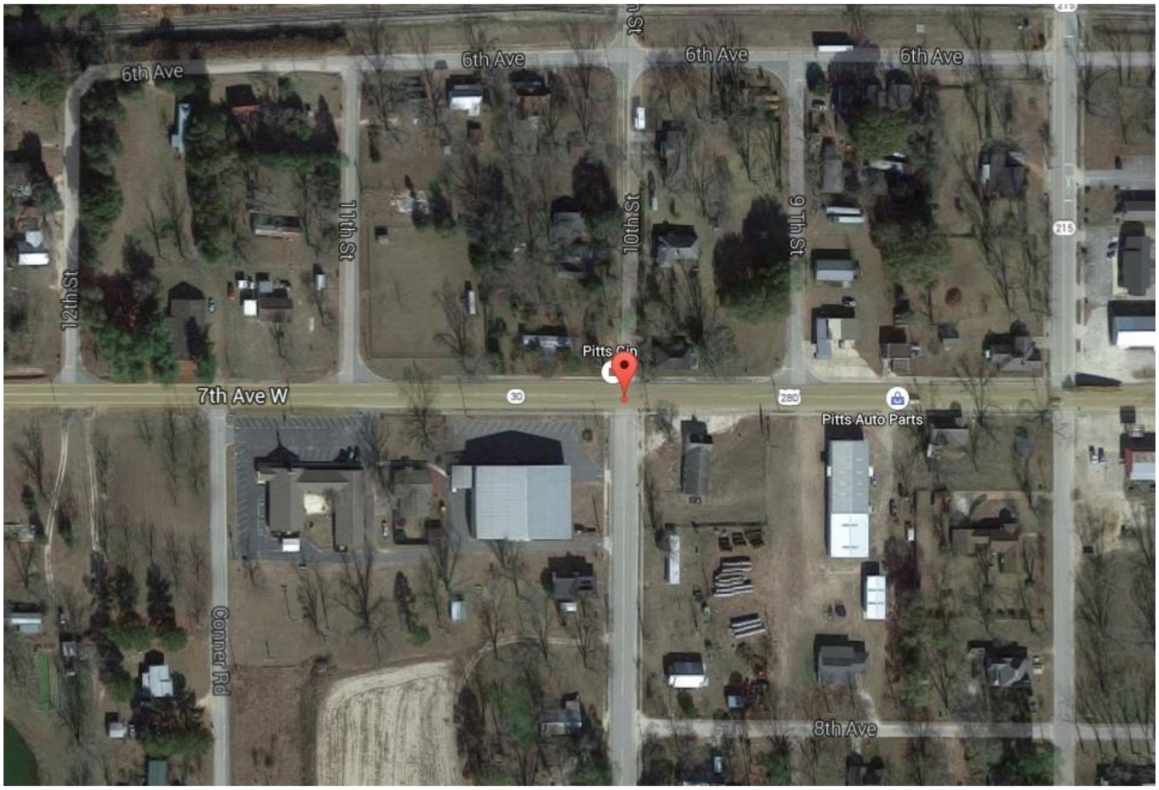

Figure F-40 Layout of Intersection #40

Intersection 41

Roads: Tabor St/ Dalton St/ N Dalton St

Latitude: 34.69849 N

Longitude: 84.481714 W

Included in Final Analysis: YES

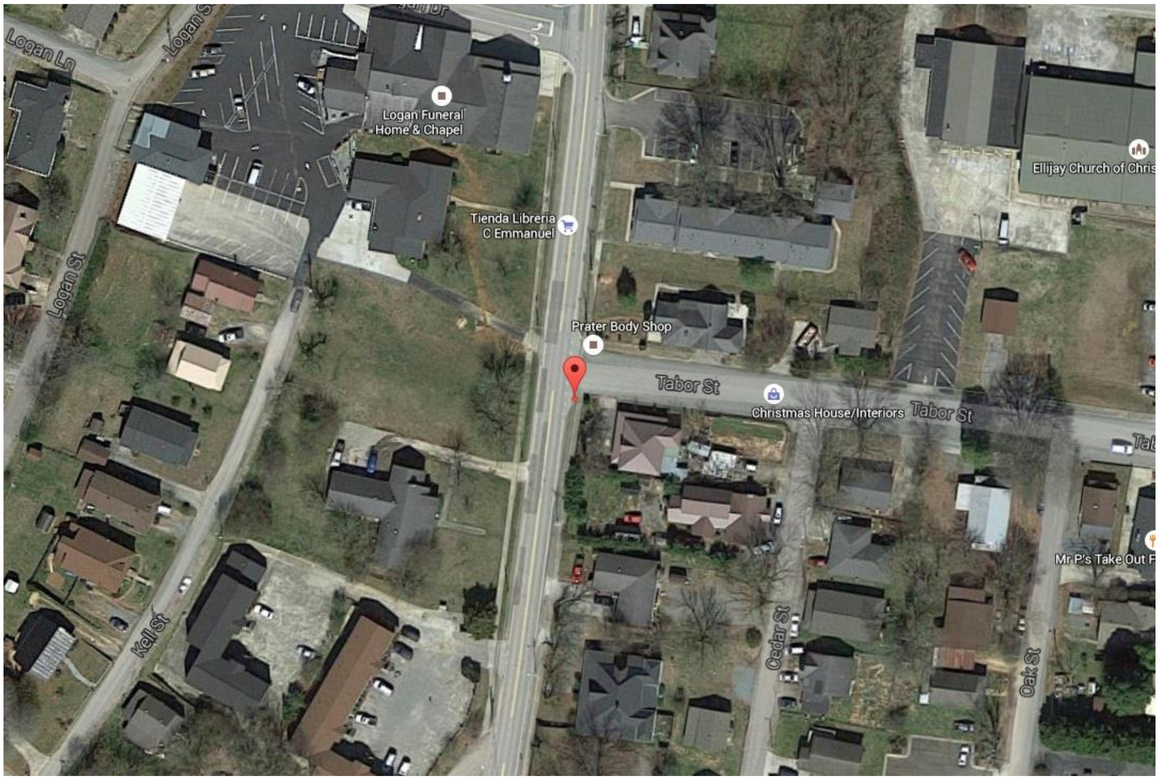

Figure F-41 Layout of Intersection #41

Intersection 42

Roads: E Gaines St/ Gaines St/ N Franklin St

Latitude: 32.541576 N

Longitude: 82.903634 W

Included in Final Analysis: YES

Figure F-42 Layout of Intersection #42

Intersection 43

Roads: River St/ North Ave

Latitude: 34.694238 N

Longitude: 84.481535 W

Included in Final Analysis: YES

Figure F-43 Layout of Intersection #43

Intersection 44

Roads: S Chattanooga St/ Pledger St

Latitude: 34.689081 N

Longitude: 85.30046 W

Included in Final Analysis: YES

Figure F-44 Layout of Intersection #44

Intersection 45

Roads: N Gilmer St/ N Dalton St

Latitude: 34.69774 N

Longitude: 84.481912 W

Included in Final Analysis: YES

Figure F-45 Layout of Intersection #45

Intersection 46

Roads: Newnan Rd/ Newnan Rd/ Mill Pond Crossing/ Education Dr

Latitude: 33.565767 N

Longitude: 85.045059 W

Included in Final Analysis: YES

Comment: Surveyed with two camera's a s #46 and 1R

Figure F-46 Layout of Intersection #46

Intersection 47

Roads: W Memorial Dr/ Memorial Dr/ N Main St/ N Main St

Latitude: 31.85 N

Longitude: 81.595833 W

Included in Final Analysis: NO – pavement was wet during one survey.

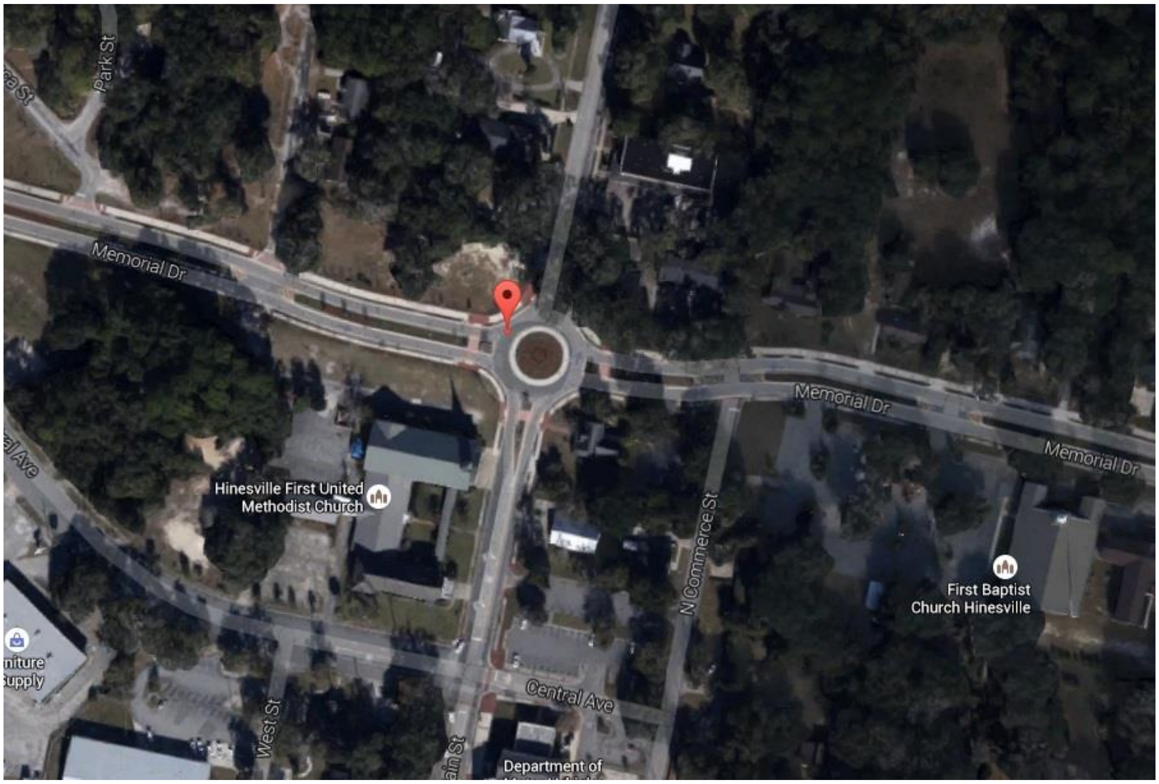

Figure F-47 Layout of Intersection #47

Intersection 48

Roads: Grady Ave/ Grady Ave/ Beauregard Blvd/ Beauregard Blvd

Latitude: 33.441022 N

Longitude: 84.457578 W

Included in Final Analysis: YES

Comment: Surveyed with both camera's as #48 and 44R

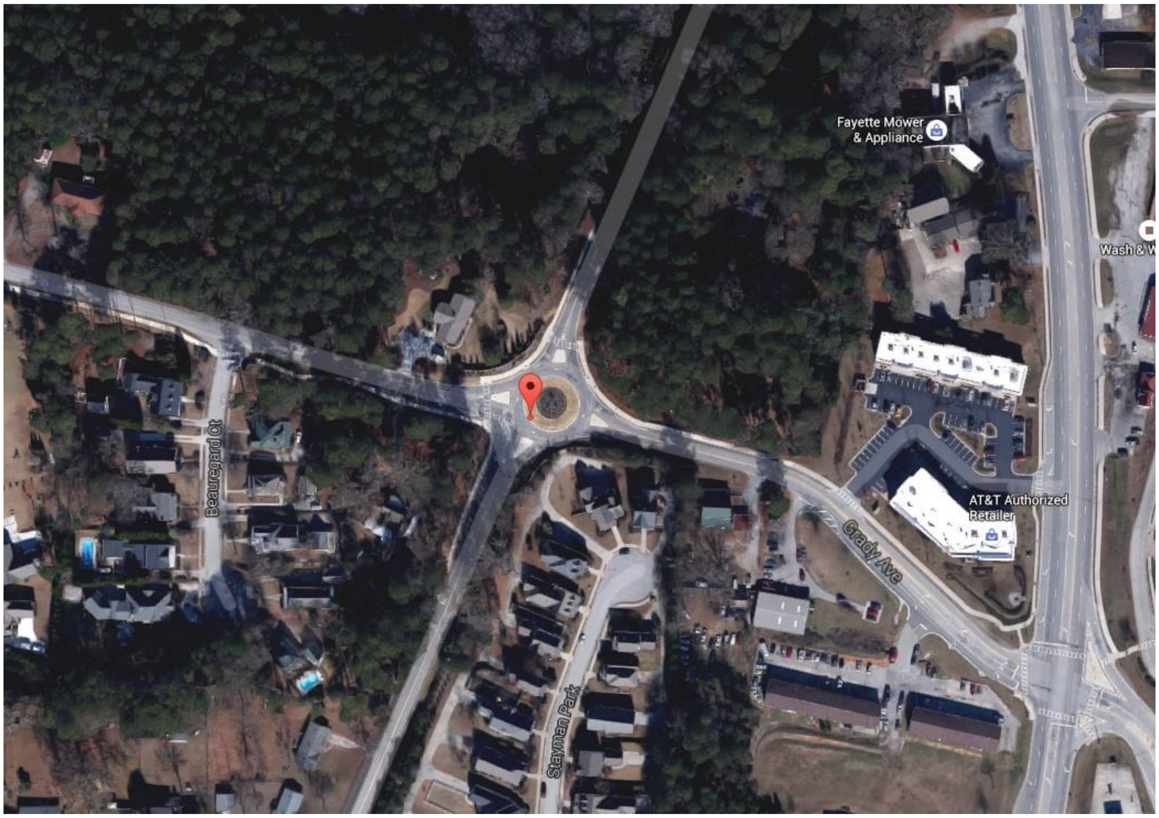

Figure F-48 Layout of Intersection #48

Intersection 49

Roads: Georgia 5/ Old Highway 27 S/ Georgia 5/ Old Highway 27 N

Latitude: 33.46 N

Longitude: 85.128611 W

Included in Final Analysis: NO – not a modern roundabout design

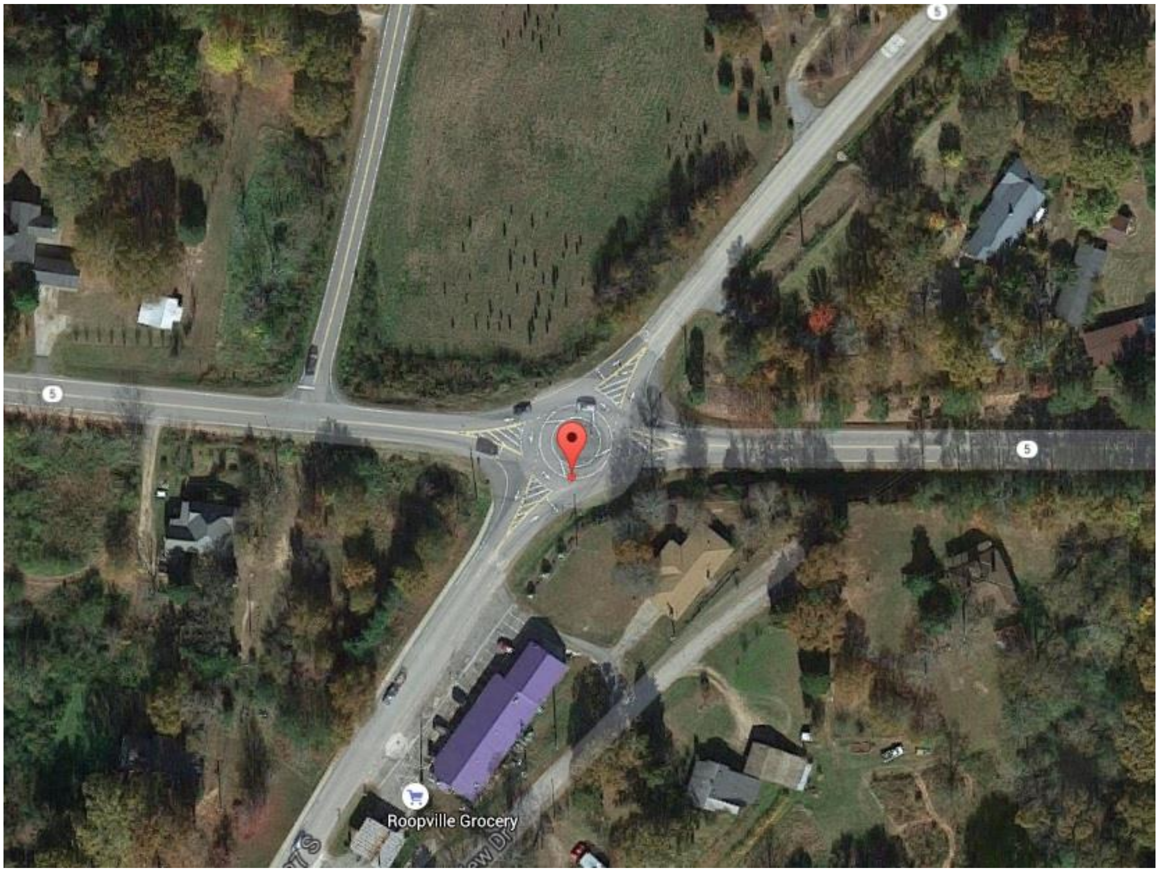

Figure F-49 Layout of Intersection #49

Intersection 50.

Roads: E Broad St/ E Broad St/ E Newnan Rd/ Greison Trail

Latitude: 33.368122 N

Longitude: 84.779261 W

Included in Final Analysis: YES

Comment: Surveyed with both camera's #50 and 42R

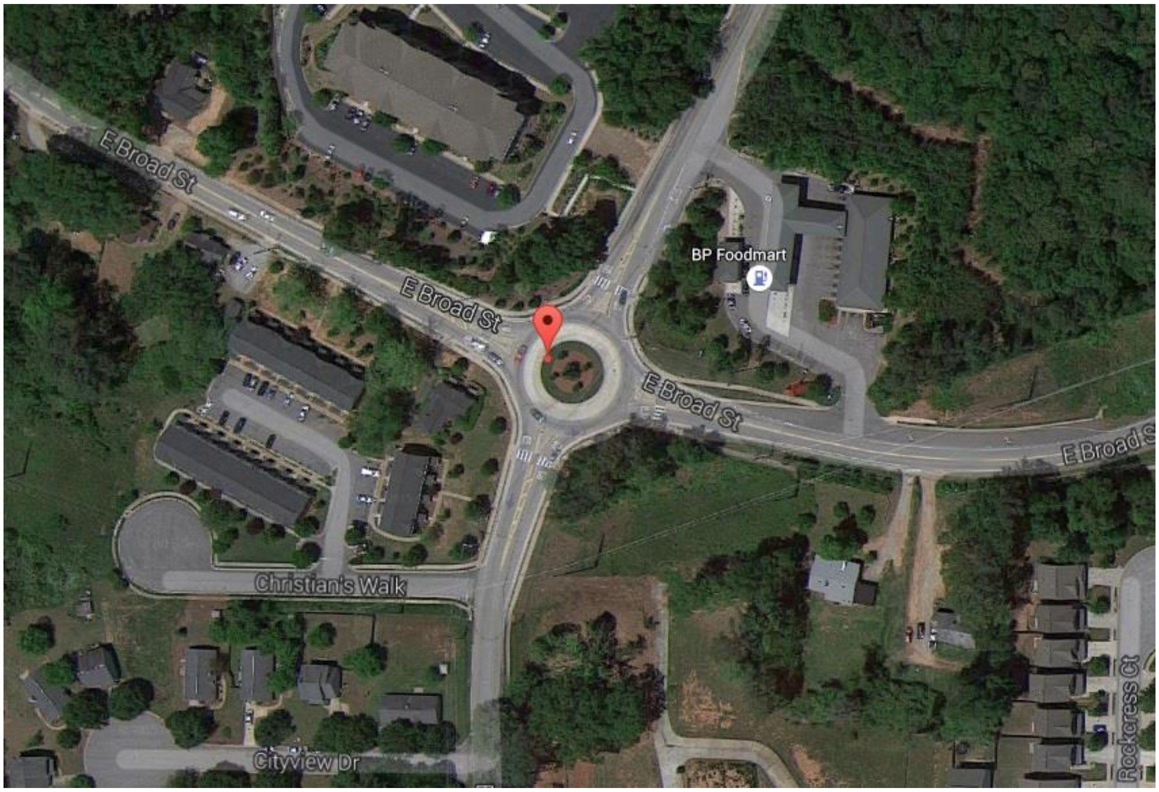

Figure F-50 Layout of Intersection #50

Intersection 51

Roads: McCutchen St/ N Main St

Latitude: 34.696972 N

Longitude: 84.480126 W

Included in Final Analysis: YES

Figure F-51 Layout of Intersection #51

Intersection 52

Roads: N Railroad St/ W Depot St

Latitude: 31.807311 N

Longitude: 83.487729 W

Included in Final Analysis: YES

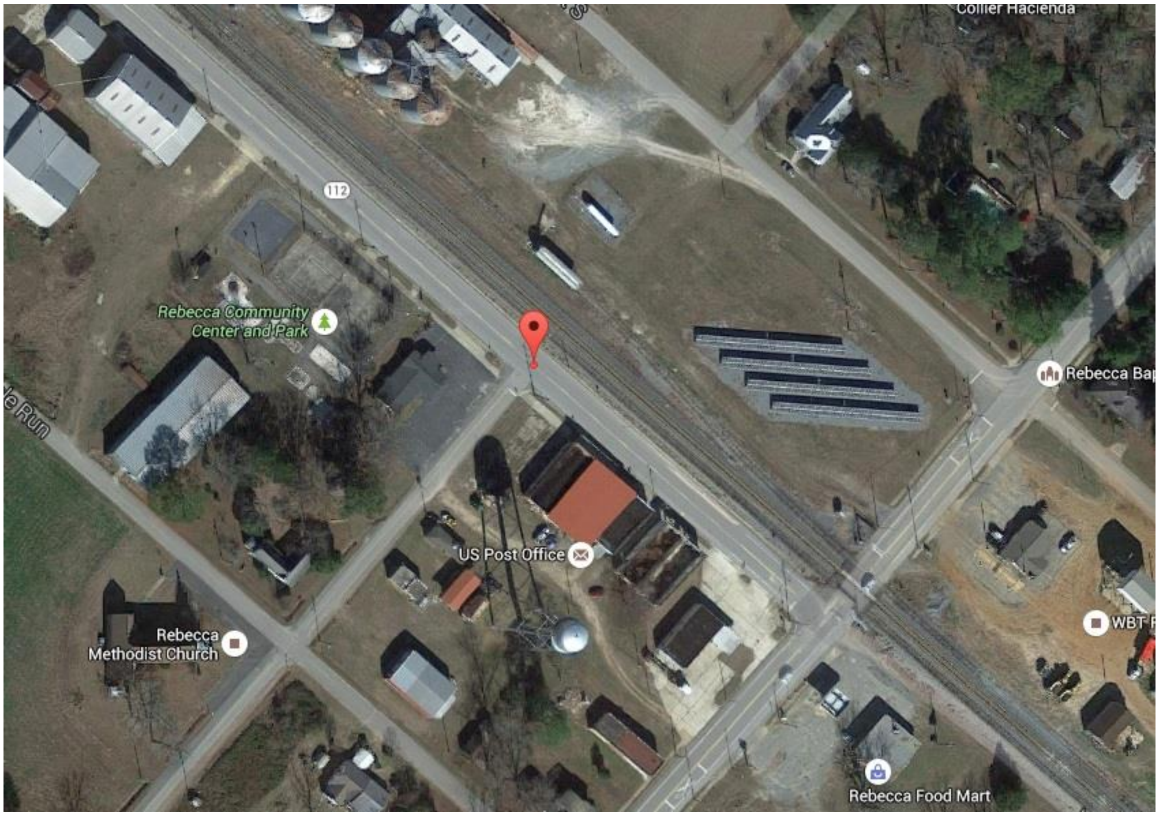

Figure F-52 Layout of Intersection #52

Intersection 53

Roads: 3rd Ave/ Ashley St

Latitude: 31.948536 N

Longitude: 83.456307 W

Included in Final Analysis: YES

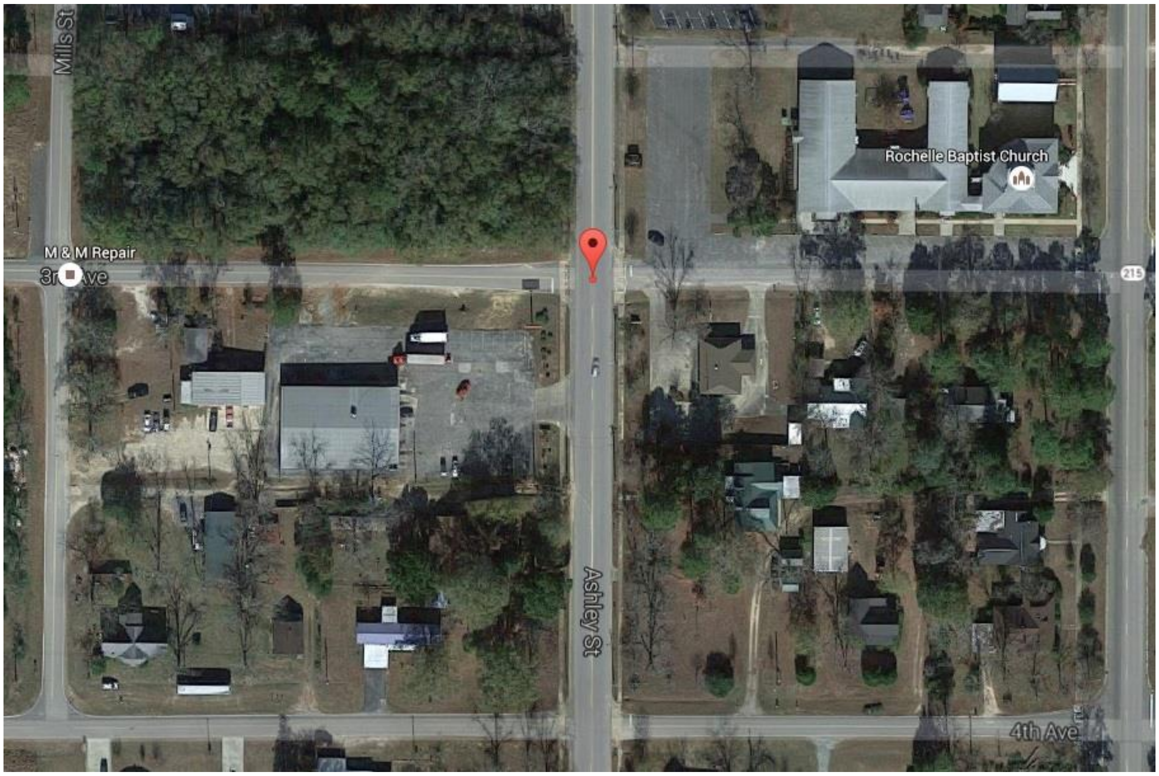

Figure F-53 Layout of Intersection #53

Intersection 54

Roads: 2nd Ave/ Gordon St

Latitude: 31.949674 N

Longitude: 83.454632 W

Included in Final Analysis: YES

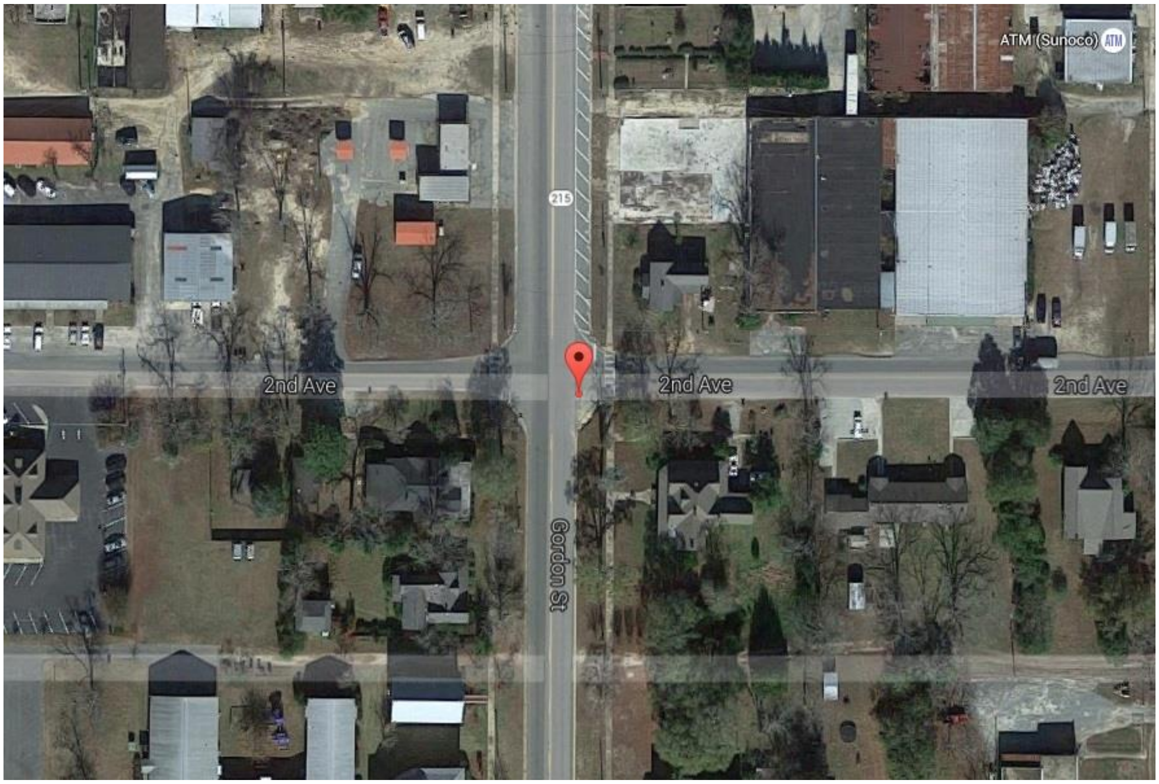

Figure F-54 Layout of Intersection #54

Intersection 55

Roads: 5th Ave/ Ashley St

Latitude: 31.946251 N

Longitude: 83.456309 W

Included in Final Analysis: YES

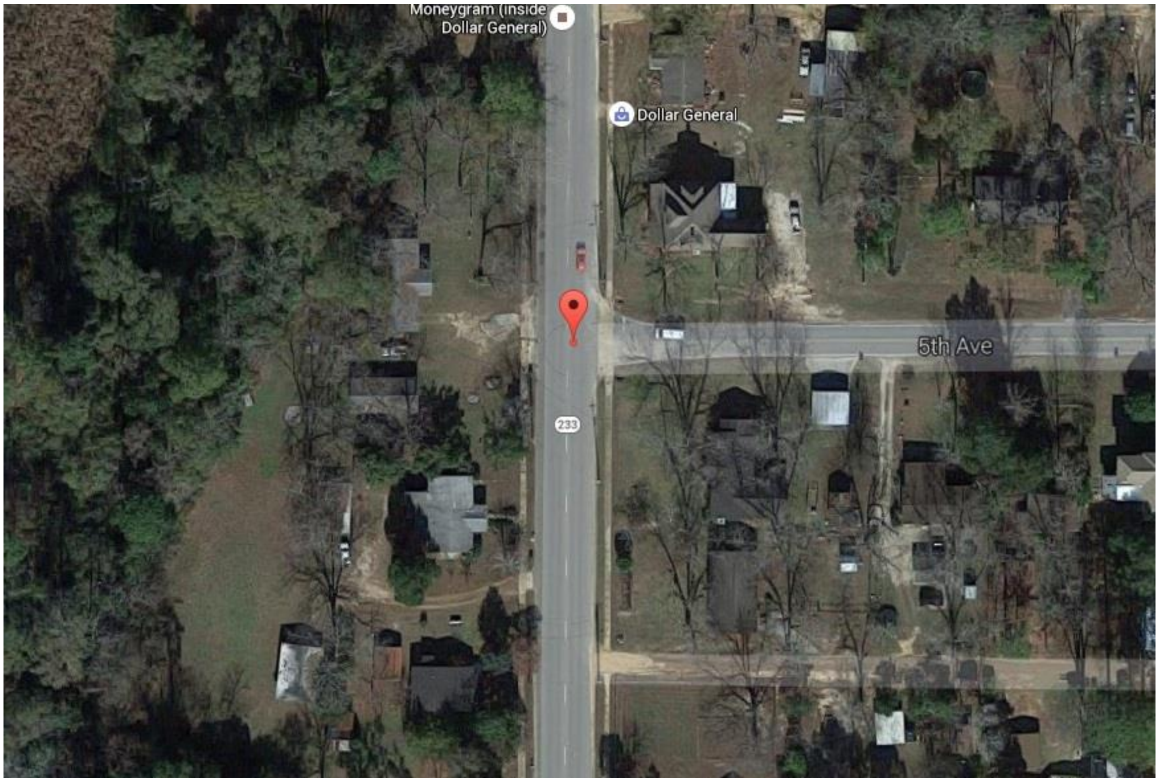

Figure F-55 Layout of Intersection #55

Intersection 56

Roads: M L King Jr Dr/ Broad St

Latitude: 32.18756 N

Longitude: 82.566154 W

Included in Final Analysis: YES

Figure F-56 Layout of Intersection #56

Intersection 57

Roads: W Madison St/ E Madison St/ S Franklin St

Latitude: 32.53928 N

Longitude: 82.90251 W

Included in Final Analysis: YES

Figure F-57 Layout of Intersection #57

Intersection 58

Roads: W Ashley St/ N Railroad St/ Sylvester Rd

Latitude: 31.809023 N

Longitude: 83.490021 W

Included in Final Analysis: YES

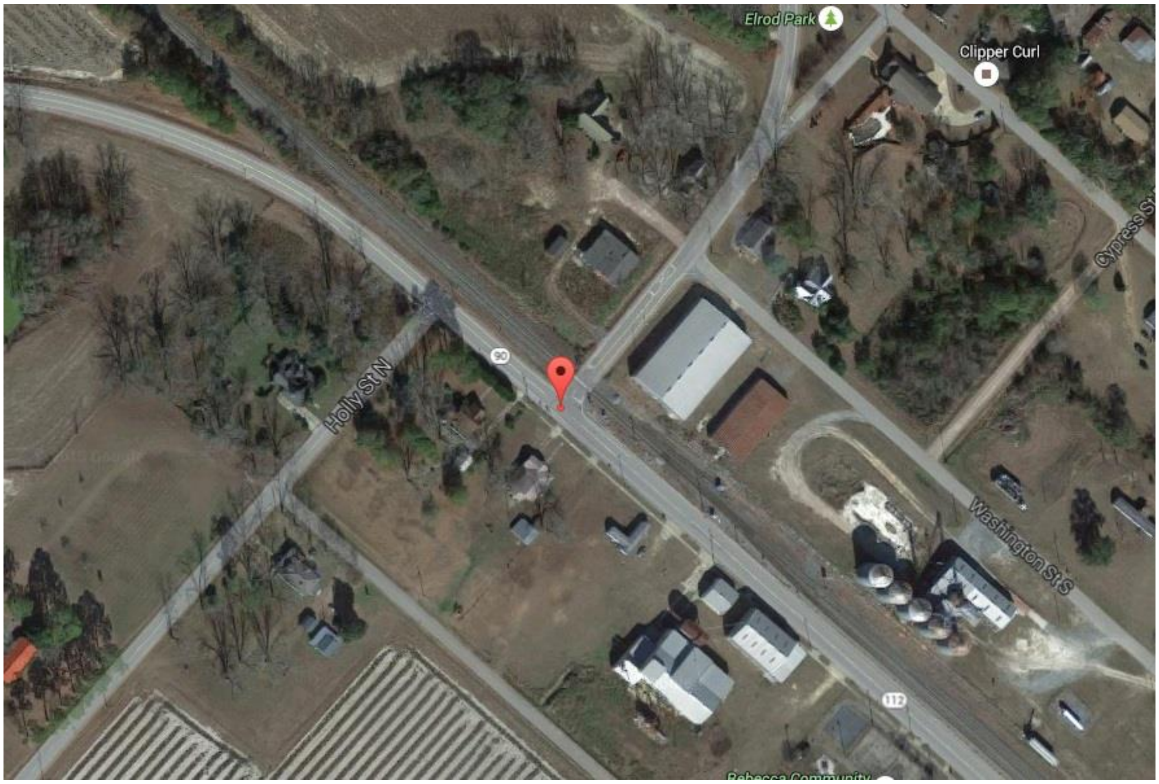

Figure F-58 Layout of Intersection #58

Intersection 59

Roads: 2nd Ave/ Ashley St

Latitude: 31.949702 N

Longitude: 83.45626 W

Included in Final Analysis: YES

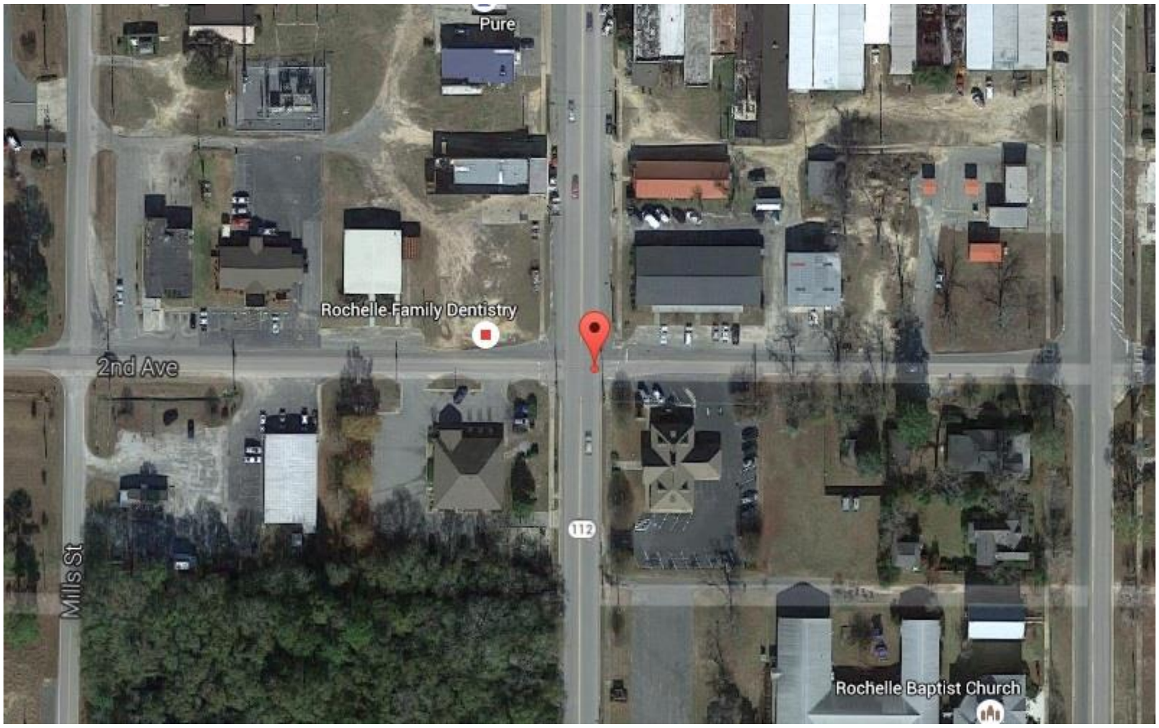

Figure F-59 Layout of Intersection #59

Intersection 60

Roads: High Shoals Rd/ Georgia 186/ Jim Edmondson Rd

Latitude: 33.791296 N

Longitude: 83.596102 W

Included in Final Analysis: YES

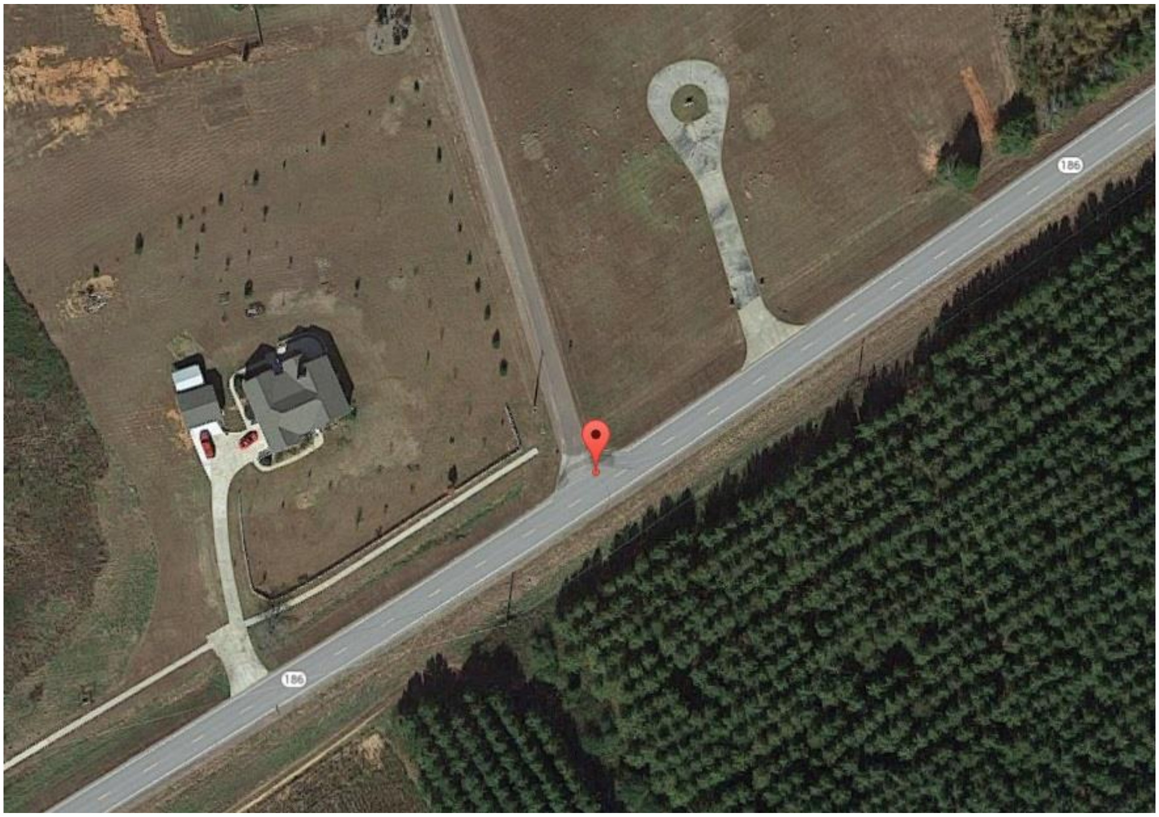

Figure F-60 Layout of Intersection #60

Intersection 22R

Roads: Hermance Dr NE/ Hermance Dr NE/ Brookhaven Ave

Latitude: 33.872842 N

Longitude: 84.3347 W

Included in Final Analysis: YES

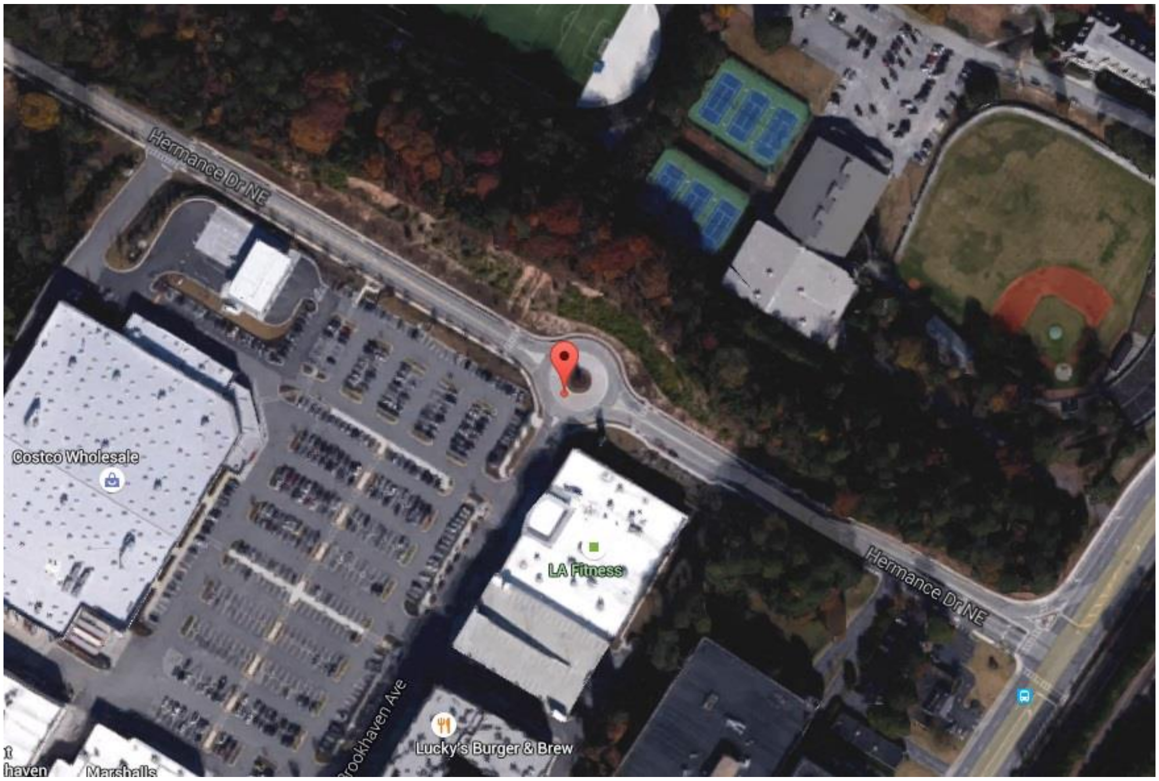

Figure F-61 Layout of Intersection #22R

Intersection 15R

Roads: Suwanee Creek Rd/ Wildwood Rd/ Suwanee Creek Rd/ Wildwood Rd

Latitude: 34.017206 N

Longitude: 84.075889 W

Included in Final Analysis: NO – residentia / recreational park areal

Figure F-62 Layout of Intersection #15

Intersection 14R

Roads: Hutchins Rd/ Arnold Rd/ Arnold Rd

Latitude: 33.902144 N

Longitude: 84.050561 W

Included in Final Analysis: NO – Purely residential

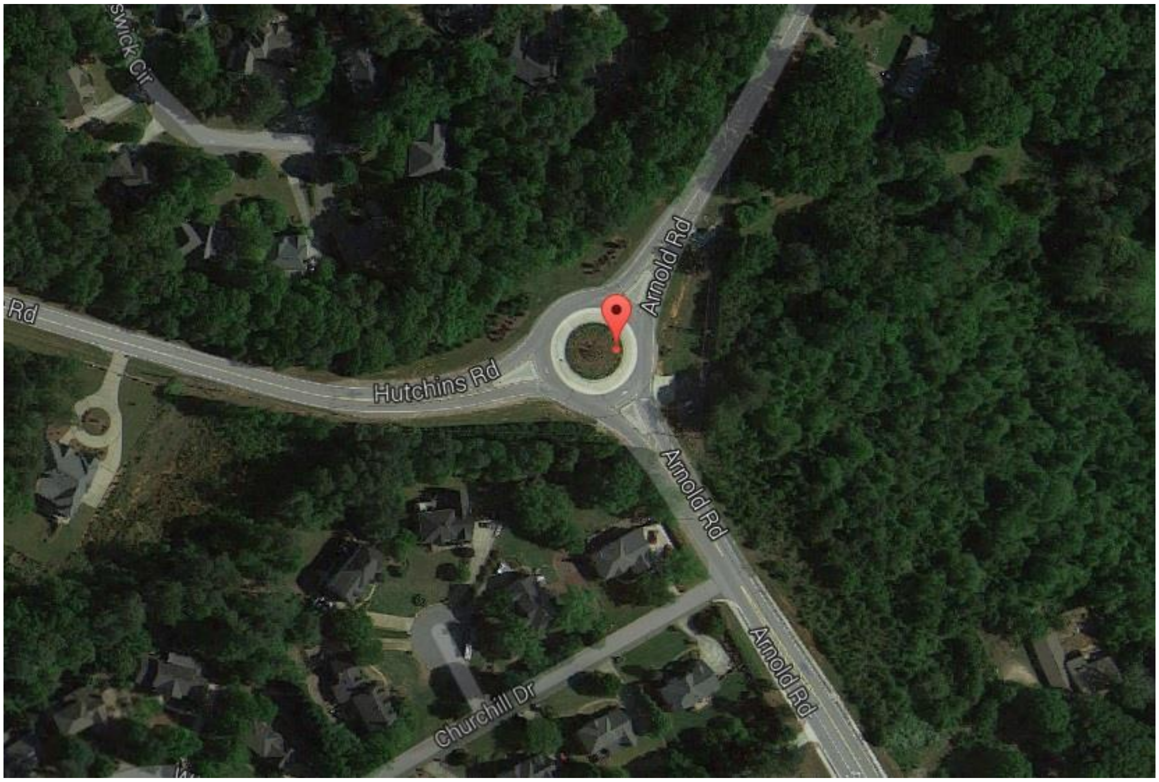

Figure F-63 Layout of Intersection #14R

Intersection 37R

Roads: Carriage Dr NE/ Carriage Dr NE/ Vernon Wood Dr NE/ Vernon Woods Dr NE

Latitude: 33.92663 N

Longitude: 84.371615 W

Included in Final Analysis: NO – Purely residential

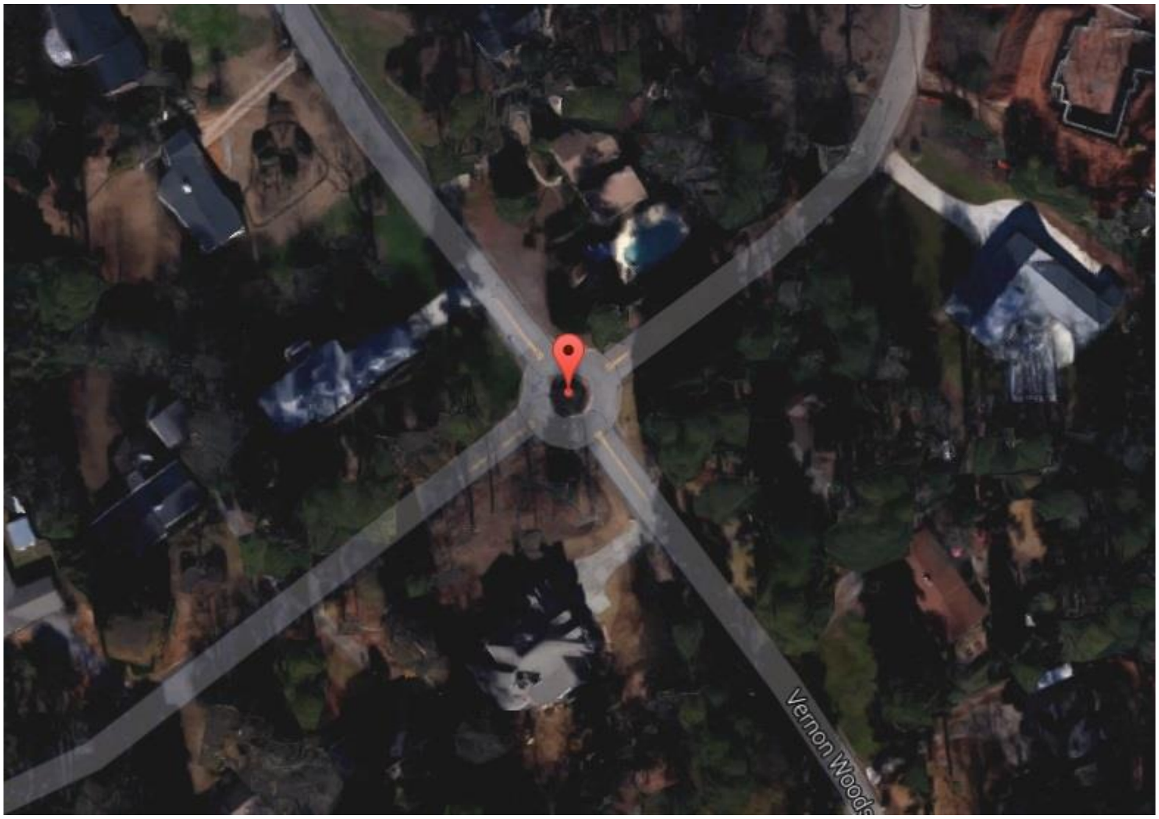

Figure F-64 Layout of Intersection #37R

Intersection 36R

Roads: Mabry Rd/ Mabry Rd/ Glenridge Dr/ Glenridge Dr

Latitude: 33.947204 N

Longitude: 84.364817 W

Included in Final Analysis: NO – Purely residential

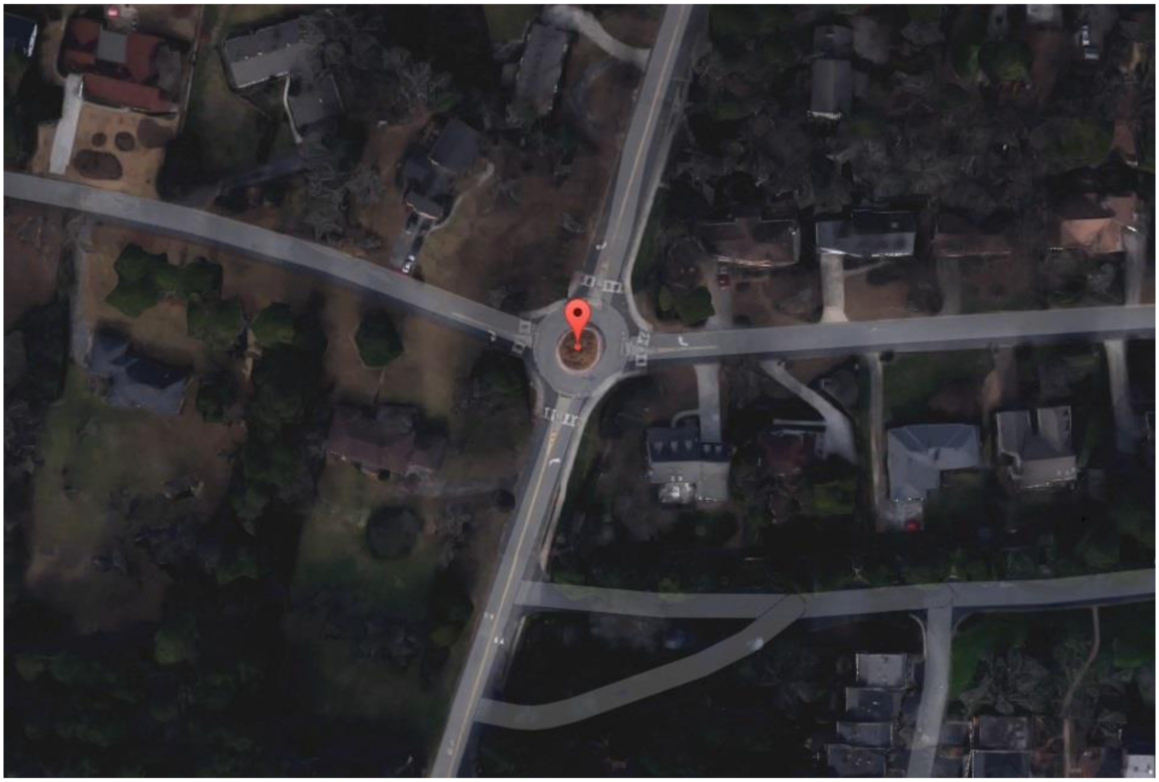

Figure F-65 Layout of Intersection #36

Intersection 24R

Roads: Oxford Rd NE/ N Decatur Rd/ N Decatur Rd/ Oxford Rd NE/ Dowman Dr

Latitude: 33.7883333 N

Longitude: 84.325833 W

Figure F-66 Layout of Intersection #24R

Intersection 34R

Roads: Hunters Branch Dr NE/ Twin Branch Rd NE/ Hunters Branch Dr NE

Latitude: 33.950407 N

Longitude: 84.349524 W

Included in Final Analysis: NO – Purely residential

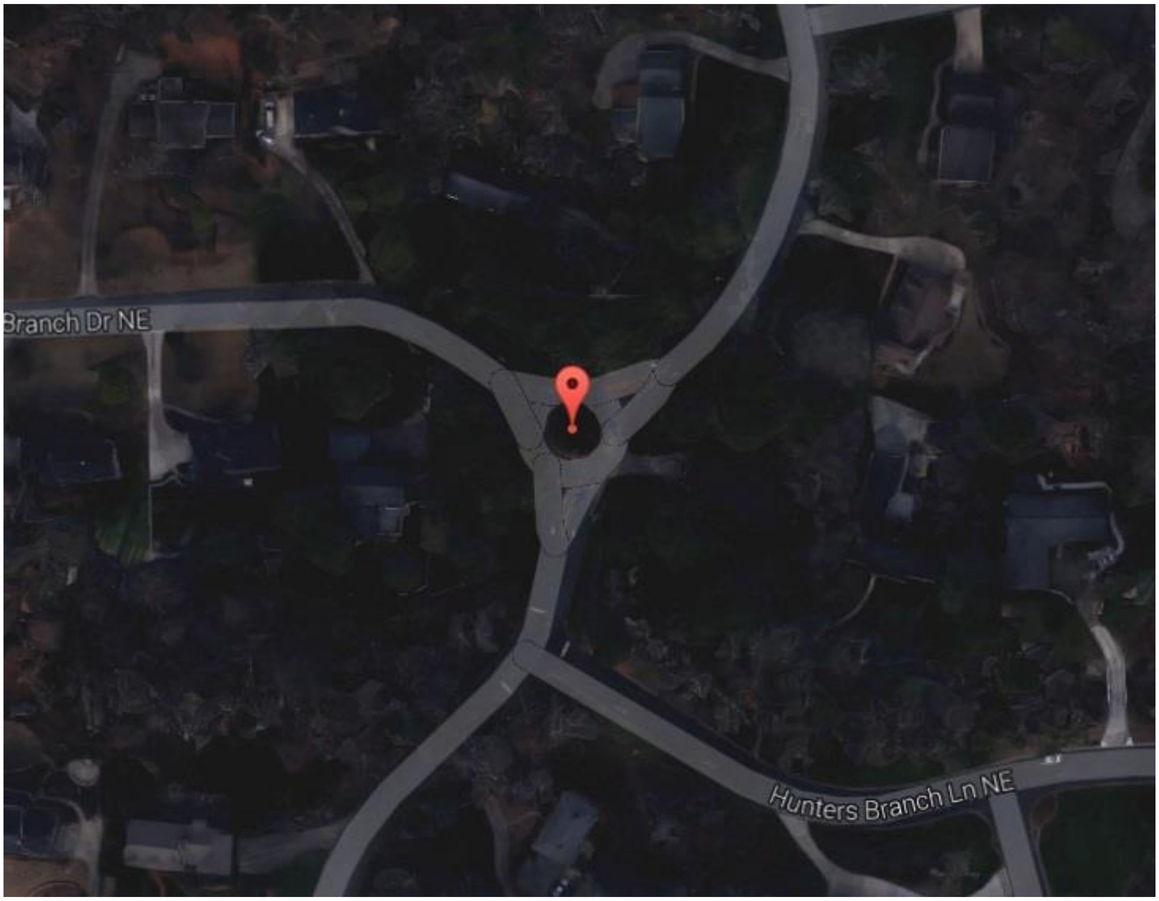

Figure F-67 Layout of Intersection #34R

Intersection 23R

Roads: N Decatur Rd/ N Decatur Rd/ Lullwater Rd

Latitude: 33.787392 N

Longitude: 84.329167 W

Included in Final Analysis: YES

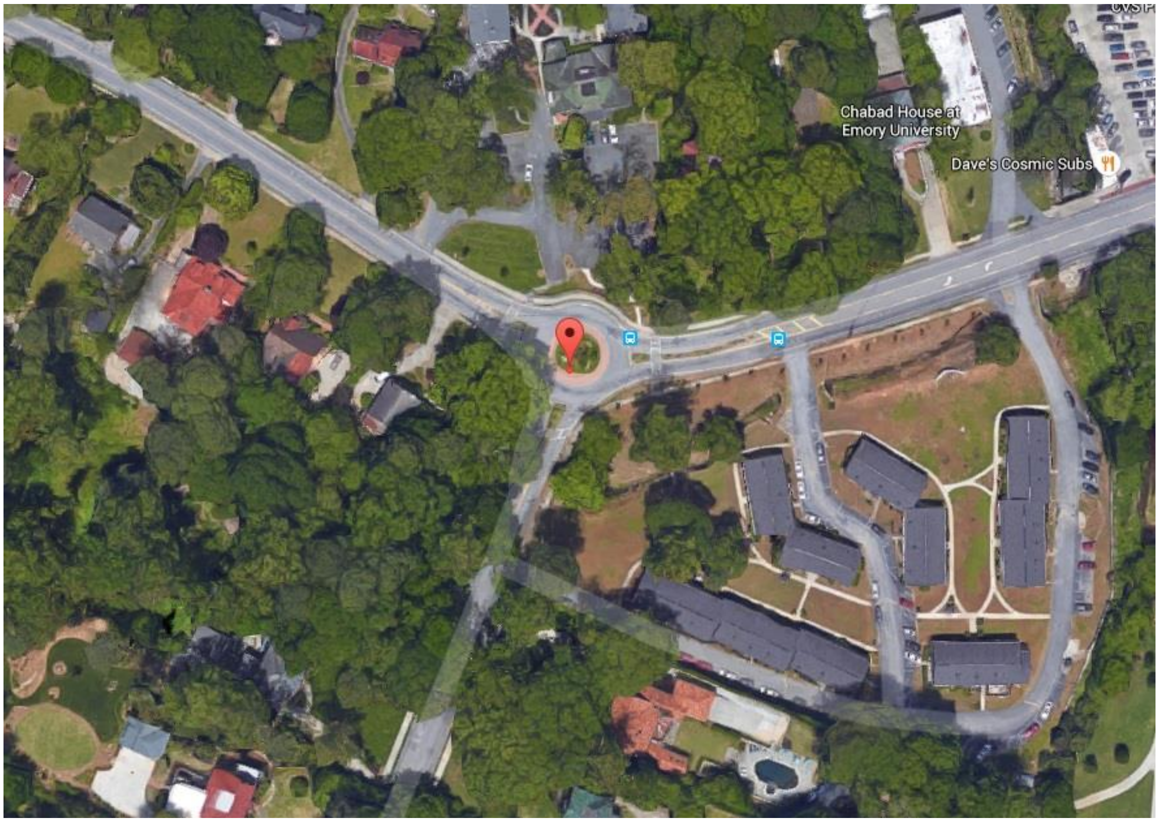

Figure F-68 Layout of Intersection #23R

Intersection 87R

Roads: Ball Mill Pl/ Ball Mill Pl/ Ball Mill Pl

Latitude: 33.9692417 N

Longitude: 84.328008 W

Included in Final Analysis: NO – Purely residential

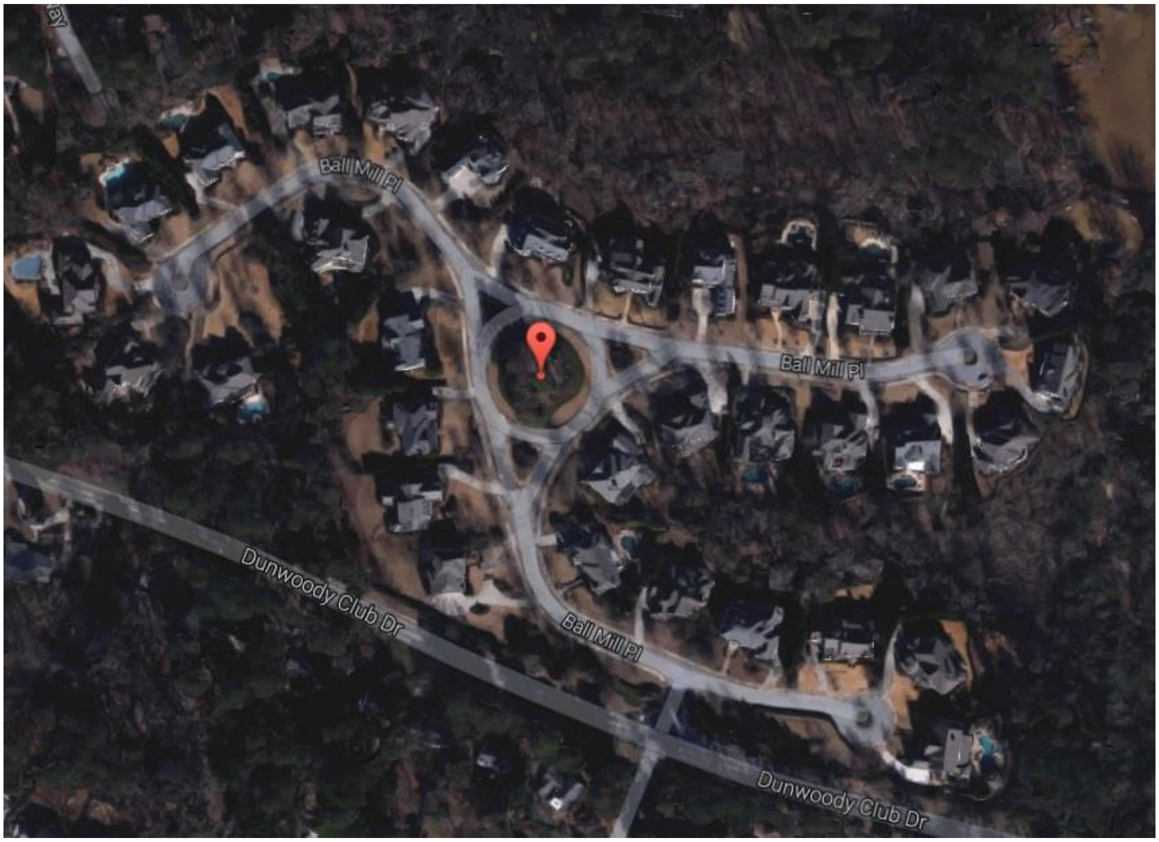

Figure F-69 Layout of Intersection #87

Intersection 93R

Roads: Meadow Park Ln/ Meadow Park Dr/ Dovecote Trail/ Meadow Bluff Ln

Latitude: 34.0636111 N

Longitude: 84.103056 W

Included in Final Analysis: NO – Purely residential

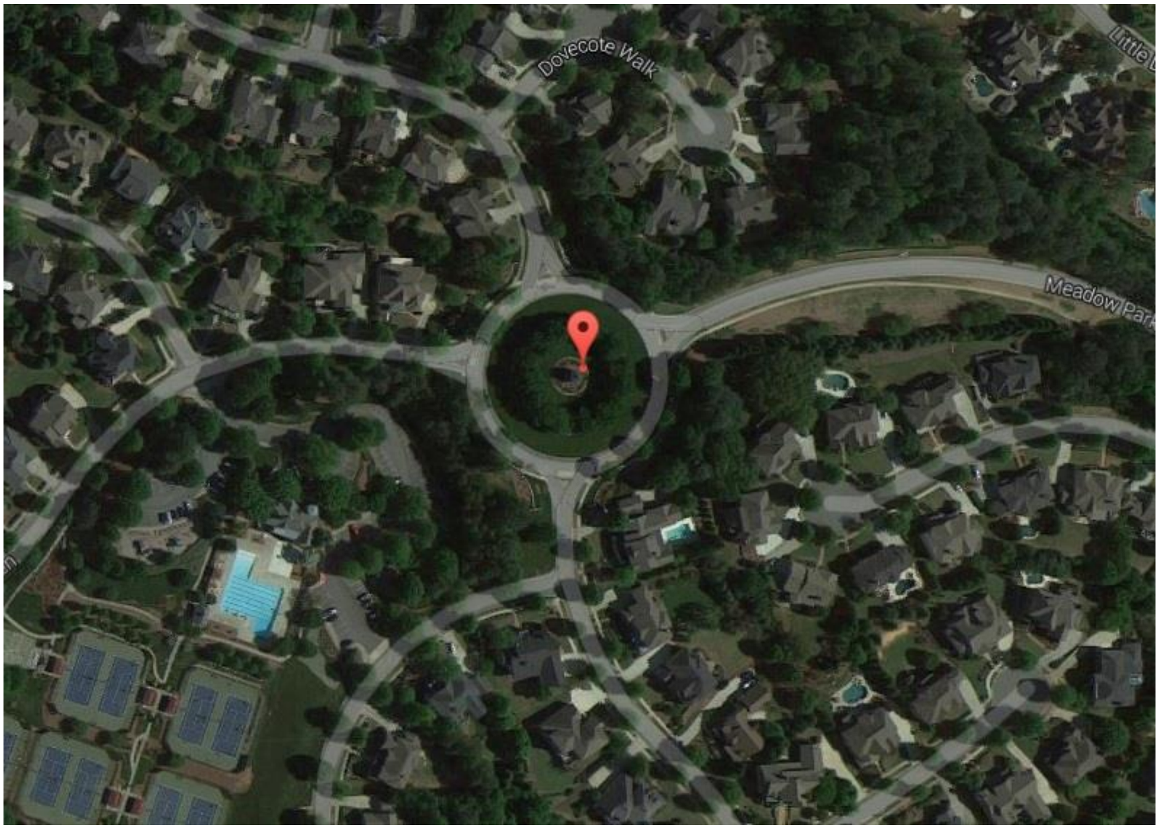

Figure F-70 Layout of Intersection #93R

Intersection 35R

Roads: Norcross St/ Warsaw Rd/ Grimes Bridge Rd/ Grimes Bridge Rd/ Melody Ln

Latitude: 34.02617 N

Longitude: 84.34475 W

Included in Final Analysis: YES

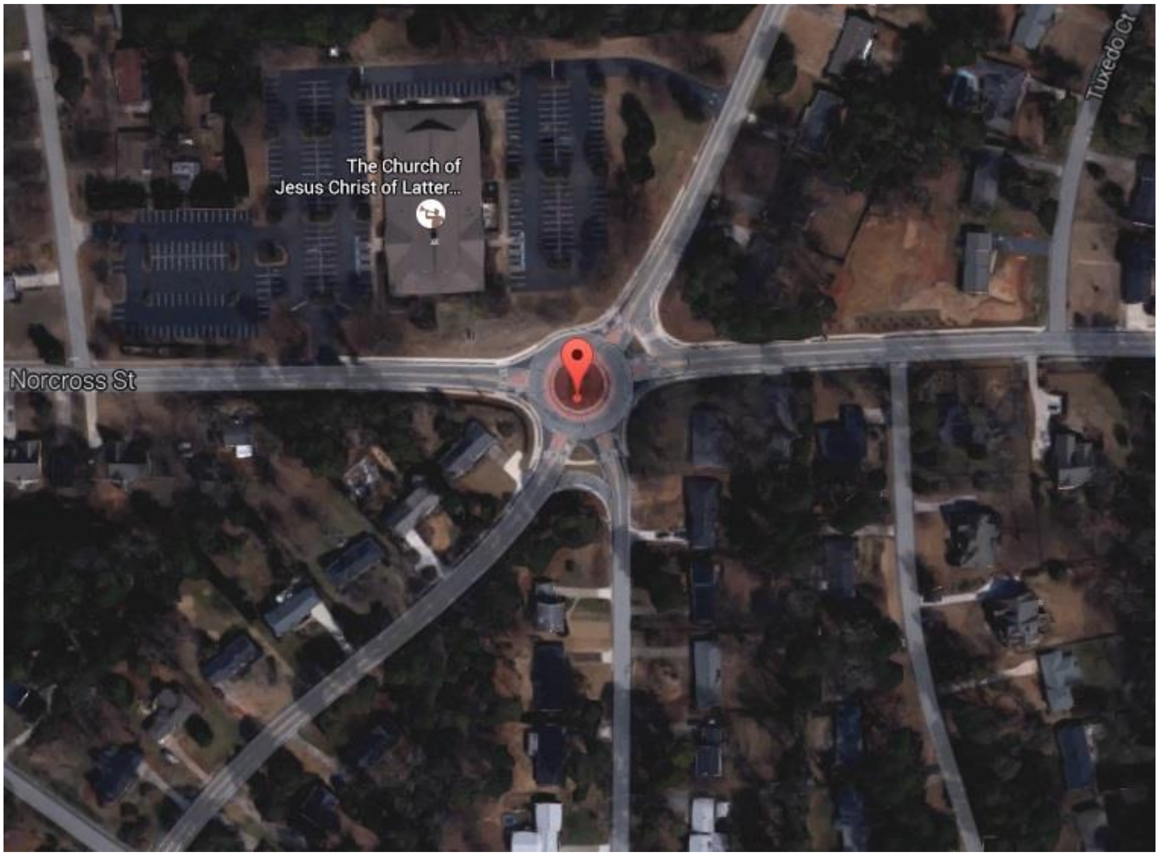

Figure F-71 Layout of Intersection #35R

Intersection 85R

Roads: Rainwater Dr/ Rainwater Dr/ Rainwater Dr

Latitude: 34.0628889 N

Longitude: 84.289097 W

Included in Final Analysis: NO – Office Complex

Figure F-72 Layout of Intersection #85R

Intersection 25R

Roads: Rockland Rd/ Rockland Rd/ Klondike Rd/ Klondike Rd

Latitude: 33.675992 N

Longitude: 84.114903 W

Included in Final Analysis: YES

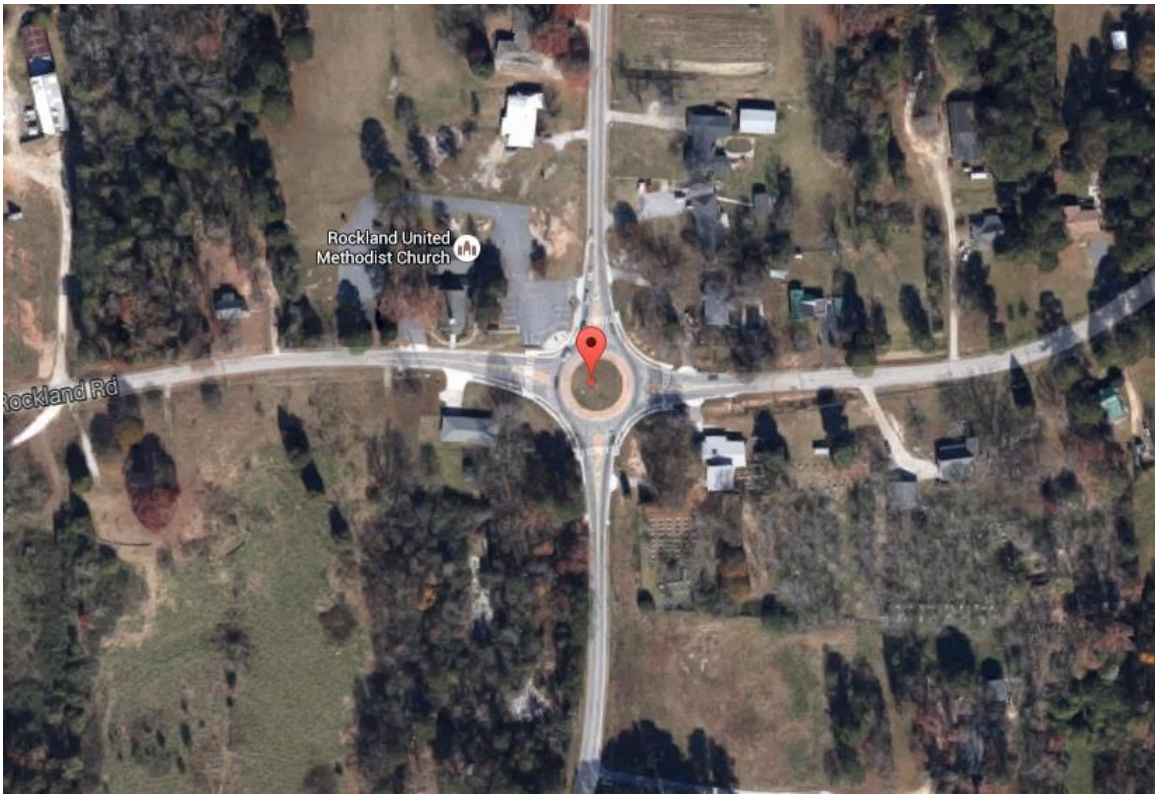

Figure F-73 Layout of Intersection #25R

Intersection 30R

Roads: Southlake Dr/ Leeward Walk Cir/ Douglas Rd/ Douglas Rd

Latitude: 34.076474 N

Longitude: 84.206831 W

Included in Final Analysis: YES

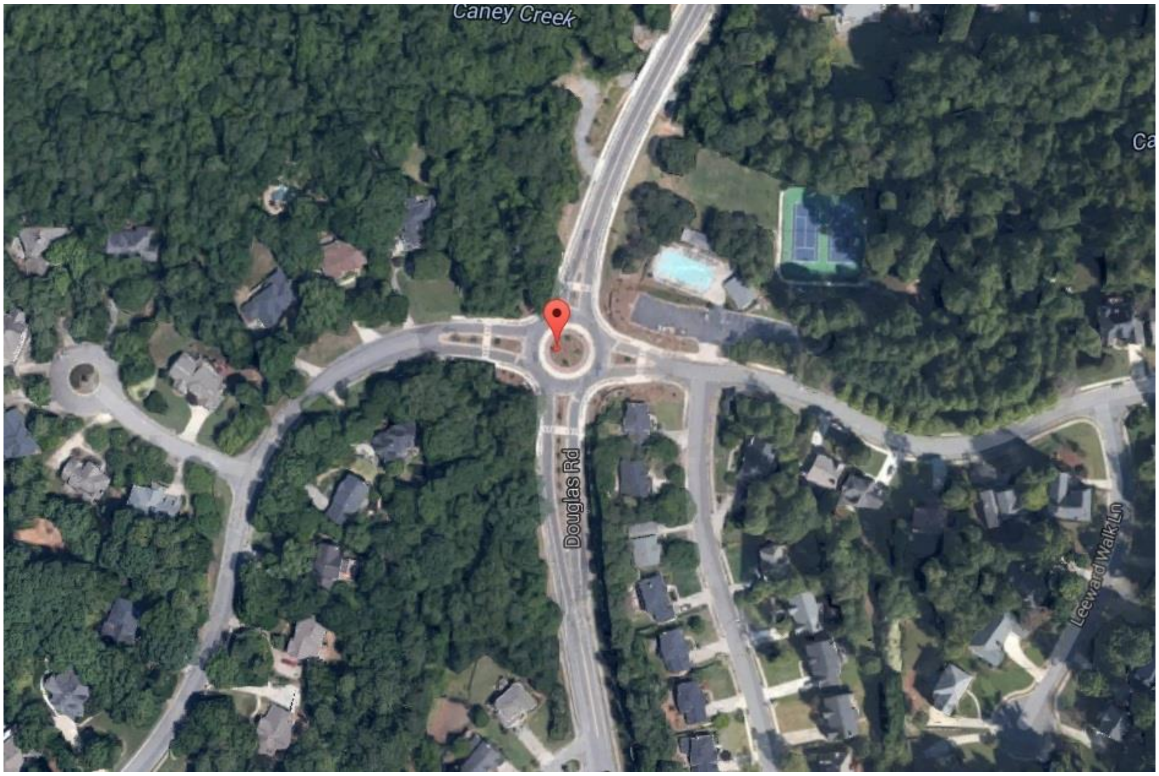

Figure F-74 Layout of Intersection #30R

Intersection 39R

Roads: Hardin St SW/ Okelly St SE/ Travis St SW

Latitude: 33.6643056 N

Longitude: 84.019722 W

Included in Final Analysis: NO – Purely residential

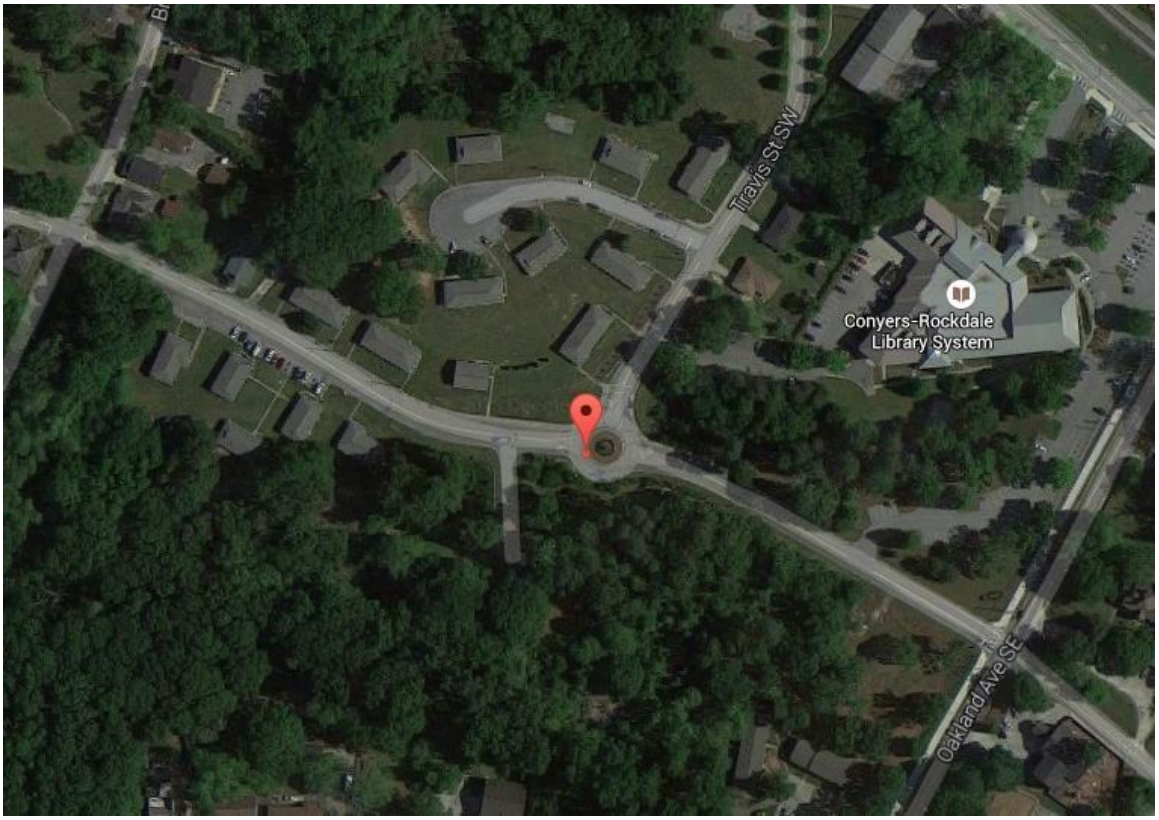

Figure F-75 Layout of Intersection #39

Intersection 89R

Roads: Redwine Pkwy/ Redwine Pkwy/ Redwine Pkwy/ Abbey Dr

Latitude: 33.6677778 N

Longitude: 84.514722 W

Included in Final Analysis: NO – Purely residential

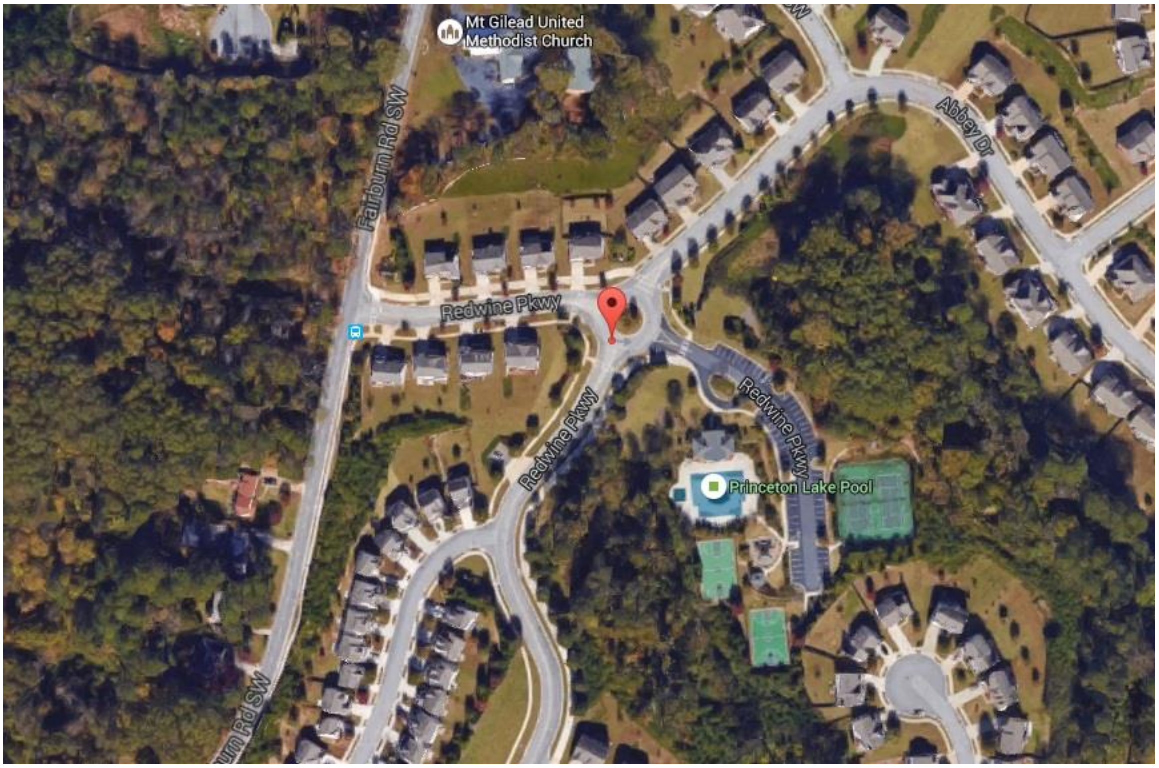

Figure F-76 Layout of Intersection #89R

Intersection 90R

Roads: Redwine Rd SW/ Redwine Rd SW/ Ramsey Close/ Tinsley Way SW

Latitude: 33.6627778 N

Longitude: 84.515 W

Included in Final Analysis: NO – Purely residential

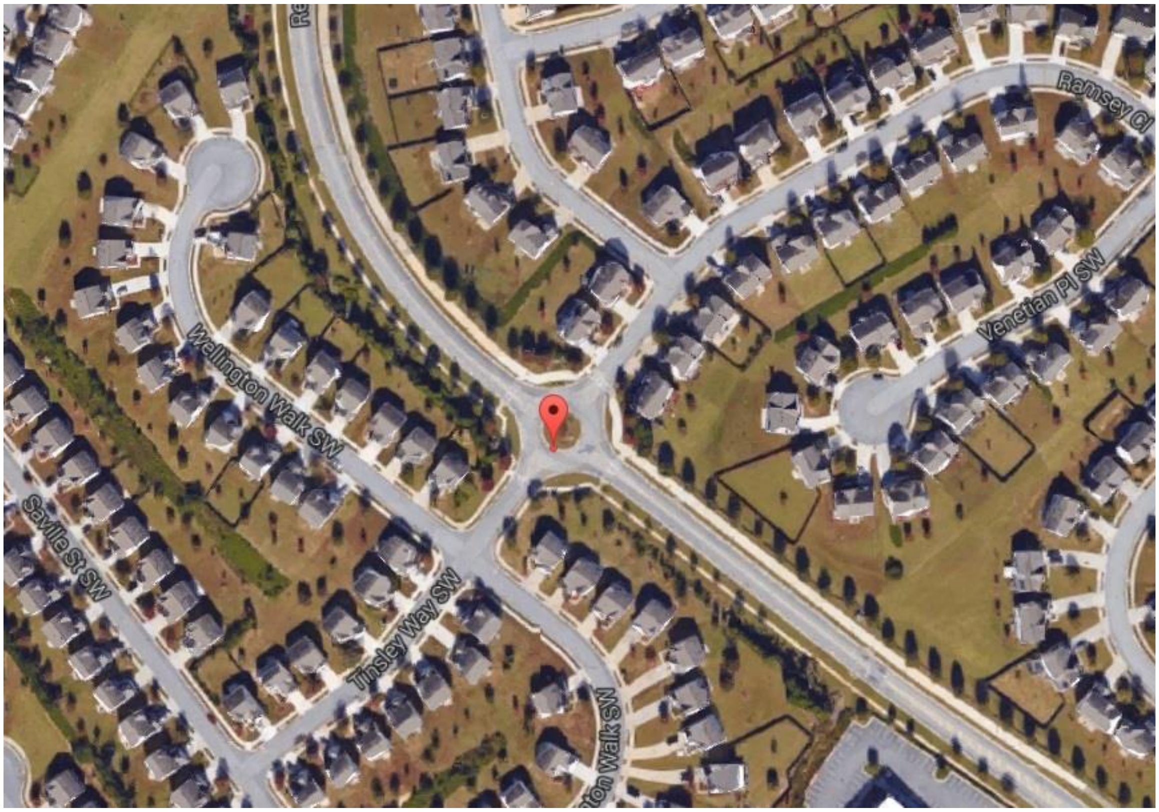

Figure F-77 Layout of Intersection #90R

Intersection 8R

Roads: Main St/ Main St/ Haney Rd

Latitude: 34.108419 N

Longitude: 84.517583 W

Included in Final Analysis: NO – pavement was wet

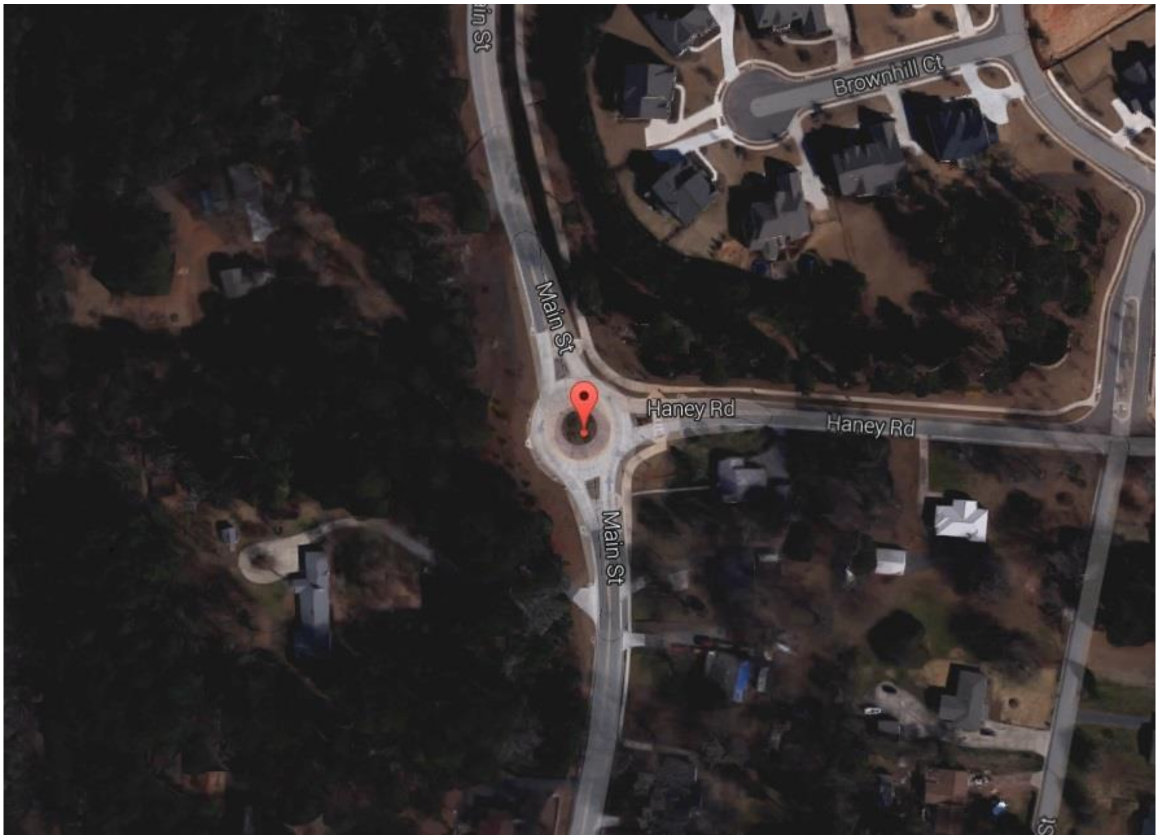

Figure F-78 Layout of Intersection #8R

Intersection 18R

Roads: Villa Rica Rd/ Villa Rica Rd/ West Sandtown Rd SW/ West Sandtown Rd SW

Latitude: 33.92704 N

Longitude: 84.63778 W

Included in Final Analysis: YES

Figure F-79 Layout of Intersection #18R

Intersection 44R

Roads: Grady Ave/ Grady Ave/ Beauregard Blvd/ Beauregard Blvd

Latitude: 33.441022 N

Longitude: 84.457578 W

Included in Final Analysis: NO – YES

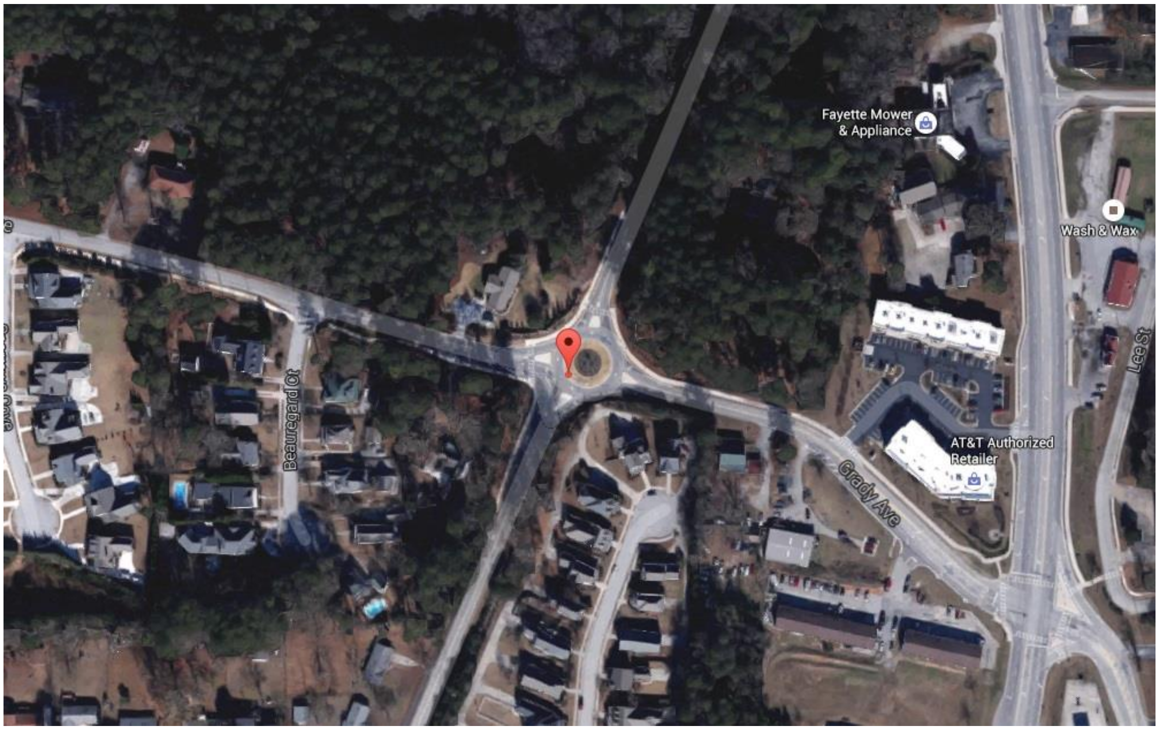

Figure F-80 Layout of Intersection #44R

Intersection 13R

Roads: Dawson Forest Rd E/ Dawson Forest Rd E/ Lumpkin Camp Ground Rd S/ Lumpkin Camp Ground Road S

Latitude: 34.354339 N

Longitude: -84.051697

Included in Final Analysis: YES

Figure F-81 Layout of Intersection #13R

Intersection 95R

Roads: Victory Ln/ Jubilee Blvd/ Jubilee Blvd

Latitude: 33.3508333 N

Longitude: 84.095556 W

Included in Final Analysis: NO – Purely residential

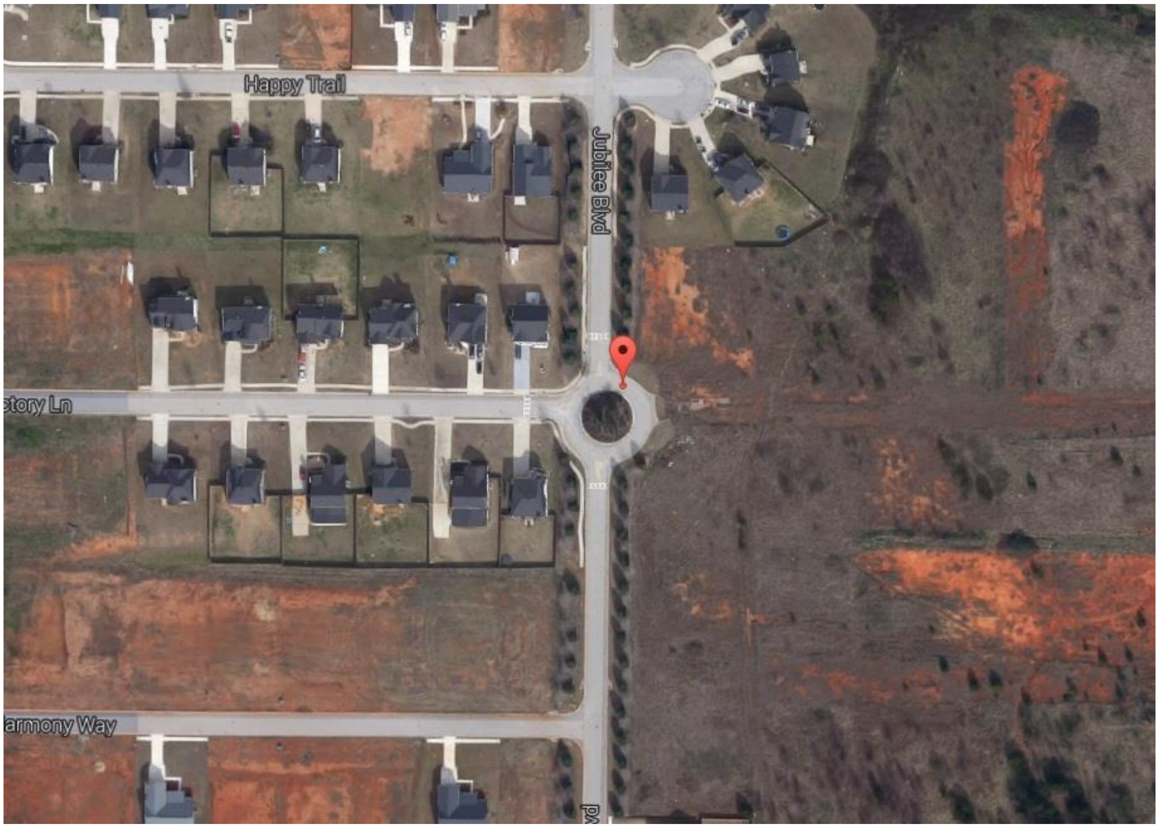

Figure F-82 Layout of Intersection #95R

Intersection 94R

Roads: Celebration Ct/ Jubilee Blvd/ Grove Rd

Latitude: 33.3480556 N

Longitude: 84.095556 W

Included in Final Analysis: NO – Purely residential

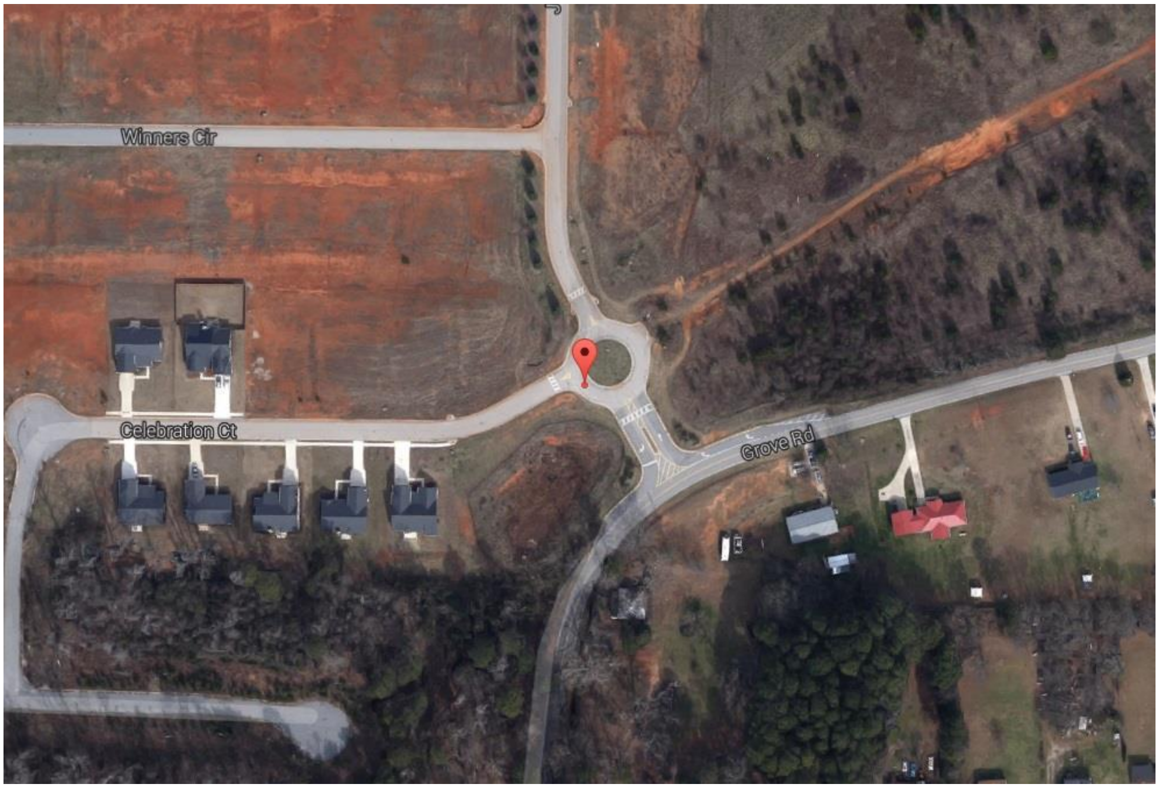

Figure F-83 Layout of Intersection #94R

Intersection 28R

Roads: Double Birch/ Double Birch/ Knotty Ridge Dr

Latitude: 33.652762 N

Longitude: 84.768535 W

Included in Final Analysis: NO – Purely residential

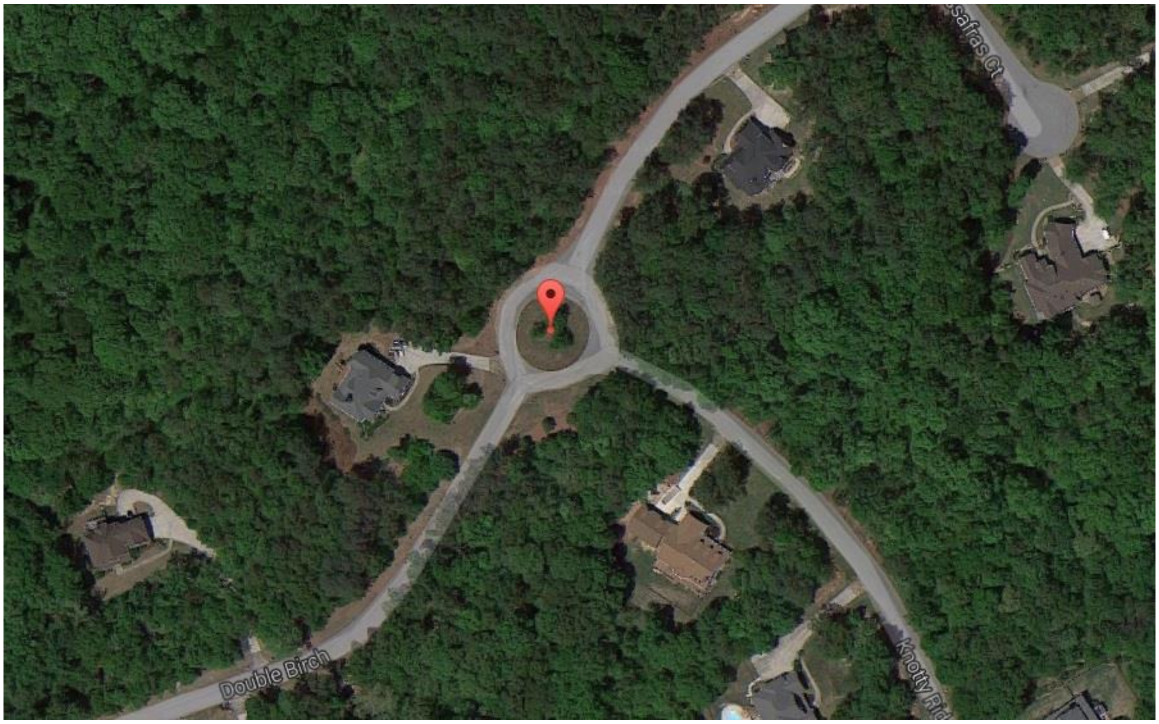

Figure F-84 Layout of Intersection #28R

Intersection 84R

Roads: Stonebridge Way/ Stonebridge Blvd/ Stonebridge Blvd

Latitude: 33.3861111 N

Longitude: 84.741944 W

Included in Final Analysis: NO – Purely residential

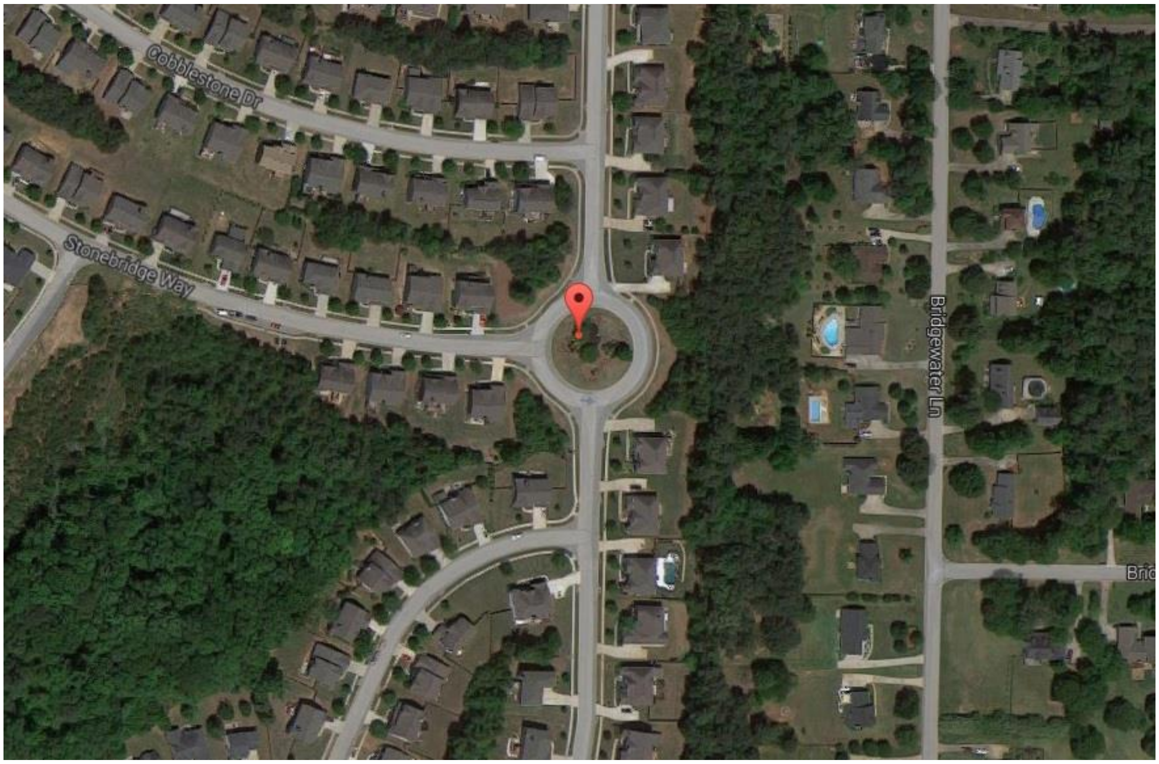

Figure F-85 Layout of Intersection #84R

Intersection 29R

Roads: Duncan Memorial Hwy/ Duncan Memorial Hwy/ Bill Arp Rd/ Bill Arp Rd

Latitude: 33.6136 N

Longitude: 84.836881 W

Included in Final Analysis: YES

Figure F-86 Layout of Intersection #29R

Intersection 1R

Roads: Newnan Rd/ Newnan Rd/ Newnan Rd/ Newnan Rd

Latitude: 33.565767 N

Longitude: 85.045059 W

Included in Final Analysis: NO – pavement was wet

Figure F-87 Layout of Intersection #1R

Intersection 9R

Roads: Chatillon Rd/ Chatillon Rd/ J L Todd Dr/ Riverside Industrial Park NE

Latitude: 34.281063 N

Longitude: 85.1657 W

Included in Final Analysis: YES

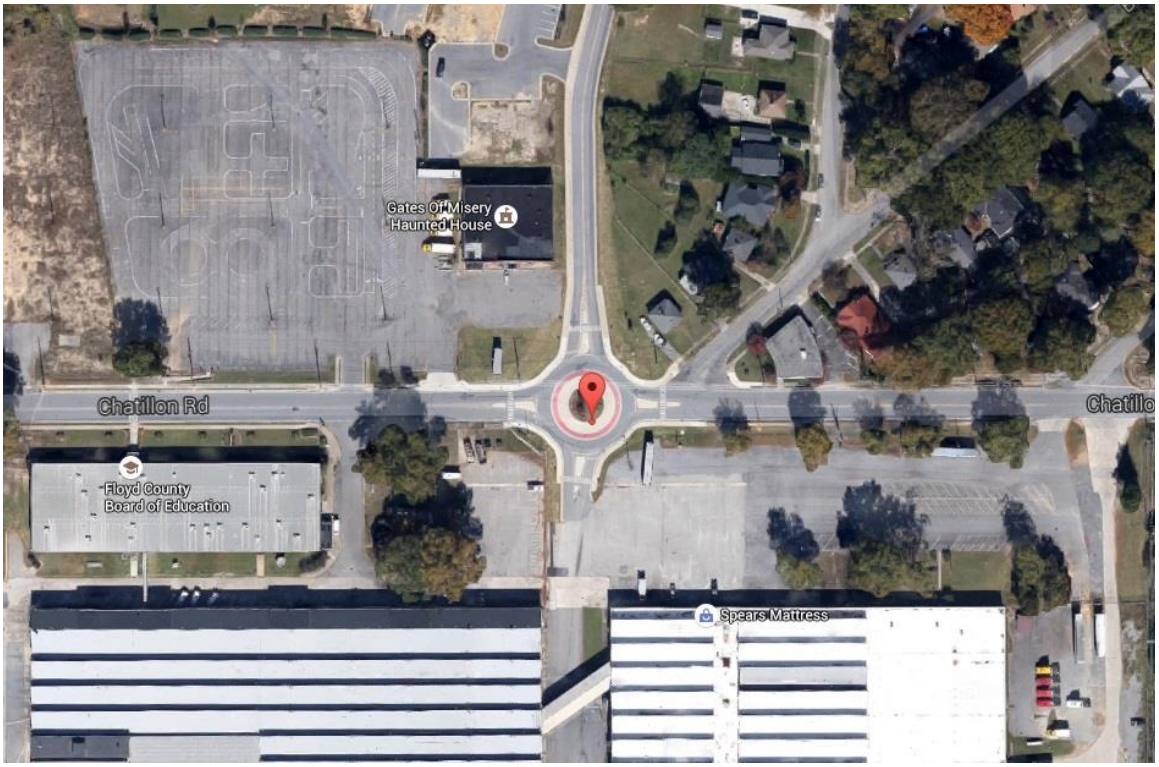

Figure F-88 Layout of Intersection #9R

Intersection 42R

Roads: E Broad St/ E Newnan Rd/ E Broad St/ Greison Trail

Latitude: 33.368122 N

Longitude: 84.779261 W

Included in Final Analysis: NO – pavement was wet

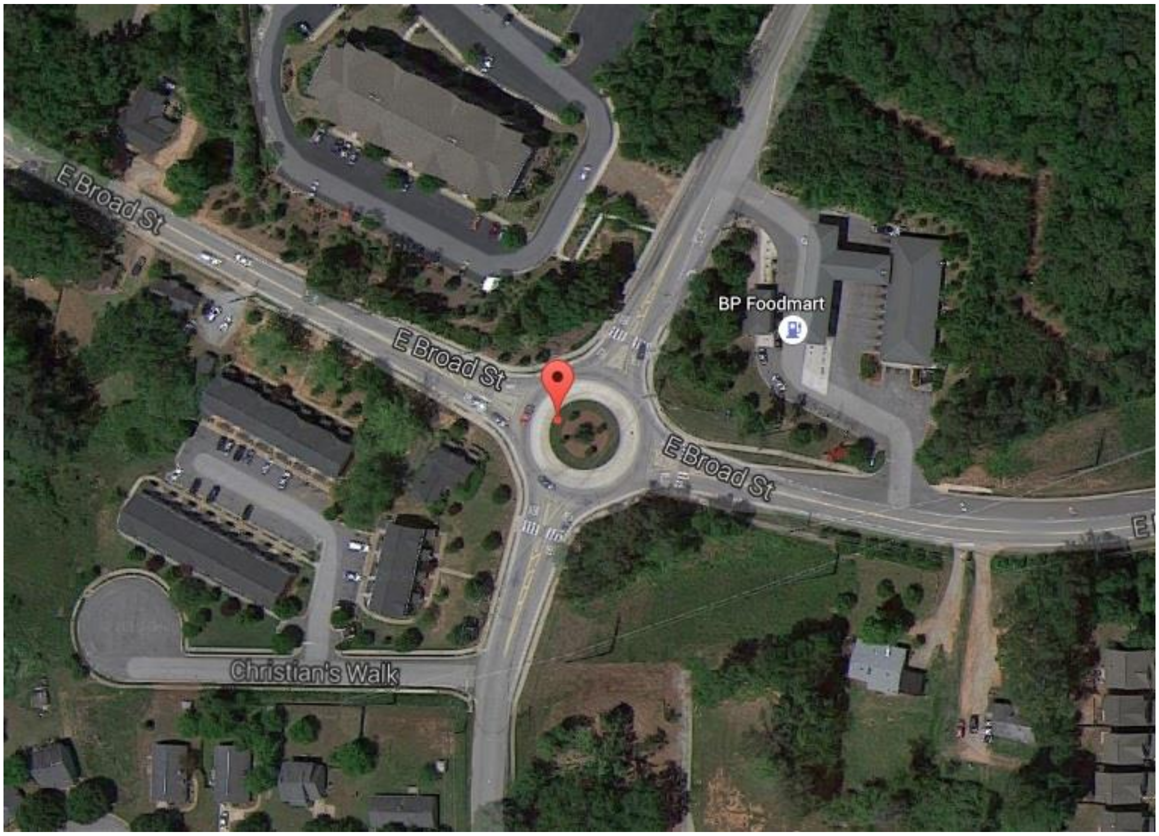

Figure F-89 Layout of Intersection #42R

Intersection 45R

Roads: Georgia 74/ Georgia 74/ U.S. 341/ Georgia 7

Latitude: 32.879497 N

Longitude: 84.090189 W

Included in Final Analysis: YES

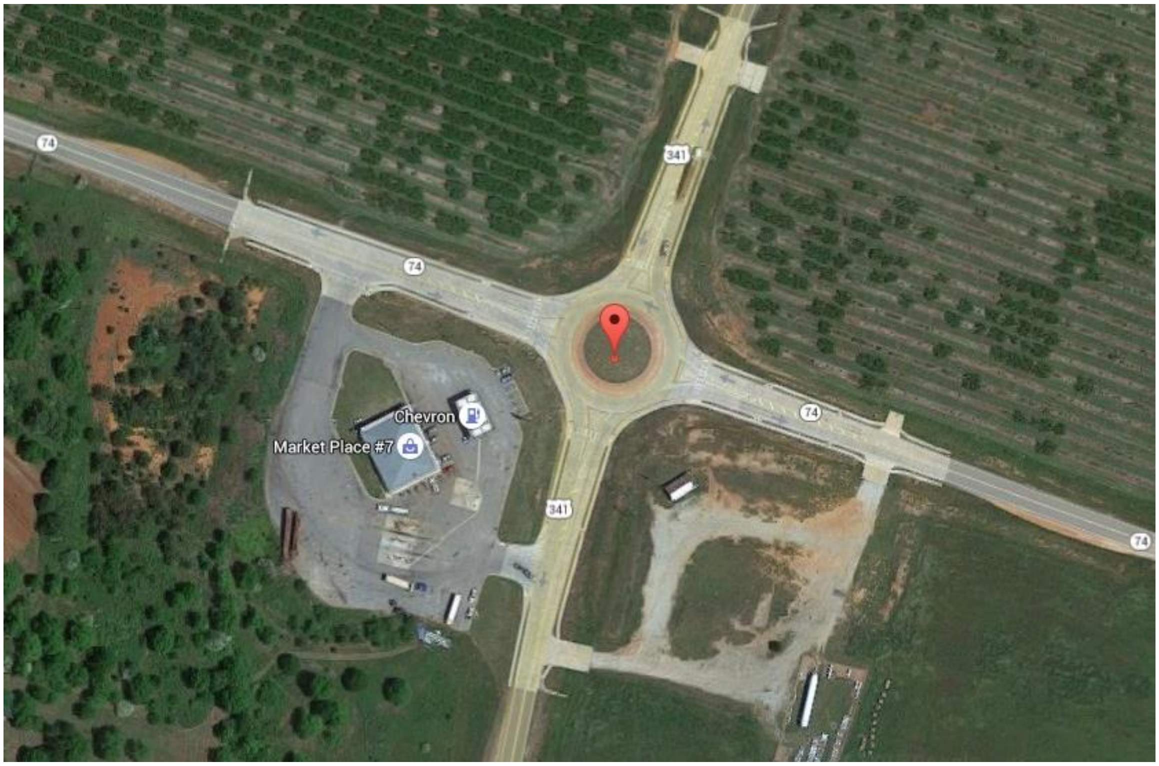

Figure F-90 Layout of Intersection #45R

Intersection 82R

Roads: Blackfoot Dr/ Blackfoot Dr/ Jamestown Ave/ Jamestown Ave

Latitude: 33.5755556 N

Longitude: 82.163611 W

Included in Final Analysis: NO – Purely residential

Figure F-91 Layout of Intersection #82R

Intersection 83R

Roads: Blackfoot Dr/ Blackfoot Dr/ Prince George Ave/ Prince George Ave

Latitude: 33.5758333 N

Longitude: 82.167778 W

Included in Final Analysis: NO – Purely residential

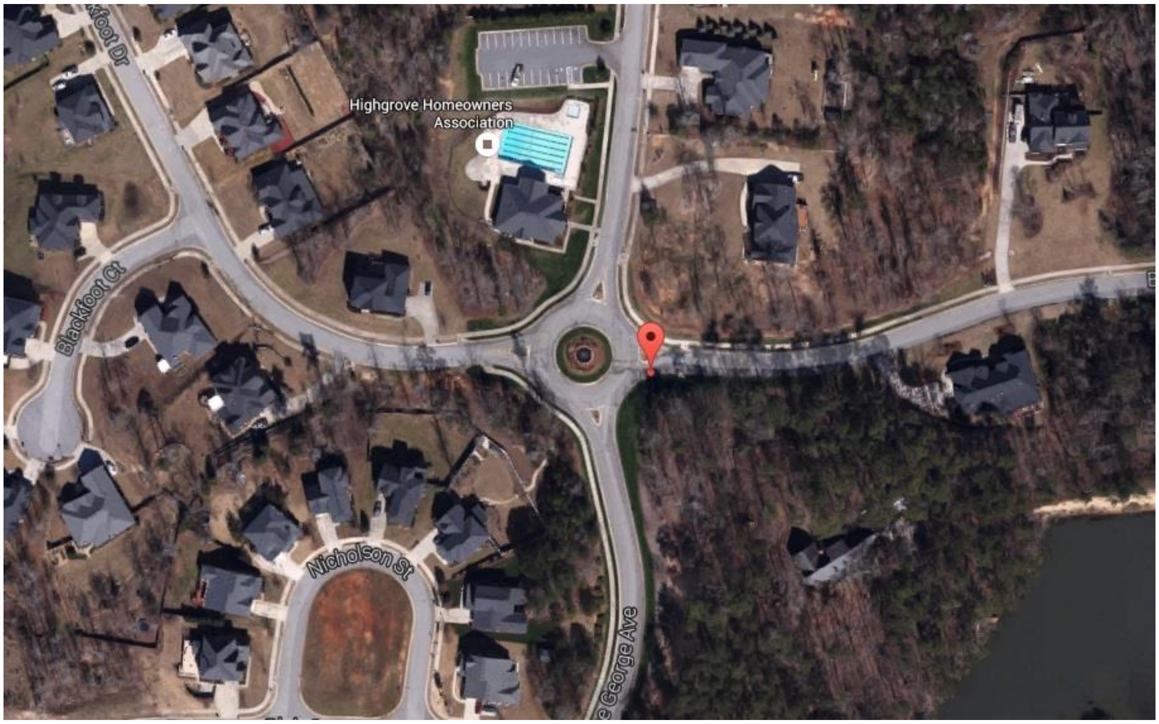

Figure F-92 Layout of Intersection #83R

Intersection 53R

Roads: W Gentilly Dr/ Bland Ave/ O’Neal Dr/ W Gentilly Dr

Latitude: 32.422583 N

Longitude: 81.775444 W

Included in Final Analysis: YES

Figure F-93 Layout of Intersection #53R

Intersection 96R

Roads: Marne Blvd/ Marne Blvd/ Tominac Dr/ Tominac Dr

Latitude: 31.8513889 N

Longitude: 81.653333 W

Included in Final Analysis: NO – purely residential

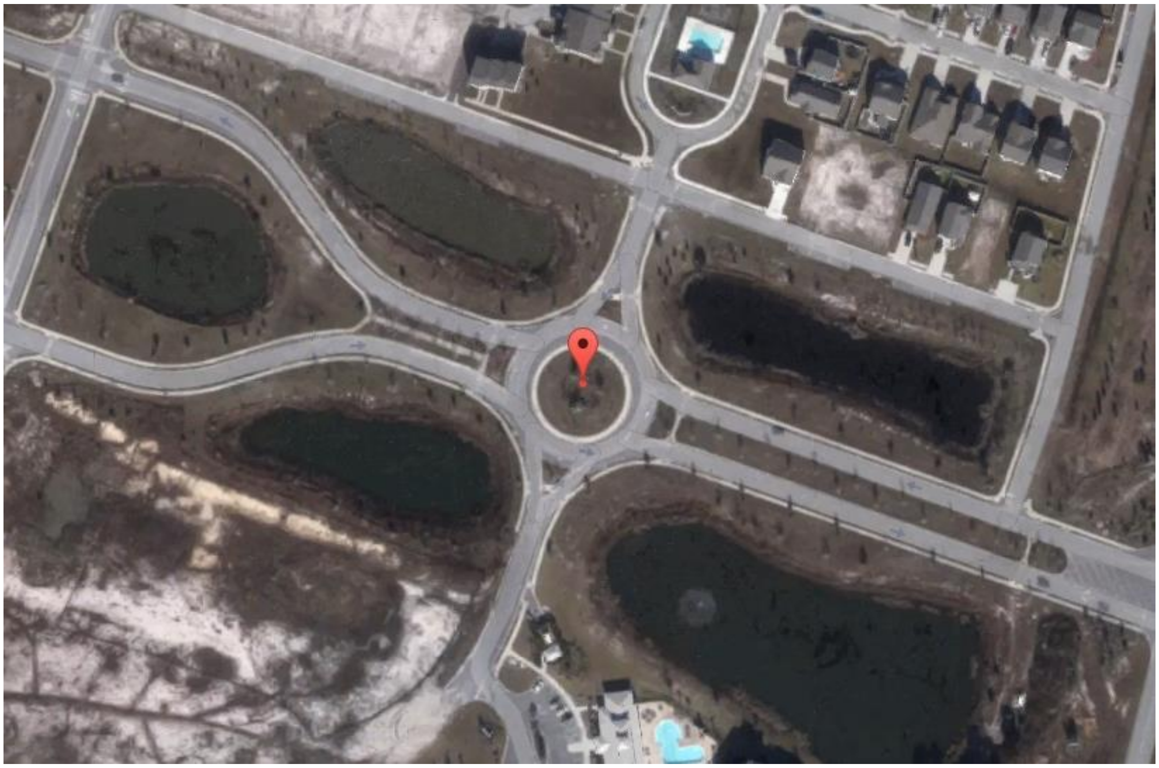

Figure F-94 Layout of Intersection #96R

Intersection 56R

Roads: Memorial Dr/ E Memorial Dr/ N Main St/ N Main St

Latitude: 31.85 N

Longitude: 81.595833 W

Included in Final Analysis: YES

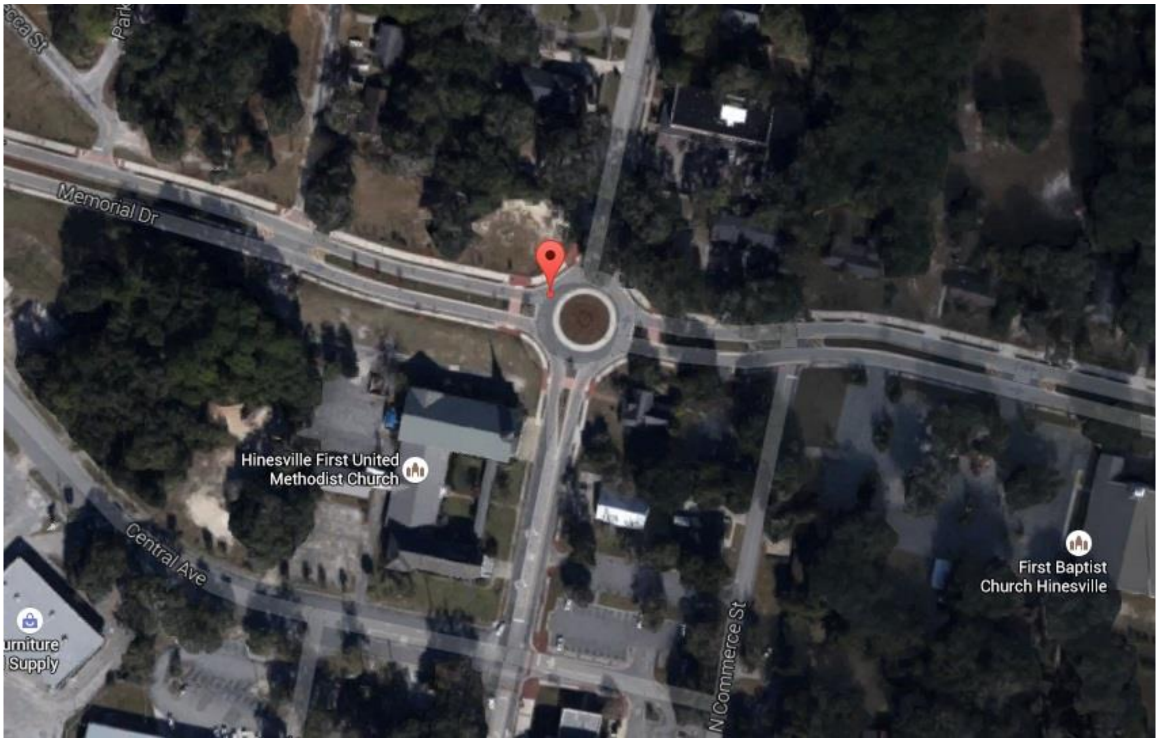

Figure F-95 Layout of Intersection #56R

Intersection 54R

Roads: Demere Rd/ Demere Rd/ Frederica Rd/ Frederica Rd

Latitude: 31.159613 N

Longitude: 81.388569 W

Included in Final Analysis: YES

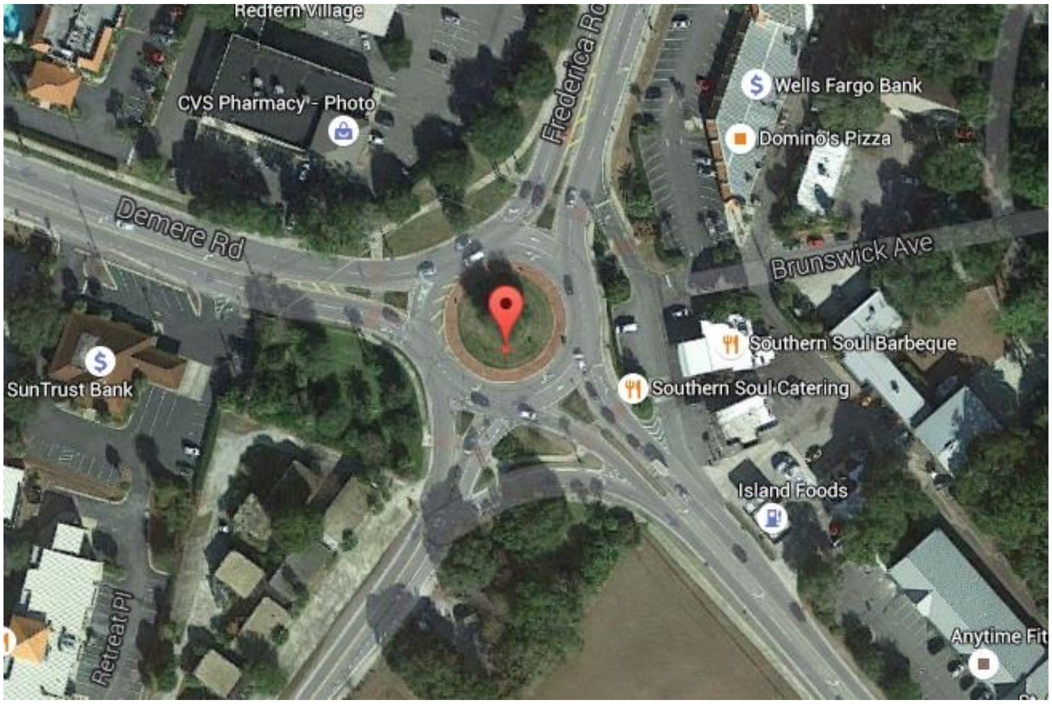

Figure F-96 Layout of Intersection #54R

Intersection 55R

Roads: Frederica Rd/ Lawrence Rd/ Frederica Rd

Latitude: 31.216497 N

Longitude: 81.375515 W

Included in Final Analysis: YES

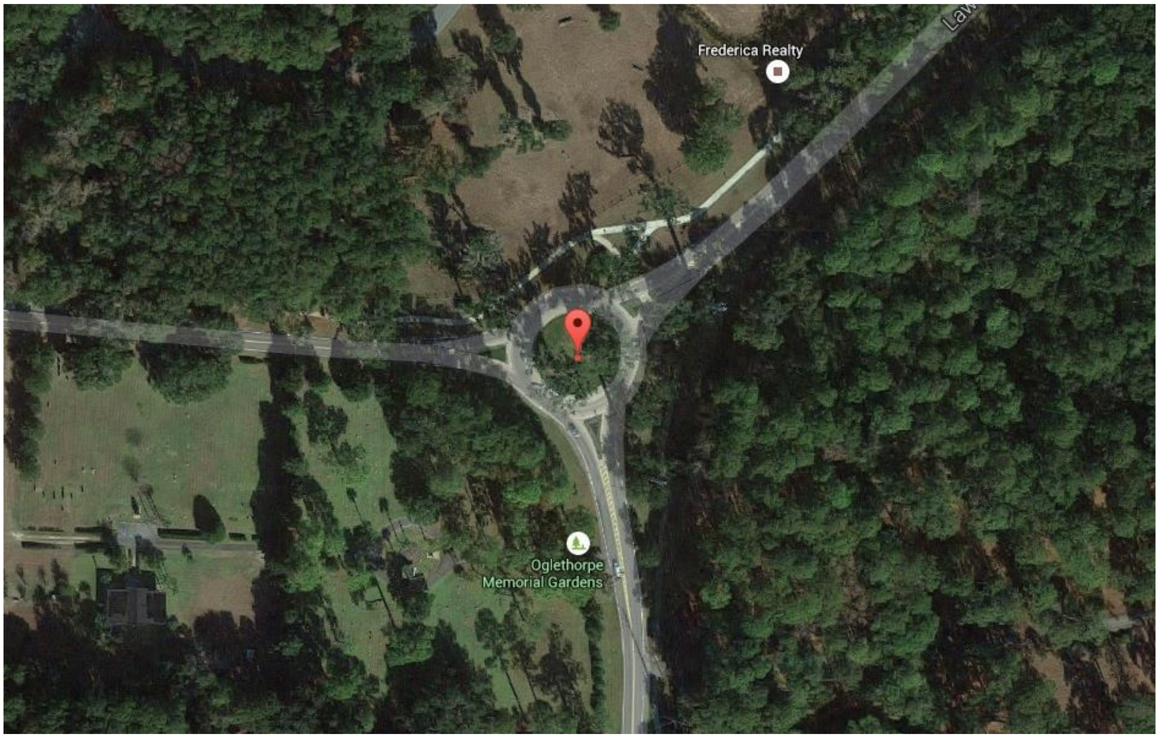

Figure F-97 Layout of Intersection #55R

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