Estimation of the Influence of Artificial Roadway Lighting on Road Collision Frequency

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ABSTRACT

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Nagham Matout

Road accidents in Quebec registered a total of 104,070 collisions with 39,541 victims of injuries and 436 fatalities in 2012 alone. Driving in dark environments increases the risk of accident likelihood for which artificial roadway lighting is typically seen as a countermeasure. However, it is unknown if non-standard levels of lighting help in reducing collision frequency, representing the case for many inconsistently illuminated roads under municipal jurisdiction. This research collected illuminance measurements for the Arthabasca region in Quebec. The collected data was combined with available operational and geometrical characteristics as well as collision frequency, to investigate what variables explain nighttime road crashes and how different levels of artificial lighting correlate with them. It was found that the presence of an intersection and having a slippery road surface produced more collisions. Roads with a complex geometry as well as traffic volume explain higher collision rates. Either standard or non-standard illuminated roads resulted in an increase of road collision frequency as compared to dark sites. Definition of standard illumination seems not to correspond to the statistical evidence herein found. Increasing the minimum level of illuminance for standard lighting helps in reducing collision frequency at standard lit sites as illuminance levels were raised. Quebec warrant grid system seems to give preference to illuminate roads at either urban locations or in the proximity to an intersection. A good correlation between all illuminated sites and a variable containing urban and suburban land uses was found. Empirical evidence also suggests that dark locations correspond mostly to rural sites (possibly with lower volumes of cars) which observe lower frequency of road collisions.

DEDICATION

To
My caring wonderful mother and my supportive brothers

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I am deeply indebted to my supervisor Dr. Luis Amador for his advice, support, encouragement and friendship during my graduate studies at Concordia University. I wish all the best to him and his family. I would like to express my appreciation to my committee members, Professor Andreas Athienitis, Professor Lan Lin and Professor Zachary Patterson.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
C.I.	Confidence Interval
CIE	International Commission on Illumination (From its French name: Commission International de l'éclairage)
DOT	Department of Transportation
FHWA	Federal Highway Administration
MTQ	Ministère des Transports du Québec
NCHRP	National Cooperative Highway Research Program
NRCC	National Research Council Canada
SAAQ	Société de l'Assurance Automobile du Québec
SPF	Safety Performance Function
TAC	Transportation Association of Canada
WHO	World Health Organization
ZINB	Zero-Inflated Poisson model
ZIP	Zero-Inflated Poisson model

CHAPTER 1
INTRODUCTION

1.1 Background

Road collisions can impact negatively thousands of individual's lives. Damage to infrastructure, labour losses, injuries, and sadly fatalities, to mention a few, are some of the negative socioeconomic impacts that may result from road-related collisions. In 2011, road fatalities were ranked ninth worldwide, making road injuries one of the top ten death leading causes worldwide (WHO 2013).

Within the past decade, around 1.24 million people have died annually as a result of road collisions (WHO 2013). In addition, twenty to fifty million other individuals were victims of road-related injuries worldwide (WHO 2013). These numbers are expected to rise within the following decades (WHO 2013). According to Transport Canada (2012), the total number of fatalities and injuries registered on Canadian roads in 2010 was 2,227 and 170,629 victims respectively. In high-income developed countries, the highest percentage of road traffic fatalities is associated to motorized vehicles (WHO 2013). In fact, more than half of the world's road fatalities, 54%, occur amongst motorized road commuters (including motorcyclists with 23%) (WHO 2013). This figure is higher for Canada reaching 81.6% of fatalities, including all motorized vehicle occupants and motorcyclists, in the year 2011 (WHO 2013). Different agglomerated areas seem to have different crash statistics. According to Transport Canada (2012), 57% of Canadian road fatalities occur in rural area; whereas, 75% of road related injuries occur in urban areas.

In 2012, Quebec registered 39,541 cases of injuries and 436 fatalities on its road network (SAAQ 2012). Quebec's road traffic fatalities follow the observed global trend with motorized users representing the highest number in road related deaths (SAAQ 2012). Also, according to City of Montreal (2007), around two-third of road collisions on Montreal's road network happen during daytime; whereas the remaining third of the crashes occurs at nighttime.

The World Bank (2004) claims that nighttime road crashes can be reduced by installing road lights, also known as luminaires. As a matter of fact, street lighting is an essential component, amongst others, that can be used as a countermeasure for nighttime road collisions. According to IESNA (2005), different levels of illumination can mitigate crashes as well as control vehicles' speed during night.

Throughout the past decade, road safety researchers from around the world have been and still trying to investigate the impact of roadway lighting on visibility and nighttime collisions.

The purpose of this study is to compare different lighting levels and find the correlation between lighting and nighttime collision frequency if any exists, while controlling for other factors. The different lighting levels defined in this study are: 1) Standard, following the Ministère du Transport du Quebec guidelines,2) Non-Standard, and 3) Non-Illumination (i.e. dark).

It is believed that provision of artificial lighting improves the visibility of the driver and allows the latter to perceive potential hazards. Providing the driver with good visibility would prevent risks of collision. With this being said, governments all around the world perceive the provision of street lighting as a good countermeasure to mitigate nighttime collisions. However, departments of transportation (DOTs) have historically limited their role to the photometric design according to the existing body of standards without auditing or analyzing the crash history and its before and after variations at locations where lighting have been improved or upgraded.

Another issue rises from the fact that existing standards are not well understood, nor are always applicable to local circumstances. The province of Quebec had basically adopted the guidelines provided by the Transportation Association of Canada (TAC), which in turn came from those specified by the American Association of State and Highway design manual (AASHTO 2005) and the Illuminating Engineering Society of North America (IESNA 2006). Although existing grid system involves several factors, it is not clear if other elements should be present.

Additionally there seems to be a practice of provincial governments to better illuminate roads crossing through urban areas leaving rural sites dark. On the other hand, municipalities are not legally required to follow provincial standards. Some municipalities (mostly large cities) do follow provincial illumination standards; others take advantage of cheaper technology and/or existent utility poles which affects the amount of roadway lighting and are generally considered deficient or non-standard.

1.2 Problem Statement

There is a need to understand which characteristics of roadway lighting seem to better explain collisions; if non-standard levels of lighting are better than no lighting, as well as the effectiveness of lighting if it is truly an accident countermeasure.

1.3 Research Objective

1.3.1 Overall Goal

Estimate if the provision of roadway lighting increases or reduces road collision frequency.

1.3.2 Specific Objectives

- Establish a procedure for the collection and processing of roadway lighting;
- Assess the impact of roadway lighting-parameters on collision frequency.

1.4 Scope and Limitations

This research aims to characterize the relationship between levels of artificial roadway lighting and nighttime collisions. In particular, it examines statistical evidence related with the common argument that lighting is a countermeasure capable of reducing road accidents at nighttime even at those locations insufficiently illuminated (non-standard).

This research is limited to roadway segments with observed collisions involving at least one motorized vehicle; hence, collisions between non-motorized users are not captured (such as bikes). Spatially, the study is restricted to the region of Arthabasca, and the city of Victoriaville and its' surroundings in central Quebec, Canada. Also, Average Annual Daily Traffic (AADT) for one day is considered in the analysis due to the unavailability and inaccessibility of nighttime AADT.

Available collision data contemplated the timeframe between 2007 and 2011. Other information such as AADT was available from 2001 to 2011. It has been assumed that geometrical and operational characteristics as well as the illumination conditions of the sites haven't changed across the study period. This assumption was made mainly because of the unavailability of such information at the time that this research was conducted. This study does not look into accident severity. This study only considers illuminance to characterize roadway lighting, leaving luminance outside this analysis for future research work.

1.5 Research Significance

This research makes the following contributions:

1. It provides practitioners with guidelines for data collection and analysis of roadway illumination.
2. It explores the fundamental question of whether artificial lighting increases or reduces road collisions, even if the amount of lighting is below the one specified by current design standards.
3. The overall research presents a first step in the understanding of what characteristics of lighting better capture its ability to improve road safety. This will eventually be used to improve the grid system used in the provision of artificial lighting for the roads of the province of Quebec.

1.6 Organization of the Thesis

This thesis is presented in five chapters as follows. Chapter 1 defines the problem and presents the objectives of the research and structure of the thesis. Chapter 2 contains a review of concepts related to roadway illumination, road collisions, safety performance function, and statistical modelling with count data. Chapter 3 presents the methodology employed for the collection, processing and analysis of the data. Chapter 4 discusses the analysis and results obtained. Chapter 5 presents conclusions and recommendations, as well as suggestions for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter is divided into two major areas: road safety and roadway artificial illumination. The first section explains typical concepts related to road safety such as collision frequency, explanatory variables, nighttime collisions, safety performance function, regression models, and statistical analysis. The second part explains road lighting, measurements, provision of lighting under Quebec's warrant system (Grilles de l'éclairage), and the minimum required standard levels of lighting according to current practices.

2.2 Road Safety Terminology and Definitions

2.2.1 Consistency, Sight Distance and Driver's Workload

Consistency is a fundamental concept in road safety (TAC 2004 and TAC 1999). Conformity to road consistency is usually addressed by road safety engineers and designers by considering the cross section of the road, its operational speed, and the driver's work overload. Drivers tend to accumulate expectancies based on the information provided by the road environment (TAC 1999). Inconsistency in road features may contribute to an increase in road collisions (TAC 1999). Therefore, providing road users with a consistent road design, with all the clues required, will help him/her to take timely decisions effectively (i.e. provide the driver with enough perception-reaction time) and avoid the risk of collision. Any violation to road consistency may translate into negative road safety outcomes (i.e. collisions).

Visibility plays a major role in consistency. According to TAC (2004), visual clues constitute 90% of the information used by the drivers on the road. With this being said, a proper and consistent road design should provide drivers with enough information and signals to prevent confusing and risks of collision. In fact, a considerable number of crashes occur in complex sites where the driver is overwhelmed with signals that he or she cannot process in a short amount of time (TAC 2004). In such complex environments, the driver has to take multiple decisions as a result of the combination of an interactive environment where different road users, complex visual settings, and limited sight distances may be present, making the driver to not react on time.

2.2.2 Road Collisions

The majority of the existing research focuses on intersections and interchanges (Abdel-Aty, Keller and Brady 2005; Santiago-Chaparro, Qin and Noyce 2010; Lord and Persuad 2000; Lovegrove and Sayed 2006). It has been found that about 40% of all road crashes has happened at intersections due to conflicting movements from approaching traffic (Barua, Azad and Tay 2010).

Few researchers had looked into road segments (Jonsson, Ivan and Zhang 2007), which may be explained by the fact that there are actually more observed accidents at intersections. The number of accidents has always been related to traffic volume (Baek and Hummer 2008; El-Basyouny and Sayed 2006; Hadayeghi Malone and De Gannes 2006), with the presence of complex geometries (El-Basyouny and Sayed 2006), in particular combinations of horizontal and vertical curves (Eassa and You 2009; Hummer *et al.* 2010).

Other research has found that wet surfaces contribute to explain higher volume of road collisions (Bullas 2004; Gilfillan 2000; Karlaftis 2002). Also, urban sites in general have been much more investigated than rural ones (El-Basyouny and Sayed 2010).

Effort has been focused on improving safety at either urban sites or intersections (Feldman, Manzi and Mitman 2010) where some of these studies had looked into traffic calming measures as possible solutions (Zein *et al.*, 1997).

Typical studies focus on motorized vehicles particularly cars, although other research had focused on motorcycles (Haque and Chin 2010). Some researchers have looked into pedestrian and their role in road safety (Lyon and Persuad 2002) considering their presence and interactions with motorized users. This is especially true for nighttime road collisions in which current guidelines IEASNA (2005) and TAC (2006) establish decision criteria for illumination warrant and levels as those found on grids G3 and G5 of *Transport Quebec* (2012) on the basis of pedestrians' presence.

2.2.3 Nighttime Road Collisions

Previous research that have focused on nighttime accidents found that presence of street lighting reduced road collision frequency as well as the number of persons killed and seriously injured (Yannis, Kondyli and Mitzalis 2013). Illuminance levels seem to affect collisions with pedestrians. Research had found that higher frequency of pedestrian crashes was observed at sites with lower levels of lighting (Zhou and Hsu 2009).

Bruneau and Morin (2005) studied sites with partial and complete interchange-only lighting settings and continuous lighting on rural highways finding smaller crash ratios at continuously illuminated segments when compared to dark sites and to interchange-only illumination.

A certain range of illumination levels have also been demonstrated to result in less frequent road collisions (Oya *et al.* 2002) especially at major urban intersections for light levels at or above 30 lux, but not for lower light levels. Monsere and Fischer (2008) found a negative impact of decreasing lighting levels on freeway interchanges from either standard to substandard or to none.

2.3 Statistical Analysis in Road Safety

Using the appropriate regression model that best fits the outcome to its explanatory variables is an important step to obtain reliable statistical results. A correlation matrix is commonly used as a first step to identify any redundancy or co-linearity amongst explanatory variables in consideration.

Safety performance functions had been developed and tested in multiple occasions finding good results (El-Basyouny and Sayed 2006). Some had used traditional statistical techniques while others have explored full Bayesian analysis. However, having many sites with no-collisions (zero) remains the main issue (Saunier and Sayed 2008). Road collisions are known as negative road safety outcomes which have to be mitigated when possible. Mathematically speaking, road traffic collisions are nothing but random aggregated integers, which are characterized as count variables. An Ordinary least squares model cannot be used for count data as this type of outcome does not follow a normal distribution and has a zero inflated mean (Zhou and Hsu, 2009). Instead, regression count models such as Poisson or Negative-Binomial (NB) are commonly used in road safety (Isebrands *et al.*, 2010).

One of the most commonly used Safety Performance Function (SPF) is the one shown in Equation 1 (Miranda Moreno 2013). This SPF is typically used for count data, which is the case for road collision frequency. This equation can be used for both intersections and segments of equal length. Equation 1 shows the relationship between collision frequency (Acc) and causal factors $(L_i, AADT_i, x_{i1}, \cdots x_{ik})$. All explanatory variables are assumed to have a linear relationship for the exception of AADT, where an exponential relationship between crash frequency and AADT has been found (AASHTO 2005). The coefficients β_n capture the nature of the correlation and the magnitude of the impact each explanatory variable has on the outcome. An error term (ε) is included in the model to take into consideration the unobserved impact of possibly missing explanatory variables (Miranda Moreno 2013). Equation 2 is equivalent to Equation 1 but is used in statistical analyses for simplicity.

$$Acc = L_i AADT_i^{\beta_1} * \exp(\beta_0 + \beta_2 x_{i1} + \cdots + \beta_k x_{ik}) + \varepsilon \quad [1]$$

$$Acc = L_i * \exp(\beta_0 + \beta_1 lnAADT_i + \beta_2 x_{i1} + \cdots + \beta_k x_{ik}) + \varepsilon \quad [2]$$

2.3.1 Omitted Variable Bias

The prediction of an outcome is dependent on the explanatory variables considered in the regression analysis of a statistical model. In the case of a safety performance function, it is almost impossible to include all predictors influencing nighttime collisions as they might be unavailable. For instance, human factors such as fatigue, visibility, to name a few, might not be reported to the police and may be an important predictor for road collisions, but are omitted due to the unavailability of such information. Therefore, the impact of omitting unobserved variables, also known as confounding factors, may result in an inaccurate model and misestimation of the regression coefficients that are present in the model (Wooldridge 2009).

Omitting a variable belonging to the population would result in Omitted Variables Bias (OVB) resulting from unobserved heterogeneity within the sample (Wooldridge 2009). Such an issue would result in biased and inconsistent regression coefficients as shown in Equation 3 (Wooldridge 2009). The impact of unobserved variables is integrated in the standard error term previously in Equation 1 as well as the regression coefficient for the observed variables (Equation 3).

$$\tilde{\beta}_j = \hat{\beta}_j + \hat{\beta}_k \tilde{\delta}_j \qquad [3]$$

In simple words, Equation 3 shows that the regression coefficient for any coefficient $\tilde{\beta}_j$ related to the population is not equal to the one found from the sample $\hat{\beta}_j$, but rather includes the impact of missing variables $\hat{\beta}_k$ and the correlation between the observed and unobserved variables (i.e. x_i & x_k, represented by $\tilde{\delta}_j$) (Wooldridge 2009). To provide the reader with a better understanding, let's consider the following example. Let's assume that the "real" SPF related to the population would have the following form:

$$Acc = L_i AADT_i^{\beta_1} * \exp(\beta_0 + \beta_2 x_{i1} + \beta_3 x_{i2}) + \varepsilon \qquad [4]$$

Now, let's assume that the SPF estimated from the sample has an omitted variable x_{i2} representing a confounding variable that was not captured in the sample. Then the SPF model would be represented as follow:

$$Acc = L_i AADT_i^{\beta_1} * \exp(\beta_0 + \beta_2 x_{i1}) + \varepsilon \qquad [5]$$

In this case, the actual regression coefficient $\tilde{\beta}_1$ is represented by Equation 6 which includes the regression coefficient found from the regression analysis of the sample ($\hat{\beta}_1$), the impact of the unobserved variable $\hat{\beta}_2$, as well as the sample covariance between x_1 and x_2 represented by $\tilde{\delta}_1$ (Wooldridge 2009). In simpler words, this means that the regression coefficient $\tilde{\beta}_1$ is bias towards the omitted variable $\hat{\beta}_2$.

$$\tilde{\beta}_1 = \hat{\beta}_1 + \hat{\beta}_2 \tilde{\delta}_1 \qquad [6]$$

Generally speaking, it is clear from Equation 3 that the regression coefficient will be unbiased under two conditions (Wooldridge 2009). The first case is when $\hat{\beta}_k$ has no impact on the outcome (i.e. $\hat{\beta}_k = 0$) making the unobserved variable to not be an important predictor that has to be included in the SPF (Wooldridge 2009). The second case is when there is no co-linearity between the observed (x_1) and unobserved variables (x_k) (i.e. $\tilde{\delta}_1 = 0$), where $\tilde{\delta}_1$is a function of the residual as shown in Equation 7 (Wooldridge 2009). The sign of the bias (i.e. a decrease or an increase) is related to the correlation between the observed and unobserved predictors as well as to the impact of the confounding factors (i.e. if $\hat{\beta}_k < 0$ or $\hat{\beta}_k > 0$) (Wooldridge 2009). The magnitude of the bias might also be problematic if large because it might result in an inaccurate prediction model (Wooldridge 2009). The magnitude of the bias is also dependent on $\hat{\beta}_k$ and $\tilde{\delta}_1$.

$$\tilde{\beta}_1 = \hat{\beta}_1 + \frac{\hat{\beta}_k (\sum_{i=1}^{n} \tilde{r}_{i1} x_{ik})}{\sum_{i=1}^{n} \tilde{r}^2{}_{i1}} \qquad [7]$$

2.3.2 Poisson and Negative Binomial Regression Models

The two most commonly used statistical models for SPF are Poisson and Negative-Binomial. The Poisson distribution is used when the count data is not characterized with over-dispersion (i.e. homogeneity). In other words, the mean of the outcome (μ) should be equal to its expected value (E(Y)) and to its variance (Var(Y)) as shown in Equation 8 (i.e. homogeneity of observations). Such an assumption may not be true mainly because of unobserved heterogeneity, randomness, and a high number of zero counts in the outcome (Miranda Moreno 2013). Unobserved heterogeneity may result from important missing sites characteristics (Miranda Moreno 2013). In such cases, the variance of the outcome would be expected to be greater than the mean, resulting in over-dispersion of the data, which is translated into standard error term shown in Equation 1. The over-dispersion issue encountered in count data can be solved using the Negative-Binomial distribution which assumes heterogeneity amongst observations (Equation 9).

$$\mathrm{Var}(y) = \mathrm{E}(y) = \mu \qquad [8]$$

$$\mathrm{E}(y) = \mu; \quad \mathrm{Var}(y) = \mu + \alpha\mu^2 \qquad [9]$$

where,

y : Response Variable (Collision Frequency);

μ : Mean of Response Variable;

E(y) : Expected Value of Response Variable;

Var(y) : Variance of Response Variable;

α : Over-dispersion Parameter.

2.3.3 Zero-Inflated Poisson (ZIP) Regression

Crash data is usually characterized to have a very high number of zeros that cannot be generated by the conventional Poisson or NB models (Miranda Moreno 2013). If such a situation is encountered, zero-inflated models can be used. Zero-inflated distributions covered in this chapter are the Zero-Inflated Poisson (ZIP) and the Zero-Inflated Negative-Binomial (ZINB).

These regression models assume that zero counts result from two different processes (Miranda Moreno 2013). Presence of over-dispersion in the data determines the type of zer-inflated regression to b used for a best-fit of the data. In other words, if the observations vary a lot from the mean, then one should use the ZINB to prevent any overestimation of the standard error (ε). The general framework, Equations (10, 11, 12 & 13) for the ZIP model has been explained elsewhere (Miranda-Moreno 2013) and is presented below:

$Y_i = 0$, with probability ε_i, [10]

$Y_i \mid \mu_i \sim Poisson(\mu_i)$, with probability $(1- \varepsilon_i)$ [11]

Equations [10] and [11] follow the following distributions respectively

$f(y_i \mid \mu_i, \varepsilon_i) = \varepsilon_i + (1- \varepsilon_i)\ Poisson(\mu_i)$ for $y_i = 0$, and [12]

$f(y_i \mid \mu_i, \varepsilon_i) = (1- \varepsilon_i)\ Poisson(\mu_i)$ for $y_i = 1, 2, \ldots$ [13]

$\mu_i = f(AADT, X_i; \beta)$ [14]

where μ_i is a function of a vector of site attributes, such as shown in Equations (1 & 14), and ε_i is the error parameter previously discussed. However, in the ZIP framework, the error term also includes a proportion of the zeros that cannot be processed by the conventional Poisson distribution. The error related to unobserved site attributes can be defined by using a logistic link function as follow:

$\varepsilon_i = \frac{e^{\omega z_i}}{1+e^{\omega z_i}},;$ [15]

where,
ω: parameter vector;
z : unobserved site characteristics vector.

“In this model, the vector of covariates z_i determines the probability of being in the zero count state and may be a function of specific-site attributes or other covariates that may be part of the vector x_i” (Miranda-Moreno 2013).

One of the ZIP’s drawbacks is that it cannot handle over-dispersion resulting from unobserved heterogeneity in the data. The ZINB takes into account such deficit in the ZIP model by assuming that the mean number of accidents is also random (Miranda Moreno 2013). To determine the type of zero-inflated regression model to be used, the variance and the expected value of the observations have to be compared.

2.3.4 Zero-Inflated Negative Binomial (ZINB) Regression

In the presence of an overall dispersed data with excessive zero count, the ZINB can be used instead of the ZIP (Mei-Ling *et al.*, 2004). As previously mentioned, zero-inflated regressions assume that zero outcomes are due to two different processes. In other words, high number of zero collisions observed in a crash data sample can be the result of two reasons. The first reason can be due to unreported collisions along the road segment in study mainly because of its observed and unobserved characteristics (i.e. good design and consistency). The second reason explaining zero crash frequency is not reporting the occurrence of collisions to the police which is expressed in Equation 15. The Negative-Binomial regression, which is a count model, is used to generate the zeros; whereas, the logit model, a binary model, is the second distribution used to associate the zero outcome to one of the two processes discussed earlier (Miranda Moreno 2013).The expected count is expressed as a combination of the two processes (Miranda Moreno 2013). Having two processes generating zero counts contribute partially to the over-dispersion related to ZINB regression in addition to what was mentioned earlier (Mullahy, 1986; Greene, 2003). The ZINB model has the following probability distribution (Equation 16, 17):

$$f(y_i \mid \mu_i, \varepsilon_i, \alpha) = \varepsilon_i + (1- \varepsilon_i)\, Poisson(\mu_i, \alpha) \text{ for } y_i = 0, \text{ and} \quad [16]$$

$$f(y_i \mid \mu_i, \varepsilon_i, \alpha) = (1- \varepsilon_i)\, NegBin(\mu_i, \alpha) \text{ for } y_i = 1, 2, \ldots \quad [17]$$

"As in ZIP model, ε_i represents the probability of being in the zero-state and is also modeled as a function of a vector of covariates z_i" as it was shown in the previous section (Miranda Moreno 2013).

2.3.5 Effect Size of Variables

Understanding the impact of each regression coefficient on the outcome is crucial. These parameters are obtained from statistical regression analysis, such as the ones discussed in the previous two sections. The coefficient of each explanatory variable impacts the outcome differently. Each coefficient provides an idea on the relationship that exists between the corresponding predictor and the outcome, while holding all other variables constant, but cannot be interpreted directly in exponential models. The effect size is a statistical measure that can be calculated to provide a proper understanding of the existing relationship between the explanatory variables and the response. It expresses the percentage increase ($\beta_k > 0$) or decrease ($\beta_k < 0$) in the outcome as a result of a 1% increase in the explanatory variable (for continuous variables) or a one unit increase (for discrete/binary variables), while all other variables are held constant. Formulas typically used to compute the effect size of each predictor, are shown in Equations 18 & 19 (Miranda Moreno 2013).

$$E_{x_{ik}}^{\mu_i} = \frac{d\mu_i}{dx_{ik}} \frac{x_{ik}}{\mu_i} = \beta_k x_{ik} \quad [18]$$

$$E_{x_{ik}}^{\mu_i} = \left(\frac{\beta_k - 1}{\beta_k}\right) \quad [19]$$

where,

$E_{x_{ik}}^{\mu_i}$: Effect Size of the Response as a Function of Predictor x_{ik};

μ_i : Safety Regression Function;

x_{ik} : Predictor x_k at Site i;

$\frac{d\mu_i}{dx_{ik}}$: Partial Derivative of μ_i with Respect to x_{ik};

β_k : Regression Coefficient Associated to Predictor x_k.

Equation 18 is used for continuous variables that do not contain zero (i.e. positive real numbers). Examples of continuous numbers are AADT and lane width respectively. On the other hand, Equation 19 is for indicator and discrete variables such as binary or dummy variables and number of lanes respectively (usually variables that contain zero value).

2.4 Roadway Illumination

Provision of artificial street lighting is used as a nighttime collision mitigation countermeasure. Increasing pedestrians' safety is another important role of roadway illumination (DMD & Associates Ltd., 2009). In fact, it was found from a before-after study that nearly significant reduction in crime rates for control areas in the US and significant crime reduction rates in the UK were observed as a result of street light provision (Rea *et al.,* 2009). The following sections cover the basic concepts of artificial roadway lighting, its use as a countermeasure to collision and warrant and design standards currently used in Canada.

2.4.1 Measures of Artificial Lighting

Photometry is a science that measures how light is transmitted to the human eyes, in terms of its apparent brightness (IESNA 2005). Photometric metrics, such as luminance and illuminance, to name a few, serve as "reasonable good reflecting variables to characterize visual response" such as reaction times (Lennie, Pokorny and Smith 1993).

Current road lighting standards consider all of luminance, illuminance, overall uniformity, uniformity of luminance and/or illuminance along the axis of the road, and glare (CIE 2007). Illuminance is defined as the amount of light transmitted from a source and arriving at the surface of the pavement and is expressed in Lux (CIE 2007). Luminance is the amount of light reflected by the pavement surface towards the driver's eyes, representing the quantity of light that is perceived by drivers (CIE 2007). Luminance depends on the pavement type as well as on the environmental circumstances and is measured in candela/m^2 [cd/m^2] (CIE 2007). Overall uniformity is the uniformity of lighting calculated as the ratio of minimum to average across and along the road (CIE 2007). Overall uniformity can be calculated for both luminance and illuminance (CIE 2007). On the other hand, uniformity of luminance/illuminance along the axis of the road (i.e. driver's eye sight axis) is calculated as the ratio of minimum to maximum (CIE 2007). Glare is another lighting measure that needs to be considered upon provision of street lighting. Glare results from the interaction between the light produced by the luminaire, by the luminance of the pavement, and by the luminance of surrounding objects (IESNA 2005). There are two types of glare: disability and discomfort glares (IESNA 2005). This aforementioned parameter will not be discussed further as it is not part of the scope of study for this research.

Illuminance can be used as a lighting criterion for roads that are not highly motorized and are used by pedestrians and cyclists; whereas, luminance is used for moderately to highly motorized roads (Rea *et al*. 2009). None of the uniformities, i.e. longitudinal uniformity and overall uniformity, included in current standards has been identified to be significant predictors of collision rates reductions (OPUS 2012).

2.4.2 The Role of Lighting on Nighttime Collisions

Increasing visibility is the main purpose in the provision of artificial roadway lighting (Bulldough, Rea and Zhou 2009). Street lighting can be used to either provide road users with just enough visibility, in some cases, while in other instances, to increase safety by providing higher levels of illumination (TAC 2004). CIE (1992) conducted a report in which the impact of street lighting on road collisions has been investigated by looking into studies that took place prior to 1992. It was found that nighttime collisions are more severe than the ones occurring during the daytime and artificial roadway lighting helped in reducing their occurrence (CIE 1992). Similar results were obtained by TAC (2004) but for intersections. In fact, reductions between ten to forty percent of all types of street collisions, and up to 65% of fatal collisions, have been observed at road segments in which artificial lighting has been installed as a safety countermeasure (TAC 2004). A similar figure (37%) in total collision rate reduction has been also found by Isebrands *et al.* (2010). Other studies investigated animal-road collisions which were inconclusive regarding the effectiveness of presence of artificial lighting; however, decrease in operational speed was found to reduce accident frequency (Sullivan, 2009).

Studies investigating the relationship between different levels of artificial roadway lighting and pedestrians' safety have been conducted by some researchers. Low levels of roadway lighting has been associated with higher frequency of pedestrian accidents as opposed to sites with higher levels of illumination, as reported by Zhou and Hsu (2009) and Isebrands *et al.* (2010). According to Yannis, Kondyli and Mitzalis (2013), presence of street lighting decreases the number of collisions in urban and rural roadways, particularly higher severity characterized collisions (i.e. fatal and severe injuries).

The impact of standard and non-standard levels of lighting associated to collision frequency has been investigated by Bruneau and Morin (2005). Both illumination levels have been found to reduce the number of nighttime collisions. However, standard and nonstandard levels were not based on the actual illumination values provided by existing bodies of standard, but rather on the luminaire's physical characteristics. In other words, Bruneau and Morin (2005) identified non-standard lights as luminaires attached to utility poles; whereas, standard lights being attached to lighting poles. Rea *et al.* criticized Bruneau and Morin (2005) lighting level characterizing system mainly because of not considering essential standard criteria such as levels of illuminance, spacing between light poles and the height of the lighting system.

Improving visual performance by using street lighting properly might have a positive impact on road safety (i.e. reduce the number of observed collisions), making glare an important lighting parameter that cannot be neglected (Bullough, Donnell and Rea, 2012). In fact, presence of glare affects drivers' visions which may contribute to negative safety consequences. Current standards define two types of glare: disability glare and discomfort glare (IESNA 2005). Disability glare is also known as veiling luminance, which has been found to alter the perceived brightness of objects found within the driver's visual field as well as that of the backgrounds (IESNA 2005). Such change in brightness, perceived by the driver, may hinder the driver's visibility (IESNA 2005). Nighttime visibility is also dependant on the driver's age. Areas with a considerable amount of elderly drivers (Rea, Bullough and Zhou 2009) may require some modification to the provided amount of illumination and control for glare (IESNA 2005).

Box (1970) investigated the relative effectiveness of different illumination levels. At illuminance ranging between three to six lux, the observed night-to-day ratio was statistically different from higher illuminance values (between 8 to 11 lux and 13 to 15 lux) and lower than those observed for unlit freeways. Road segments with the highest illumination levels had the highest crash ratios amongst all different lighting level scenarios. These findings go against one's expectation, where higher levels of lights are associated to higher collision frequency. Box (1970) suspects that glare might be a contributing factor to the observed high number of collisions at sites with higher illumination levels. Several explanations can be found in the literature as to why such a relation exists between higher levels of illumination and collision frequency. CIE (1992) suggests that higher levels of illumination can be achieved by decreasing the distance between light poles. Doing so will result in 1) a higher number of light poles increasing the risk of vehicle collision with fixed objects, and 2) a reduction in the uniformity ratio. A reduction in the uniformity ratio physically translates into uniform lighting which makes it difficult to the driver to perceive certain objects against the background.

Griffith (1994) conducted a cross-sectional study where the effect of continuous lighting and interchange-only lighting on urban freeways was investigated. Results were such that freeway segments with continuous lighting significantly reduced the number of observed nighttime collisions by 16% (i.e. between interchanges) as opposed to inconclusive results for interchange-only lighting.

There are two types of existing lighting systems which are referred to as extended and localised (Rea, Bullough and Zhou, 2009). Extended lighting refers to continuous lighting; whereas, localized lighting refers to the presence of one lighting unit, commonly found at rural intersections. Possible negative effects related to the lack of transitioning from dark to standard have not yet been vigorously studied.

2.4.3 Roadway Lighting Warrant System and Provision Design Guidelines

Artificial roadway lighting guidelines are divided into two categories: 1) a score-based warrant system considering a multitude of criteria (Table 1) and 2) a design criteria establishing minimum recommended illumination levels as well as maximum permissible variation measured through uniformity ratios (Table 2). Road lighting can be classified into one of the three groups: standard, nonstandard, and non-illuminated areas which are classified as dark. Road segments classified as non-standard are those that do not meet minimum levels as defined by local applicable guidelines, in the case of Canada those established by TAC (2006).

Different countries have different road lighting standards. For instance, Canada follows the street illumination guidelines designed by the Transportation Association of Canada (TAC 2006);

whereas some of the American states follow the American Association of State Highway and Transportation Officials (AASHTO 2005). With this being said, some municipalities have taken a step forward and have either customized these national standards according to their needs or have simply came up with their own guidelines regarding this matter. Others just provide lighting on the basis of opportunity from existing utility poles.

Table 1 Sample Grid, Assessment System for Quebec (Transport Quebec, 2012)

Grille d'évaluation « G1 » (voir note 2)									
Élément évalué:									
Longueur du tronçon:				Niveau (1, 2 ou 3):					
Description des critères analysés		Valeurs réelles	Pointage de classement «PT»					Pondération «PD»	Valeur pondérée «PD x PT»
			1	2	3	4	5		
Groupe 1 : Géométrie (voir note 4)									
1	Nombre total de voies		≤ 4	5	6	7	≥ 8	0.15	
2	Largeur des voies (m)		>3,6	3,4 à 3,6	3,2 à 3,4	3,0 à 3,2	<3,0	0.30	
3	Largeur du terre-plein central (m)		>12	7,5 à 12	3,5 à 7,5	1,2 à 3,5	<1,2	0.30	
4	Largeur de l'accotement (m)		>3,0	2,5 à 3,0	1,8 à 2,5	1,2 à 1,8	<1,2	0.30	
5	Pente du talus de bas-côté (0 à 7)		> 6:1	6:1	4:1	3:1	< 3:1	0.30	
6	Rayon de courbure horizontal (m)		>3500	1750 à 3500	1750 à 875	575 à 875	<575	4.90	
7	Gradient vertical (pente en %)		<3,0	3,0 à 4,0	4,0 à 5,0	5,0 à 7,0	>7,0	0.25	
8	Distance (fréquence) entre les échangeurs (km)		>6,5	5,0 à 6,5	3,5 à 5,0	1,5 à 3,5	<1,5	1.85	
								Sous-total géométrie:	0
Groupe 2 : Opération									
9	Niveau de service nocturne (heure de pointe de noirceur)		A	B	C	D	≥ E	3.05	
									0
Groupe 3: Environnement									
10	% de développement		0	0 à 24	25 à 50	50 à 75	>75	1.85	
11	Distance des développements à partir de la route (m) (voir note 3)		>60	45 à 60	30 à 45	15 à 30	<15	1.85	
									0
Groupe 4 : Sécurité (accidents)									
12	Rapport des accidents Nuit/jour		<1,0	1,0 à 1,2	1,2 à 1,5	1,5 à 2,0	>2,0 (voir note 1)	4.90	
									0
Notes: 1- Éclairage justifié 2- Vitesse courante: 80 km/h (la vitesse de nuit au 95e centile si on la connaît, sinon, la vitesse affichée) 3- Développement défini comme englobant les bâtiments commerciaux, industriels ou résidentiels. 4- Utiliser les facteurs géométriques les plus défavorables pour le tronçon de route.								Grand total: Pointage requis pour éclairer Écart	0 60

Even though many important elements are considered in the criteria-based grid system, it fails to take into consideration existing levels of lighting (i.e. having road segments with non-standard illumination) as a criterion for the provision of standard illumination. In such cases an increase in lighting level may turn to be the solution to reduce nighttime collisions.

Table 2 Illuminance Criteria Recommended by Type of Road (after IESNA 2005)

Road and Pedestrian Conflict Area		Pavement Classification (Minimum Maintained Average Values)			Uniformity Ratio E_{avg}/E_{min}
Road	**Pedestrian Conflict Area**	**R1 lux/fc**	**R2 & R3 lux/fc**	**R4 lux/fc**	
Freeway Class A		6.0/0.6	9.0/0.9	8.0/0.8	3.0
Freeway Class B		4.0/0.4	6.0/0.6	5.0/0.5	3.0
Expressway	High	10.0/1.0	14.0/1.4	13.0/1.3	3.0
	Medium	8.0/0.8	12.0/1.2	10.0/1.0	3.0
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0
Major	High	12.0/1.2	17.0/1.7	15.0/1.5	3.0
	Medium	9.0/0.9	13.0/1.3	11.0/1.1	3.0
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0
Collector	High	8.0/0.8	12.0/1.2	10.0/1.0	4.0
	Medium	6.0/0.6	9.0/0.9	8.0/0.8	4.0
	Low	4.0/0.4	6.0/0.6	5.0/0.5	4.0
Local	High	6.0/0.6	9.0/0.9	8.0/0.8	6.0
	Medium	5.0/0.5	7.0/0.7	6.0/0.6	6.0
	Low	3.0/0.3	4.0/0.4	4.0/0.4	6.0

The Transportation Association of Canada (TAC) and the province of Quebec (MTQ) follow the guidelines established by IESNA (2005). There are other existing roadway lighting provision guidelines, such as the one proposed by the National Cooperative Highway Research Program (NCHRP Report 152), which uses an analytical cost benefit approach (Preston and Schoenecker, 1999).

2.5 Literature Review Findings

The literature review done for this research shows that the majority of studies have looked at the impact of roadway lighting on nighttime collisions at intersection settings, mostly at urban sites with only a few considering roadway segments at rural locations. Some before-after studies (Hauer 2008) have measured the impact of artificial lighting on nighttime collisions was measured by observing the change in collision rates and its trends for a period of years before and after the implementation of lighting. It should be noted that, sites considered in all previous studies were originally non-illuminated with only one study that have looked at downgrading illuminated sites (Monsere and Fischer 2008). No study was found for partially illuminated sites laying under standard levels being upgraded to standard illumination.

One cross-sectional study was found (Griffith 1994) comparing urban freeway illuminated segments and interchanges with those non-illuminated during the same period of time. In addition, the only study that has looked into the impact of standard and non-standard illumination in the province of Quebec, conducted by Bruneau & Morin in 2005, suffers from a major dropback. This study classifies intersections (not road segments) based on whether the lighting pole belonged to the Ministry of Transportation of Quebec (deemed standard) or to an utility company (deemed non-standard) rather than considering photometric parameters of lighting. This poses a problem, because it makes the assumption that municipal lighting will never achieve the minimum levels of illumination and uniformity required to be classified as standard, and makes the strong assumption that all roads lit by MTQ fall under the standard category. This may be false as there may be roads to which lighting maintenance is not provided, alignment has changed, lamp power has decreased and etcetera.

Based on these findings it is clear that there is a need to better understand how non-standard illumination relates to nighttime collisions, especially for road segments at rural locations as compared to urban sites. No literature was found conducting statistical analysis to test the appropriateness of lighting levels tied to statistical evidence of collision reduction. Current levels of illuminance, as provided by IESNA (2005), are generic and they may not result in a reduction of collisions. It should be noticed that IESNA recommends minimums and that it is up to each road agency to decide the levels that respond to their needs. Selection of such levels should be based on an objective method. Per instance, a statistical analysis based on locally observed circumstances can be used to identify recommended average (not minimum) levels of illuminance that actually result in a reduction of road collisions.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter presents the methodology used for data acquisition and for database preparation as well as to evaluate the correlation between roadway lighting and road collisions. The chapter is divided into three sections; the first section (3.2) explains the method used to measure road lighting. The second section (3.3) presents the method used to prepare the database used in the analysis; and the final section (3.4) explains the statistical approach followed to analyze the data.

3.2 Measuring Roadway Lighting

According to IESNA (2005) there are two major lighting metrics required to properly lit a road during nighttime. The first light quantity is illuminance which is "the amount of light incident on the roadway surface from the roadway lighting system". The second light quantity is luminance which captures the amount of light as perceived by the driver. It is the amount of light reflected by the pavement in the direction of the driver and is usually referred to as the "brightness" of the road (IESNA 2005). Illuminance units are read in Lux and luminance are candela per square meter.

This study collected measurements of illuminance; this goes in line with previous studies (Rea et al. 2009) that recommend the use of illuminance-based analysis for those roads with low levels of AADT and presence of pedestrians and bikers. As seen on Table 3, historical AADT for various land uses and illumination condition for the study zone ranges from about 1,500 to about 2,300, which can be classified as low volumes of traffic, especially when compared to traffic at other nearby highways such as Hwy-20 with levels fluctuating at about 30,000 vehicles per day nearby the exit ramp to Victoriaville. Luminance was left for a future research in which roads with higher volumes of traffic are included.

Table 3 Daily Average Traffic (AADT) per Land Use and Illumination Condition

Criteria		AADT	Correlation
Land Use	Rural	1,553	0.68
Illumination	Non-illuminated (Dark)	1,691	
Land Use	Urban & Suburban	2,394	0.68
Illumination	Illuminated (Std. & Non Std.)	2,317	

Key: Std = Standard, Non Std. = Non-standard

The selected device consisted of a *SpectroSense 2+* GPS (Figure 1). This equipment was selected because of its ability to record and store illuminance readings in Lux, with an integrated GPS that provides spatial location. Two single channel light sensors (Model SKL 310/SS2) have been used for data collection from which similar results were obtained. The two sensors were roughly centered on top of a passenger car, above the driver's seat (Figure 2). The light sensors are placed in a way to capture the incident light from the light source (i.e. illuminance). Also, the GPS equipped with a magnet has been placed on the roof of the car (Figure 2). The sensors are connected to the logger which is operated from inside of the vehicle. The default light units recorded by the logger are in kilo-Lux; therefore, each observation needs to be multiplied by 1,000 in order to obtain the base unit of Lux. The data collection's time and date are registered on the logger for each recorded point. The logger has a capacity of storing data for approximately 45 minutes at a rate of 1 observation per second. In order to compensate for any loss in signal of the equipment's GPS, an android assisted-GPS application with the name of *My Tracks* has been used in parallel on a cellular phone. The recorded variables of interest obtained from *MyTracks* are discussed in a later section. The recording time interval is different for the two devices; the *MyTracks*' GPS records data based on signal availability, whereas the *Spectrosense*'s GPS is set to collect data at every one second. Both devices are turned on at the same time while the vehicle is stationary to ensure the ability to tie both datasets together if required. The vehicle was driven at no more than 70 kilometers per hour as an attempt to have observations at about 20 meters at most from each other. After each data collection trip, the data is transferred from the logger to a computer.

Figure 1 SpectroSense2+ Logger and light sensor

Figure 2 Setup of Spectrosense Sensors and GPS

3.3 Database Preparation Procedure

3.3.1 Dataset Cleaning

The collected data from both *SpectroSense2+* and *MyTracks* is saved in a Comma-Separated Values format (.CSV) which can be easily opened using Excel Microsoft Office. Both datasets have to be cleaned and trimmed before any farther use or manipulation. In the *SpectroSense2+* spreadsheet, proper labels such as “Longitude, Time, etc.” have to be included on top of its corresponding column. Moreover, head titles and the dataset found in the excel spreadsheets can only include numbers and alphabetical letters, and exclude formulas, to avoid improper interpretation by the software *ArcMap10*, a product of *ArcGIS*, used later on. Each data point has been assigned an ID which is essential when importing the data into *ArcMap10* as it will be explained in section 0. The next step is solely performed when there is missing coordinates in the lighting measurements done by the *Spectrosense*. It requires combining a portion of the *MyTracks* dataset into that of the *Spectrosense* (i.e. lighting database) to create one single file. This step is done to avoid losing lighting data observations for which spatial location is missing. The files for both datasets are then saved in an (.XLS) file format in order to be able to import into *ArcMap10*.

3.3.2 Importing/Displaying Datasets into ArcGIS

Lighting measurements with latitude and longitude coordinates were imported into *ArcMap10*. The North American Datum geographic coordinate system (NAD1983.prj) was selected as a global coordinate system. Each displayed file is then converted into a shape file to be able to manipulate the original database when using geo-processing tools. Visual inspection was done to identify the segments with the missing data. A more detailed description of the incorporation of the missing data is discussed in the following section.

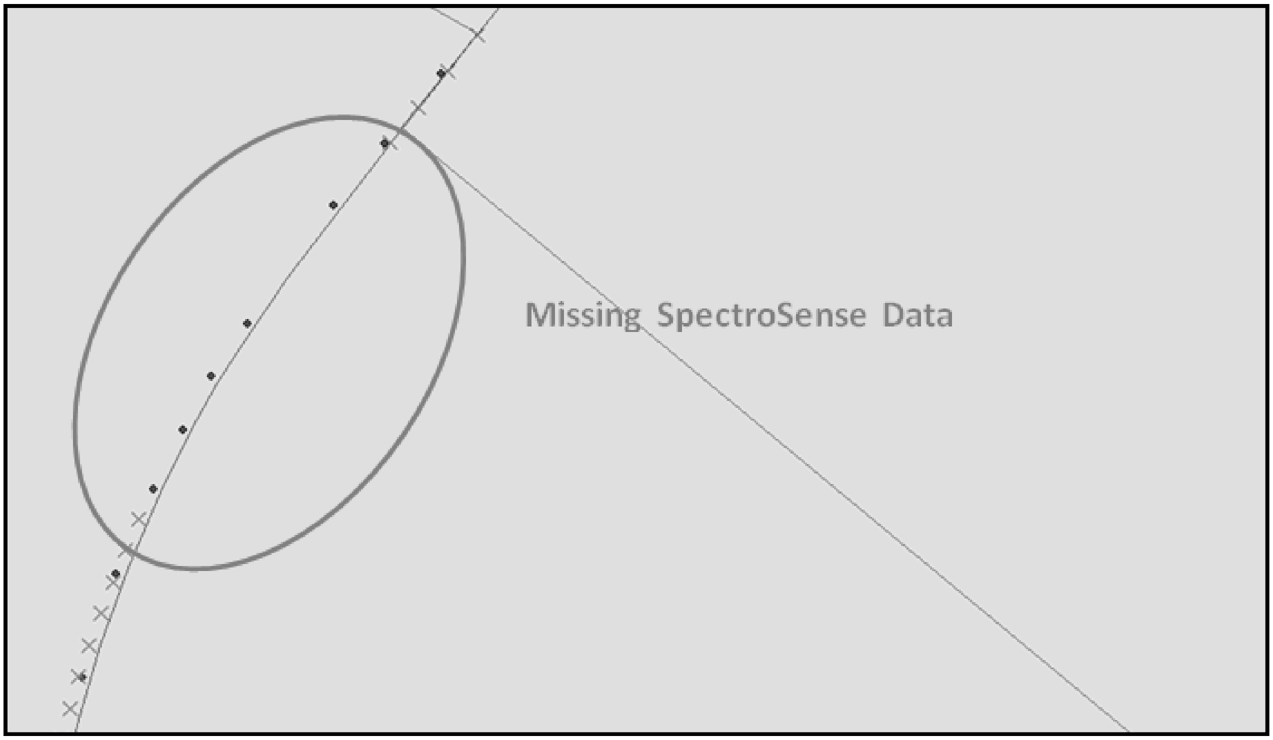


Figure 3 Missing Lighting Observation

3.3.3 Integrating Missing Coordinates into the Lighting Dataset

The location of the missing data is identified spatially by using *ArcMap10* (Figure 3). An ID field is created in the original datasets to identify the starting and ending points of the portion with the missing observations. Cumulative time increment is the only common parameter between the two datasets given that the recording time intervals as well as the geographic coordinates are not the same. Two extra columns, “time increment” and “cumulative time increment”, are calculated and added to each dataset. Based on the calculated cumulative time increment found in each dataset, a vertical lookup function is used in excel. This function assigns the missing coordinates from the *MyTracks* file to the *Spectrosense* file for points with the same cumulative increment time. Unfortunately, not all missing coordinates were retrieved in such a direct way. Some recorded lighting data did not have a common cumulative time increment amongst both datasets. In this case, an average of the geographic coordinates recorded before and after that specific time increment is calculated and assigned to the lighting point in question. This will not give us the exact precise geographic location of the recorded lighting data but is a very good proxy. All of the individual lighting datasets were combined into one single file. The final database included lighting and spatial attributes related to the road segments under study in Victoriaville. The lighting data has to be processed in order to remove any outliers to obtain a reliable raw data.

3.3.3 Processing of Lighting Data

Lighting data of the road segments under study was combined and stored into a single shapefile. All observations that fall outside of the study zone were trimmed as shown in **Error! Not a valid bookmark self-reference.**. Concentrated lighting data from a temporarily stopped vehicle were also removed to prevent biasing the mean value of lighting of the corresponding segment (Figure 5).

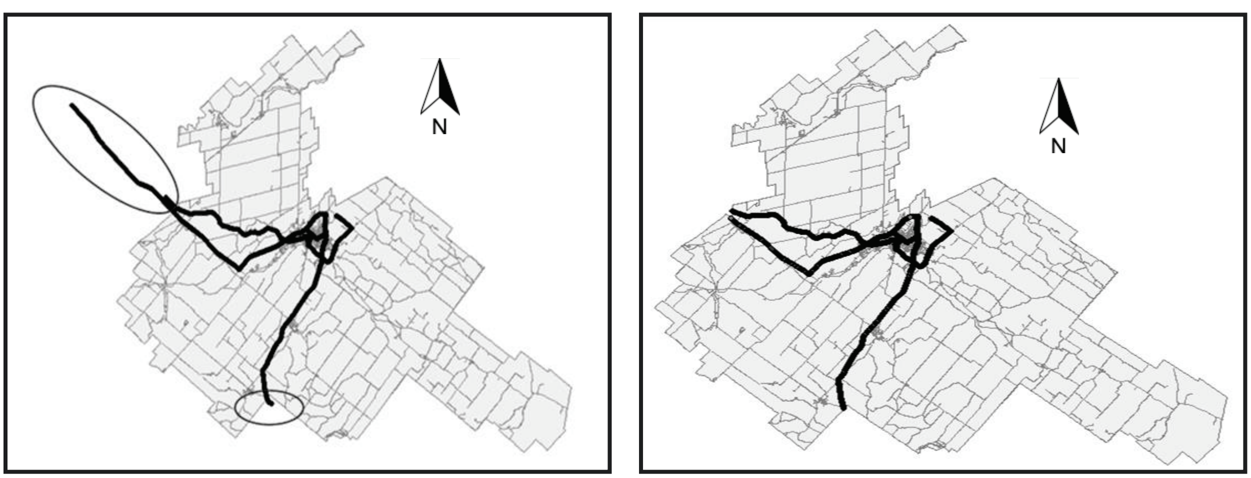


Figure 4 Lighting Observations Before and After Trimming

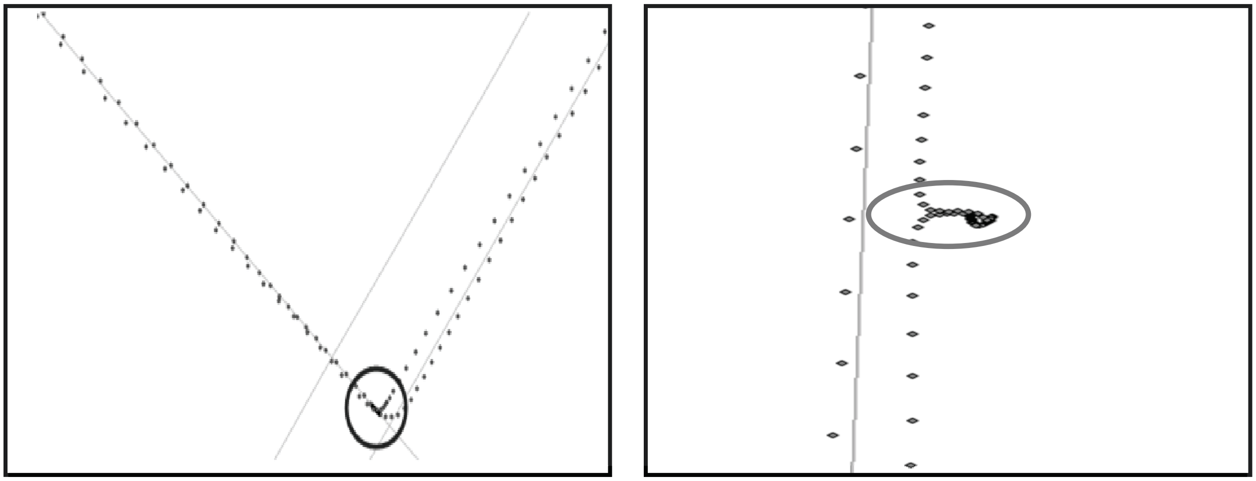


Figure 5 Left: Overconcentration of values. Right: Spatial outliers

The sensor's calibration was set to read roadway lighting which produced some problems with those values falling outside the expected measurement interval. Roadway lighting outliers (illuminance above 100 lux), were removed. The sensors also recorded negative values of illuminance at dark sites because of the aforementioned calibration issues. Given that no such negative illuminance exists, all recorded negative values have been assigned a value of 0 if both sensors have recorded negative values. An exception to this rule is applied when each sensor recorded values with different signs.

Minimum illuminance was set to 1 lux in order to limit outliers; such a value came from the illuminance of twilight. The average value of illuminance was calculated if both readings were beyond 1 lux, otherwise if one reading was beyond 1 lux but the other is negative, then the average illuminance is calculated by bringing the negative reading to zero and taking the average of the positive value. This averaging comes from the fact that the sensors on the roof of the car may have not been perfectly levelled and therefore one sensor may have been partially reading lighting from other sources apart from purely the one emitted by street lamps. As for positive outliers, it is assumed that any measurements higher than or equal to 100lux for at least one of the sensors, is a result of lighting pollution from possibly nearby commercial lighting (Guth, 2013), and hence was trimmed. The next step is to isolate the road network under consideration which is explained in the next section.

3.3.4 Isolating Road Network Under Study

The road segments of this study were isolated from the entire network (Figure 6). *ArcMap10* was used to display and execute the aforementioned modifications for both the lighting data and the road network.

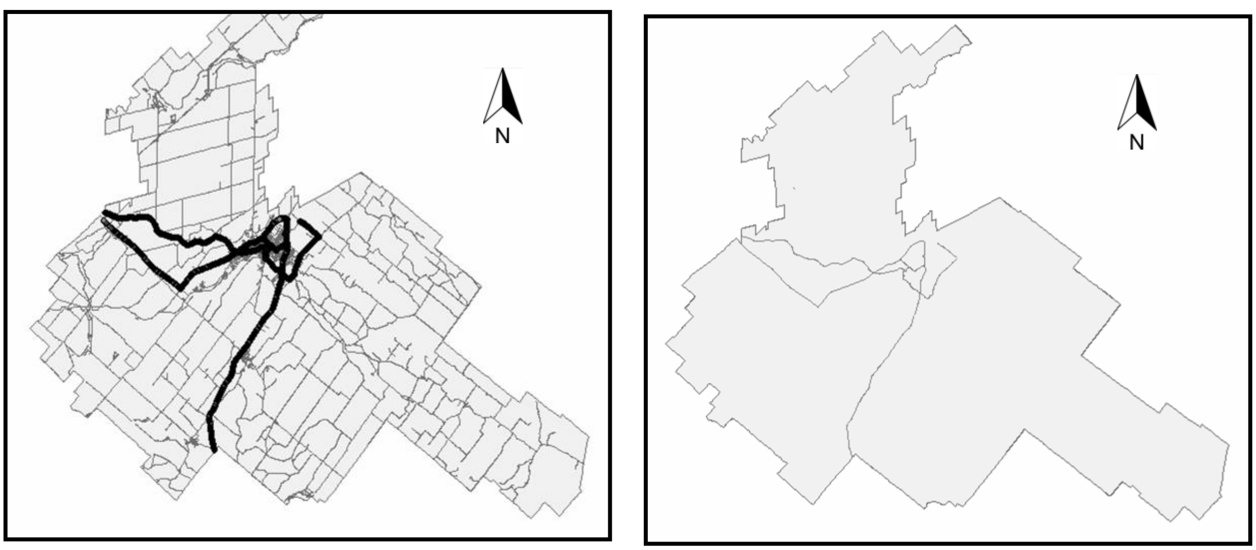


Figure 6 Final Road Network Before and After Trimming

In order to keep the road network dataset as clean as possible, only variables (i.e. fields) of interest were kept in the table of attributes (i.e. when opened on *ArcMap10*). This is an essential step specially that the number of columns increases when the files are combined together. The segments provided by the dataset are of unequal length.

So far the segments of the road network are split between two consecutive intersections resulting in unequal length. For simplicity purposes, it was decided to equally divide the segments for each road, mainly to increase the number of segments to be analyzed and to better capture the location of sites with higher frequency of collisions. Routes were created for each numbered or named road and then split into 100m segments. Such a segment size results from the need to identify hotspots, and is an arbitrary choice. Nineteen routes were broken down into 981 one hundred meter segments. The generation of routes erases the original attributes allocated on each segment; hence it is important to reintegrate these attributes once again from the original road network database. Identifying intersections in the road network under consideration is another important step that is discussed in the following section.

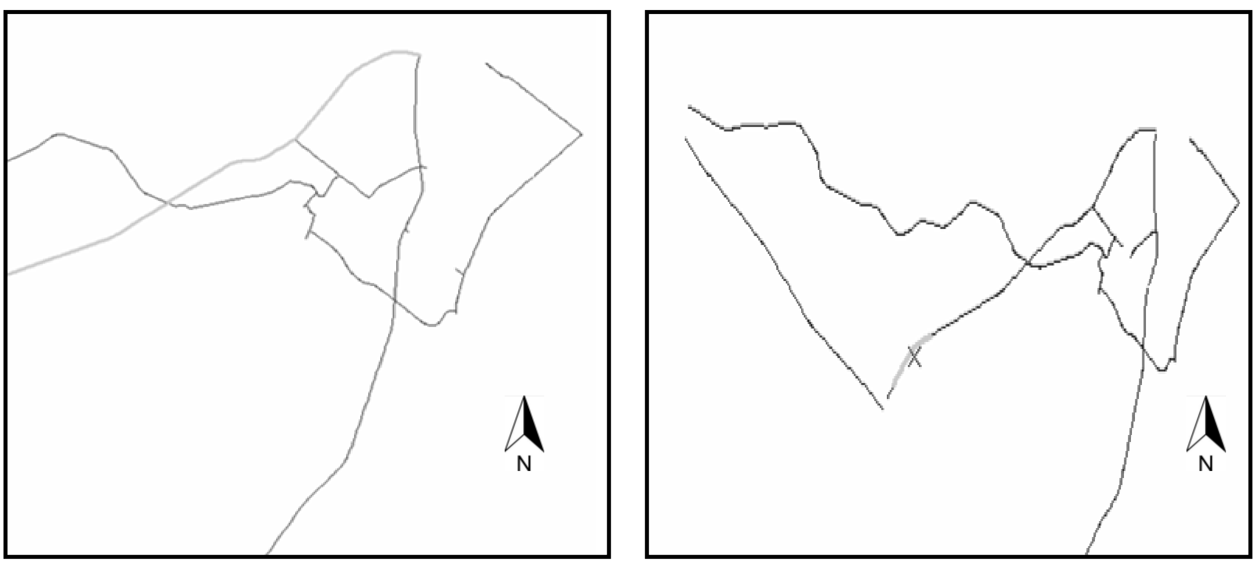


Figure 7 Merging (Right) and Splitting (Left) of Road Segments

3.3.5 Identifying Road Intersections

Presence of intersections is one of the variables that will be considered in the analysis. This is because most of researchers have mainly looked at intersections when conducting road safety studies. A 20m buffer was created to properly identify intersections. The 20m buffer was chosen based on the highest number of lanes in the sample, which is four. Hence, it was assumed that an approach has four lanes, with approximately 3.5meters width and two shoulders/sidewalks of three meters each, resulting in a buffer with a 10m radius (Figure 8). This step is crucial because intersections had special characteristics than those of mainline segments. An extra binary variable was added to the dataset identifying whether the segment (after being split) crosses an intersection or not. The collision database provided includes both daytime and nighttime accident. Nighttime crashes had to be isolated for the sake of analysis.

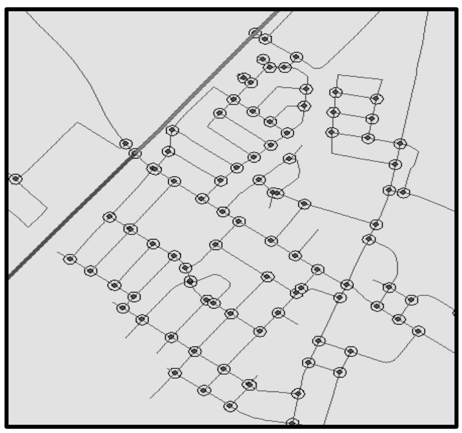


Figure 8 Identifying Intersections

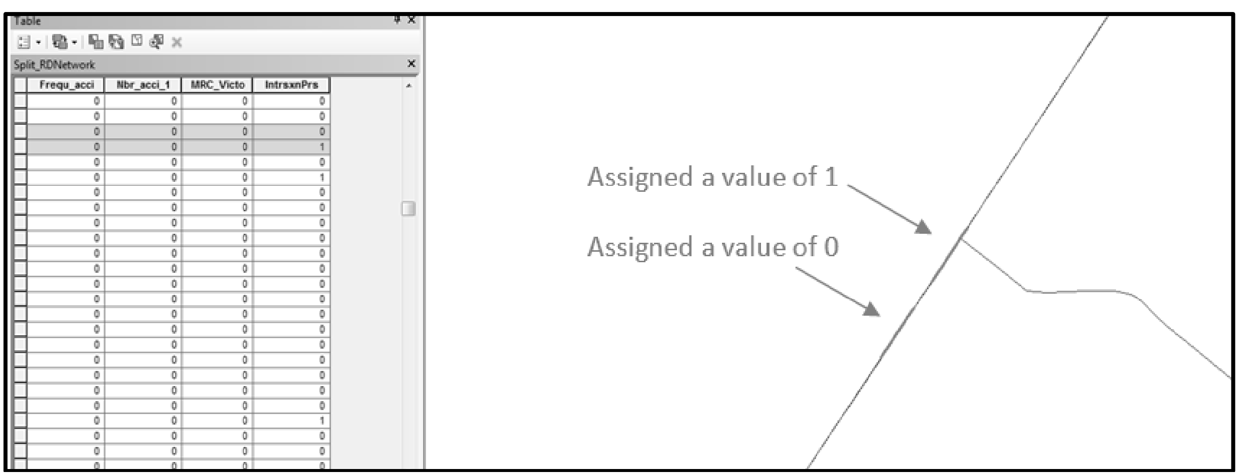


Figure 9 Identifying Segments Crossing Intersections

3.3.6 Isolating Nighttime Collisions

The next step is to only keep road collisions that occurred during nighttime on the roads for which lighting data has been collected. The dataset includes accidents for five years from the 1st of January 2007 to the 31st of December 2011. Both the date and the time of each reported accident are included in the database, making the removal of day time accidents an easy task. Given that the amount of day hours varies according to different seasons of the year, a chart from NRCC (2013), was used to determine the time of full darkness. In order to come up with a precise and an accurate frequency of nighttime accidents, the night period for this study is determined to be from the end of civil twilight (i.e. civil dusk) to the beginning of civil twilight (i.e. civil dawn). This subcategory of twilight has been chosen because artificial lighting is necessary during this time according to the United States Naval Observatory (USNO, 2011). The times for which artificial lighting is required has been retrieved from the website of National Research Council Canada (NRCC, 2013). The dataset obtained from this website provided the starting and ending times of civil dusk and civil dawn respectively for every day of the year for the city of Victoriaville (Table 4). Hence, according to the definition of dark by the USNO, both dusk and dawn are part of the night-time period and accidents occurring at these times will be considered as night-time accidents. The geographic coordinates used for the region of Victoriaville, in the Arthabaska Regional County Municipality located in central Quebec, are 46°05’N and 71°57’W for the latitude and longitude respectively (Comission de toponymie of Quebec, 2013).

Table 4 Sample of Daily Civil Twilight Start and End Times (NRCC, 2013)

Date	Civil Twilight Start	Sunrise	Local Noon	Sunset	Civil Twilight End	Hours of Illumination		
						Day	Sky	Total
Jan-01	6:56	7:30	11:51	16:12	16:47	8.7	1.15	9.85
Jan-02	6:56	7:30	11:52	16:13	16:48	8.72	1.15	9.87
Jan-03	6:56	7:30	11:52	16:14	16:49	8.74	1.15	9.88
Jan-04	6:56	7:30	11:53	16:15	16:50	8.75	1.14	9.9
Jan-05	6:56	7:30	11:53	16:16	16:51	8.77	1.14	9.91
Jan-06	6:56	7:30	11:54	16:17	16:52	8.79	1.14	9.93
Jan-07	6:55	7:30	11:54	16:19	16:53	8.81	1.14	9.95
Jan-08	6:55	7:29	11:54	16:20	16:54	8.84	1.14	9.97
Jan-09	6:55	7:29	11:55	16:21	16:55	8.86	1.13	10
Jan-10	6:55	7:29	11:55	16:22	16:56	8.89	1.13	10.02
Jan-11	6:54	7:28	11:56	16:23	16:57	8.91	1.13	10.04
Jan-12	6:54	7:28	11:56	16:24	16:58	8.94	1.13	10.07
Jan-13	6:54	7:27	11:56	16:26	16:59	8.97	1.12	10.09
Jan-14	6:53	7:27	11:57	16:27	17:00	9	1.12	10.12
Jan-15	6:53	7:26	11:57	16:28	17:02	9.03	1.12	10.15
Jan-16	6:52	7:26	11:57	16:29	17:03	9.06	1.11	10.18

Some collisions did not contain either the date or the time, and therefore a secondary criterion was used in this case to determine whether they occurred during the daytime or the nighttime. This variable included four subcategories: “daytime”, “nighttime with lit road”, “nighttime with unlit road”, “Between day and nighttime”, and “not precised” (Table 5). This variable is used for observations without a recorded time as last resort to identify the period at which the accident occurred (i.e. day vs. night). There were some discrepancies observed between this variable and the time of the accidents for a few observations making us believe it is subjective and is dependent on the police officer’s judgment. All observations with no recorded time and imprecise accident time have been discarded from the database. It is assumed that the observations classified as nighttime accidents based on the subjective variable have happened during the nighttime cut-off points (i.e. between civil dusk and civil dawn). The original accidents database contained 3099 accidents in total, out of which 912 were nighttime accidents. The final step is to come up with one database that includes all of lighting observations, nighttime collisions, and road attributes at their respective places along the road network to be able to analyse the data.

Table 5 Subjective Variable Used for Nighttime Accident Identification

Date	Number vehicles	Lighting	Severity	Time
070709	1	Nuit-chemin Eclaire	Materiel majeur	0427
080906	2	Nuit-chemin non Ecl	Materiel majeur	2301
100615	1	Jour-clarte	Materiel majeur	1945
080917	1	Jour-clarte	Leger	1100
101026	2	Jour-clarte	Materiel majeur	1700
080429	1	Nuit-chemin non Ecl	Leger	2020
101210	1	Jour-clarte	Materiel majeur	1400
070610	1	Non precise	Materiel mineur	
090411	1	Jour-clarte	Materiel majeur	0600

3.3.7 Integration of Lighting and Night Collisions into Roads of Interest

The ultimate purpose of this section is to come up with one dataset that combines the predictors and the outcome which will be used later on for the statistical analysis. In this case, the predictors included lighting data as well as road attributes and the outcome is the frequency of night-time collisions. Including the lighting dataset into the road network was done by doing a spatial join where each road segment is given a summary of the lighting points that are closest to it (Figure 10). By doing so, an average of the lighting data found on each road segment will be assigned to each route. A similar procedure was done to incorporate nighttime crashes but where a small manipulation of the data has to be done prior to that. A new column had to be added into the lighting data file with the label "Count" and a value of 1 is assigned for all rows (Figure 11). Once the spatial join is done, the total number of nighttime collisions that is closest to each segment will be assigned to the corresponding street section. This step finalizes data processing and one is ready to use the new dataset for analysis.

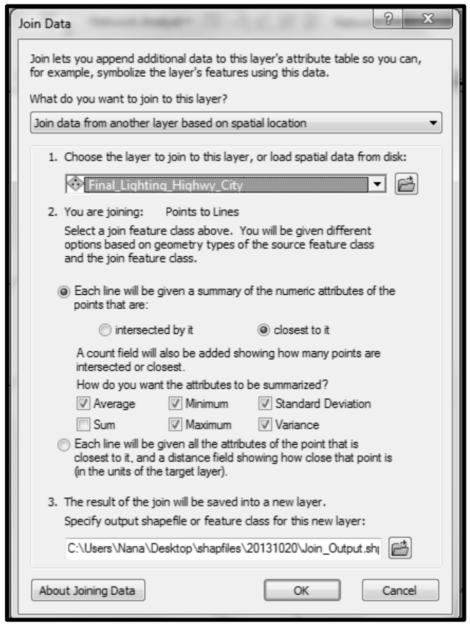
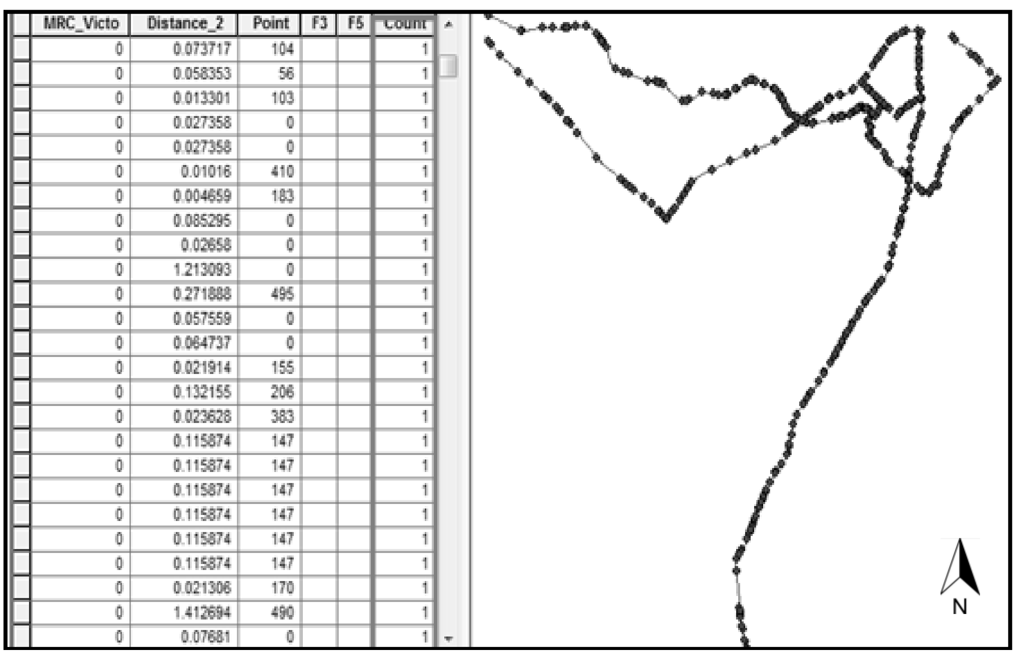


Figure 10 Importing Lighting Data onto Road Segments



MRC_Victo	Distance_2	Point	F3	F5	Count
0	0.073717	104			1
0	0.058353	56			1
0	0.013301	103			1
0	0.027358	0			1
0	0.027358	0			1
0	0.01016	410			1
0	0.004659	183			1
0	0.085295	0			1
0	0.02658	0			1
0	1.213093	0			1
0	0.271888	495			1
0	0.057559	0			1
0	0.064737	0			1
0	0.021914	155			1
0	0.132155	206			1
0	0.023628	383			1
0	0.115874	147			1
0	0.115874	147			1
0	0.115874	147			1
0	0.115874	147			1
0	0.115874	147			1
0	0.115874	147			1
0	0.021306	170			1
0	1.412694	490			1
0	0.07681	0			1

Figure 11 Assigning Nighttime Accidents to Road Segments

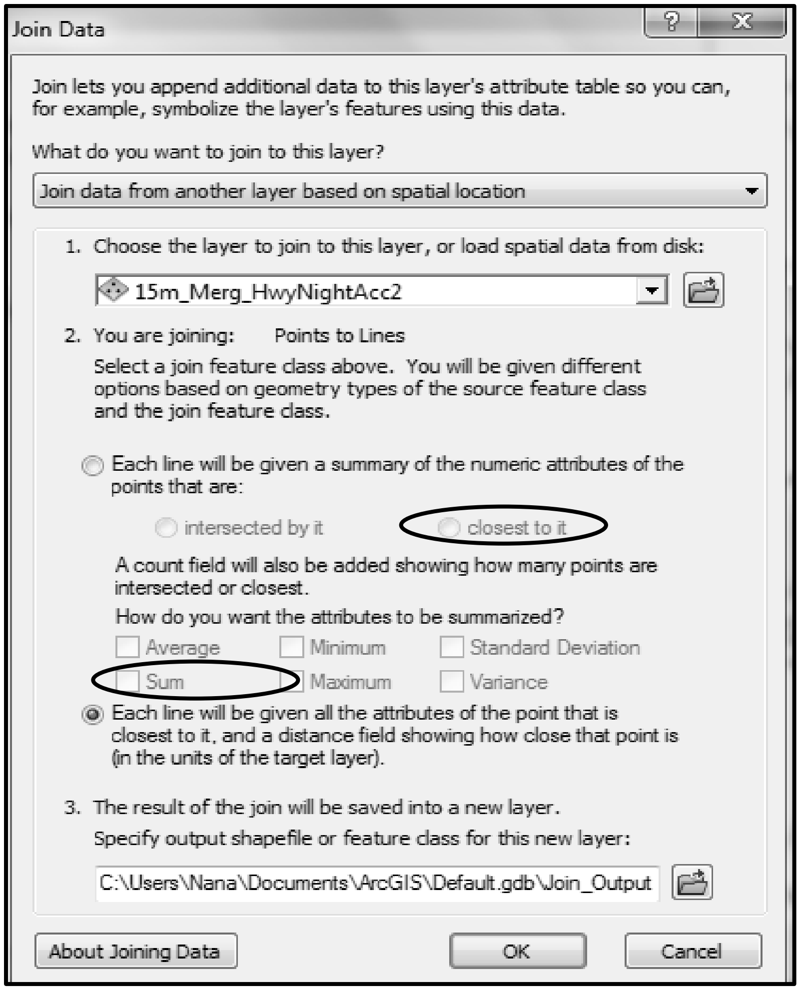


Figure 12 Spatial Join Based On Summary of Attributes

3.4 Statistical Model

High zero-count is commonly observed in road collision data. In this research, around 73% of the 100m-length segments have zero crashes (Figure 13). A zero-inflated model is chosen for the statistical analysis to take into account the high number of segments with zero-collision frequency. Zero-Inflated Negative-Binomial (ZINB) regression is used for the statistical analysis. This is because the variance of the outcome was found to be much bigger than the mean which violates Poisson model's assumption (i.e. mean = variance), resulting in over-dispersion of the data. The Zero-Inflated Negative-Binomial is preferred over the Zero-Inflated Poisson model mainly because it takes into account over-dispersion.

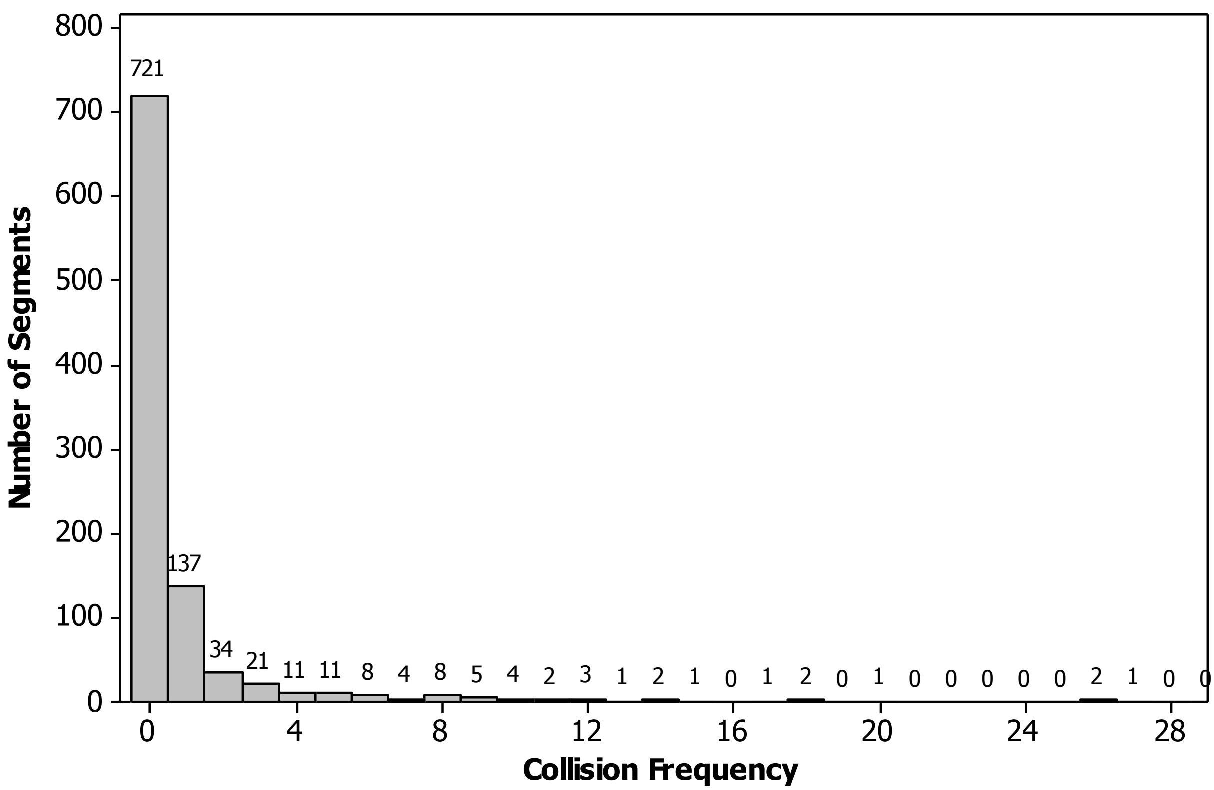


Figure 13 Distribution of Observed Collisions

This research used an exponential model to capture the correlation between explanatory variables and collision frequency as shown in Equation 1 which was briefly discussed in section 2.3. The equation will be discussed more in depth in the following chapter.

CHAPTER 4
ANALYSIS

4.1 Introduction

This chapter presents the analysis of roadway lighting measures such as illuminance, its variation and homogeneity and its relationship with collision frequency. The effect of other geometric and operational variables was also investigated; such variables serve to control the analysis. Because of the high count of zero crashes in the sample as well as the difference between the mean and the variance (over-dispersion), the Zero-Inflated Negative-Binomial regression model was chosen to find the correlation between nighttime collision frequency and road related attributes and lighting.

4.2 Database of Explanatory Variables

Table 6 summarizes the variables used for the regression. Some geometric and operational characteristics of the segments along with lighting measurements and nighttime crash counts were used for the analysis. Geometry attributes included: segment crossing an intersection (i.e. presence of intersection), number of lanes, pavement weather-related condition, complex geometry, average posted speed, land use (i.e. rural or urban), and a ten-year-average AADT. Pavement weather-related condition represents the number of accidents that have occurred in adverse weather conditions, such as rain, snow, and/or ice. Complex geometry represents the number of nighttime road collisions that occurred in the presence of a curve and a slope.

Table 6 Variables Used in Analysis

	Variable	Type			Value
		Binary	Discrete	Continuous	
Predictors	Crossing of Intersection	X			Yes: 1 No: 0
	Number of Lanes		X		1,2,3,4
	Variation in Average Illuminance (lux)			X	
	Pavement Weather-Related Condition		X		
	Complex Geometry		X		
	Average Posted Speed (km/h)		X		50, 70, 90, 100
	Land Use	X			**Urban:** Yes: 1; No: 0 **Suburban:** Yes: 1; No: 0
	Presence of Standard Light	X			Yes: 1 No: 0
	Presence of Non-Standard Light	X			Yes: 1 No: 0
	Uniformity			X	
	Average AADT		X		
Outcome	Accident Count		X		

Light related variables included variation in average illuminance (i.e. standard deviation), presence of standard level lighting and non-standard level lighting which were each represented by a dummy variable. The criteria employed to determine standard lighting followed those provided by IESNA (2005) (Table 7).

Table 7 Illuminance Method - Recommended Value (IESNA 2005)

Road and Pedestrian Conflict Area		Pavement Classification (Minimum Maintained Average Values)			Uniformity Ratio E_{avg}/E_{min}
Road	**Pedestrian Conflict Area**	**R1 lux/fc**	**R2 & R3 lux/fc**	**R4 lux/fc**	
Freeway Class A		6.0/0.6	9.0/0.9	8.0/0.8	3.0
Freeway Class B		4.0/0.4	6.0/0.6	5.0/0.5	3.0
Expressway	High	10.0/1.0	14.0/1.4	13.0/1.3	3.0
	Medium	8.0/0.8	12.0/1.2	10.0/1.0	3.0
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0
Major	High	12.0/1.2	17.0/1.7	15.0/1.5	3.0
	Medium	9.0/0.9	13.0/1.3	11.0/1.1	3.0
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0
Collector	High	8.0/0.8	12.0/1.2	10.0/1.0	4.0
	Medium	6.0/0.6	9.0/0.9	8.0/0.8	4.0
	Low	4.0/0.4	6.0/0.6	5.0/0.5	4.0
Local	High	6.0/0.6	9.0/0.9	8.0/0.8	6.0
	Medium	5.0/0.5	7.0/0.7	6.0/0.6	6.0
	Low	3.0/0.3	4.0/0.4	4.0/0.4	6.0

The software *Stata11* was used for the statistical analysis. Table 8 summarizes some of the basic statistics of the considered explanatory variables. There were 981-one-hundred-meter segments analyzed in this study where the minimum number of nighttime crashes was zero and the maximum observed (at an intersection) was of 58 crashes during nighttime (Table 8). It is observed that 78% of the road segments cross an intersection and about 80% have two way, two lanes single carriage way. Also, the 90 km/h and 100 km/h are the most predominantly observed posted speeds in the studied segments.

Table 8 Basic Statistics

Variable	Category	Number of Observations	Percentage (%)
Crossing of intersection	Yes	767	78.19
	No	214	21.81
Number of Lanes	2	783	79.82
	3	92	9.38
	4	106	10.81
Road Functional Classification	Highway	542	55.25
	Arterial	291	29.66
	Collector	107	10.91
	Local	41	4.18
Average Posted Speed (km/h)	50	156	15.90
	70	143	14.58
	80	28	2.85
	90	532	54.23
	100	122	12.44
Land Use	Urban	377	38.43
	Suburban	41	4.18
	Rural	563	57.39
Lighting Level: Very High	Standard	116	11.82
	Non Standard	230	23.45
	Dark	635	64.73
Lighting Level: High	Standard	141	14.37
	Non Standard	205	20.90
	Dark	635	64.73
Lighting Level: Medium	Standard	197	20.08
	Non Standard	149	15.19
	Dark	635	64.73
Uniformity	Below 3	912	93.00
	Below 4	927	95.50
	Below 6	944	96.23

As shown on Table 8, the majority of road segments (55%) are highways, with local street segments representing a minority of the sample (4%). Around 65% of the sample contained dark sites, which was earlier defined to be road segments with an illumination of one lux and below. Based on lighting standard defined for medium pedestrian conflict area (values taken from Table

7), 20% of the road segments are classified as standard and 15% are classified as nonstandard. Table 8 also presents the percentage distribution of standard levels of illumination for three groups of lighting levels further discussed in the analysis. As expected, higher cut-off point of standard levels of lighting resulted in decreased percentages of road segments falling into the standard light category. More than one-third of the road segments studied is found within urban areas; whereas, 58% are found in rural areas. Only between four to seven percent of the sample conform to uniformity as specified by TAC (2005) (Table 7), which might be caused by the high number of dark sites and those with the presence of a localised lighting source. An assumption where the geometrical and operational characteristics as well as the illumination condition of the sites haven't changed across the study period was made mainly because of the unavailability of such information at the moment that this research was conducted.

A correlation matrix describing the degree of relationship between two independent variables is shown in (Table 9**).** The variables having a correlation of 0.7 and above with one or more other variables had to be dropped and were not considered in the analysis. As expected, there is a high correlation between standard deviation and variance of illuminance. This makes sense given that the variance is the square of the standard deviation. The same observation was found for the variables of standard deviation and variance of posted speed. The correlation matrix also shows that there is a strong positive correlation between the presence of standard lighting and illumination-related-variables such as average and standard observed illumination on the road segments. However, average illuminance and the categorical variable for standard illumination were kept in the analysis because there was a need to check if the amount of illuminance could explain lower collision rates. Also, there was a need to see if those standardly illuminated sites explained fewer collisions than non-illuminated road segments. Also, there seems to be a good correlation between land use (i.e. urban and rural) and posted speed as well as land use and traffic volume. This makes sense as usually lower speeds are enforced within urban areas as opposed to rural locations. Posted speed, land use and lighting levels are all correlated according to the values obtained in the correlation matrix. This makes sense given that urban areas are usually lit and observe lower speeds (-0.567) than those at rural areas which are typically not lit with higher posted speeds (0.668). This also translates into the existence of co-linearity between measured illuminance and posted speeds; given that levels of lighting are linked to functional classification and the latter to posted speed, as seen at the illuminance cut-off values provided on Table 7. Also, there is a negative correlation between non-lit and standardly-lit road segments. This is purely due to the variable type (i.e. binary) of both predictors which are mutually exclusive. Therefore, dark variables had to be dropped from the analysis (and used as the base case for comparison) whereas standard and non-standard categories are kept for further investigation. The same has been observed for land use, where a strong correlation has been found between rural and urban sites; urban and suburban were kept for further analysis. There is no strong correlation observed amongst the other explanatory variables. In fact, there seems to be almost no correlation amongst the majority of the independent variables. Based on these observations, the variances of posted speed and illuminance are ruled out as potential predictors and instead this research uses average posted speed as well as standard deviation of illuminance which is expressed in the same units as the original variables.

The uniformity of illuminance is calculated based on IESNA (2005), where

$$Uniformity = \frac{Average\ Illumination}{Minimum\ Illumination} \quad [20]$$

Table 9 Correlation Matrix of Studied Variables

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
V1	1.000															
V2	0.198	1.000														
V3	-0.474	-0.374	1.000													
V4	0.345	0.330	-0.567	1.000												
V5	0.196	0.129	-0.256	-0.212	1.000											
V6	-0.437	-0.373	0.668	-0.679	-0.573	1.000										
V7	0.085	0.371	-0.117	0.290	0.097	-0.316	1.000									
V8	0.251	-0.008	-0.087	0.164	0.037	-0.165	0.073	1.000								
V9	0.292	0.006	***-0.098***	0.176	0.061	-0.194	0.082	***0.960***	1.000							
V10	0.378	0.437	***-0.636***	***0.883***	0.020	***-0.755***	0.310	0.128	0.142	1.000						
V11	0.118	0.119	***-0.233***	0.344	-0.028	-0.267	0.084	0.022	0.019	0.436	1.000					
V12	0.331	0.293	-0.558	***0.726***	0.087	-0.674	0.211	0.098	0.102	***0.830***	***0.783***	1.000				
V13	0.324	0.122	-0.547	0.525	0.197	-0.588	0.405	0.156	0.169	0.552	0.147	0.463	1.000			
V14	-0.334	-0.319	0.580	-0.541	-0.302	0.680	-0.460	-0.151	-0.169	-0.588	-0.201	-0.505	***-0.917***	1.000		
V15	0.038	0.492	-0.105	0.061	0.266	-0.251	0.152	-0.008	0.007	0.112	0.139	0.122	-0.165	-0.242	1.000	
V16	-0.059	-0.004	-0.036	-0.032	0.149	-0.085	-0.061	-0.015	-0.017	-0.004	0.003	0.042	0.022	-0.016	-0.015	1.000

where,
V_1 = Crossing of Intersection;
V_2 = Number of Lanes;
V_3 = Average Posted Speed;
V_4 = Presence of Standard Light (Medium);
V_5 = Presence of Non-Standard Light (Medium);
V_6 = No-Lighting (Dark-Medium);
V_7 = Average Annual Daily Traffic (ln(AADT));
V_8 = Variation of Speed;
V_9 = Standard Deviation of Speed;
V_{10} = Average Illuminance;
V_{11} = Variation of Illuminance;
V_{12} = Standard Deviation of illuminance;
V_{13} = Urban Area;
V_{14} = Rural Area;
V_{15} = Suburban Area;
V_{16} = Uniformity.

According to IESNA (2005), the uniformity ratios are dependent on the functional classification of the road (Table 7). The values provided in Table 7 are the maximum allowable values that can be observed on road segments. Road segments in the database where classified as being standard by looking into the average illuminance measured, observed uniformity and the functional classification to meet IESNA recommended illumination as described in Table 7. There was no observed co-linearity between uniformity and other predictors.

It was found that the standard deviation of the collision count is 3.21, meaning a variance of 10.30 whereas the mean is of 0.934. This clearly shows that the variance is much greater than the mean and the existence of over-dispersion in the data. Based on this observation, the Zero-Inflated Negative-Binomial model was chosen to be used.

4.3 Model

The Zero-Inflated Negative-Binomial (ZINB) model was chosen as a regression model because the count data had a highly non-normal distribution, a large number of zeros and over-dispersion as shown in Figure 14.

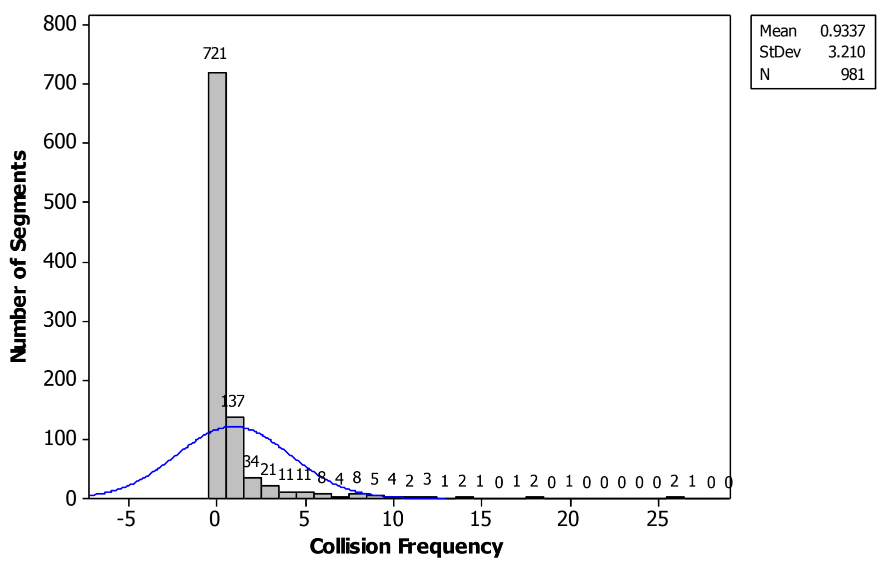


Figure 14 Histogram of Accident Frequency

The safety performance function used in the regression analyses is presented in Equation 21. The SPF is an exponential function that has twelve explanatory variables in addition to AADT.

$$= \;_{i} \qquad _{i}^{\beta_1} \quad (\beta \quad \beta_{ik} \;\; _{ik}) \qquad [21]$$

where,
i = Variable Number (1,2,3,…,12);
β_i = Coefficient Corresponding to Explanatory Variable k at Segment i;
Acc = Frequency of Nighttime Collisions on Segments i;
L_i = Length of Segment i;
$AADT_i$ = Average Annual Daily Traffic of Segment i;
X_{i1} = Number of Lanes on Segment i;
X_{i2} = Crossing of Intersection on Segment i;
X_{i3} = Variation in Average Illuminance on Segment i;
X_{i4} = Pavement Weather-Related Condition on Segment i;
X_{i5} = Complex Geometry on Segment i;
X_{i6} = Average Posted Speed on Segment i;
X_{i7} = Presence of Segment i in Urban Area;
X_{i8} = Presence of Segment i in Suburban Area;
X_{i9} = Presence of Standard Light on Segment i;
X_{i10} = Presence of Non-Standard Light on Segment i;
X_{i11} = Uniformity on Segment i.

Given that all sample segments are of uniform length, the parameter L_i is replaced by 1 in the model presented above.

4.4 Prior Expectations for the Impact of Different Predictors

Literature review and expert criteria provides an idea of the impact of the predictors on the outcome (i.e. nighttime collision frequency). For instance, one would expect an increase in the number of nighttime collisions in the presence of an intersection as opposed to those road segments located at access-controlled sites. An increase in the number of collision is expected along with increases in AADT. Presence of complex geometry, higher operational speeds and adverse weather conditions are expected all to increase the number of collisions. Moreover, given that functional classification is dependent on AADT, an increase in collision frequency is also expected at urban and suburban sites when compared to rural areas, this seems reasonable for the area of study as shown on Table 3. Overall levels of safety are expected to improve, i.e. lower number of nighttime crashes, at illuminated sites with either standard or non-standard illumination when compared to dark. However, given that more inconsistent lighting is associated to non-standardly illuminated sites, one would expect higher rates of road collision at such sites. Variation in the amount of light projected on the pavement surface (i.e. illuminance) might increase or decrease collision frequency during nighttime depending on the measured illuminance given that certain studies have found an increase in the number of nighttime accidents at high illumination levels.

4.5 Discussion of Results

The natural logarithm of AADT has been chosen as a predictor to inflate the regression. This is because the number of crashes is related to AADT. An increase in the number of accident is expected for high traffic areas as opposed to road segments with low AADT. Three analyses of standard illumination levels are presented in this section. The first analysis investigates standardly illuminated sites based on medium level of pedestrian conflicts. Minimum illumination level was modified in the second analysis to high levels of pedestrian conflicts to increase the amount of light in an attempt to find more effectiveness in crash reductions with higher levels of illuminance. Two more analysis increased illuminance and proved this hypothesis. Some predictors were controlled for in the analysis herein presented, with some variables having more than one level. In this analysis, three levels of illumination were considered: 1) Standard, 2) Non-Standard, and 3) Non-Illuminated (i.e. dark). In this case, non-illuminated sites were the control group which explains their omission in the regression analysis.

Three levels were also used to categorize land use where rural sites were omitted in the analysis and served as a control group. The three levels of land use were: 1) Urban, 2) Suburban, and 3) Rural.

4.4.1 Zero-Inflated Negative-Binomial

The outcome of the first regression model for medium illuminance levels is shown in Table 10. As any statistical regression, some of the variables will be statistically significant whereas others will be insignificant. Number of lanes was statistically insignificant. However, previous research has found that an increase in the number of lanes would decrease collisions frequency. Presence of intersections resulted in more collisions ($p = 0.000$), the condition of the road surface (either wet, icy or with snow) resulted in increments in accident frequency as compared to roads with dry surface at the time of the observed collision which goes in line with finding from previous studies. Variation in average levels of illuminance was insignificant, having a complex geometry (that is the presence of a vertical and/or horizontal curves as well as a slope at the same time) did explain having more crashes which is similar to what other researchers have found. Average posted speed, even though significant, explained less accidents, possibly from the fact that vehicles at higher speeds maintain larger gaps between each other. This is opposite to what was found in the existing literature mainly because the majority of existing studies have looked at operational speed rather than posted speed. Being at an urban area or at a suburban area was incapable of explaining any relationship with accident frequency, same happened with uniformity probably due to the small size of the sample. Studies conducted regarding this topic have mainly looked at urban sites where an increase in the number of collisions was observed at such sites. Rural sites from previous sites did not have as many nighttime crashes when compared to urban and suburban areas.

Table 10 ZINB Statistical Analysis Medium Levels of Illuminance

Variable	Coefficient	Std. Err.	Z	P>z	[95% Conf. Interval]		Effect size (%)
Number of lanes (X_{i1})	-0.027	0.080	-0.340	0.735	-0.184	0.130	
Crossing of intersection (X_{i2})	***0.913***	0.131	6.960	0.000	0.656	1.171	59.9
Variation in average illuminance (X_{i3})	-0.005	0.009	-0.590	0.554	-0.023	0.013	
Pavement Weather-Related Condition(X_{i4})	***0.457***	0.037	12.440	0.000	0.385	0.529	36.7
Complex Geometry(X_{i5})	***0.407***	0.206	1.970	0.049	0.003	0.812	33.4
Average Posted Speed (X_{i6})	***-0.015***	0.005	-3.230	0.001	-0.025	-0.006	-1.5
Urban area (X_{i71})	-0.109	0.195	-0.560	0.577	-0.492	0.274	
Suburban area (X_{i8})	-0.365	0.311	-1.180	0.240	-0.974	0.243	
Presence of Standard light (Medium) (X_{i9})	***0.599***	0.231	2.600	0.009	0.147	1.051	45.1
Presence of nonstandard light (Medium) (X_{i10})	***0.433***	0.202	2.140	0.032	0.037	0.830	35.2
Uniformity (X_{i11})	-0.003	0.006	-0.430	0.669	-0.014	0.009	
Log(AADT) (X_{i12})	***0.565***	0.147	3.840	0.000	0.277	0.853	56.5
Model Constant	-5.228	1.177	-4.440	0.000	-7.534	-2.921	
Over-dispersion	0.469	0.085			0.328		

Finally being at a site with standard illumination or non-standard illumination did show statistical significance; however, they both explained higher crashes rates as compared to dark sites. Dark sites (not in this analysis) were found to be significant contributors to lower crash rates. Opposing the literature, this model suggests that the presence of standard lighting produces more accidents than non-standard lighting (when both compared to dark). This disagrees with previous researchers that have all found that the presence of (standard levels of) lighting is a countermeasure capable of explaining less accidents. Hence, this may suggest problems with the definition of standard lighting. One of two situations may be happening: (1) truly dark segments experience less number of collisions. Hence, the observed positive coefficient for standard sites is correct, however, common sense dictates that is should be smaller than that of non-standard sites (as both compare with dark locations). (2) Observed positive coefficient for standard lighting is inadequate and cut-off point definition should be reviewed.

The analysis herein presented was based on a definition for standard lighting that assumed medium level of pedestrian conflicts (in lieu of the absence of such data). As seen on Table 10, results are not showing either of the aforementioned expected trends. Therefore, the only possible explanation is that the setup of breakpoint for segregating standardly illuminated segments is wrong. Based on the definitions provided by IESNA (Table 2), three additional analyses were conducted to test if by shifting levels of illumination required to define standard illuminance one can observe a lesser frequency of collisions at such segments than that of nonstandard segments both as compared to dark sites. Parameters related to the statistical model such as log-likelihood and numbers of observations are found in Table 15 for all of the three analyses presented herein.

The first model was identical to the one in Table 10 but with increased levels of standard lighting as defined by IESNA (2005); its results are presented in Table 11. Levels used to define standard illumination for this analysis correspond to high pedestrian activity (Table 2).

Table 11 ZINB for High Levels of Illuminance

Variable	Coefficient	Std. Err.	Z	P>z	[95% Conf. Interval]		Effect Size (%)
Number of lanes (X_{i1})	-0.024	0.081	-0.300	0.763	-0.182	0.134	
Crossing of intersection (X_{i2})	***0.910***	0.132	6.920	0.000	0.653	1.168	59.8
Variation in average illuminance (X_{i3})	-0.001	0.009	-0.150	0.880	-0.020	0.017	
Pavement Weather-Related Condition(X_{i4})	***0.463***	0.037	12.460	0.000	0.390	0.536	37.1
Complex Geometry(X_{i5})	***0.408***	0.208	1.960	0.050	-0.001	0.816	33.5
Average Posted Speed (X_{i6})	***-0.016***	0.005	-3.310	0.001	-0.025	-0.006	-1.6
Urban area (X_{i71})	-0.101	0.195	-0.520	0.604	-0.483	0.281	
Suburban area (X_{i8})	-0.412	0.309	-1.330	0.183	-1.018	0.195	
Presence of Standard light (High) (X_{i9})	***0.465***	0.246	1.890	0.059	-0.018	0.947	37.2
Presence of nonstandard light (High) (X_{i10})	***0.479***	0.197	2.440	0.015	0.094	0.865	38.1
Uniformity (X_{i11})	-0.003	0.006	-0.490	0.626	-0.015	0.009	
Log(AADT) (X_{i12})	***0.579***	0.146	3.960	0.000	0.292	0.866	57.9
Model Constant	-5.311	1.178	-4.510	0.000	-7.619	-3.003	
Over-dispersion	0.481	0.086			0.338	0.683	

Even though results for presence of standard illumination are only significant at the 93.8 percentile for this analysis, one can see that standard illuminated roads are explaining slightly less frequent accidents than non-standard illuminated roads, both as compared to dark. This translates in a case where dark roads experience less frequent collisions and either level of illumination (standard or non-standard) explain more collisions; however, with a better performance for the standard illuminated ones. This suggests a possible lack of correlation between current levels for standard illumination and the statistical evidence at least for the extent of this research.

Table 12 ZINB for Very High Levels of Illuminance

Variable	Coefficient	Std. Err.	z	P>z	[95% Conf. Interval]		Effect Size (%)
Number of lanes (X_{i1})	-0.022	0.081	-0.270	0.786	-0.180	0.136	
Crossing of intersection (X_{i2})	***0.908***	0.132	6.900	0.000	0.650	1.166	57.9
Average illuminance (X_{i3})	0.000	0.009	0.010	0.993	-0.018	0.018	
Pavement Weather-Related Condition(X_{i4})	***0.463***	0.037	12.540	0.000	0.391	0.536	37.1
Complex Geometry(X_{i5})	***0.414***	0.209	1.980	0.047	0.005	0.824	33.9
Average Posted Speed (X_{i6})	***-0.016***	0.005	-3.370	0.001	-0.026	-0.007	-1.6
Urban area (X_{i71})	-0.106	0.195	-0.540	0.588	-0.489	0.277	
Suburban area (X_{i8})	-0.417	0.308	-1.350	0.176	-1.021	0.187	
Presence of Standard light (Very High) (X_{i9})	0.405	0.255	1.590	0.112	-0.094	0.905	33.3
Presence of nonstandard light (Very High) (X_{i10})	***0.480***	0.197	2.440	0.015	0.095	0.866	38.1
Uniformity (X_{i11})	-0.003	0.006	-0.480	0.628	-0.015	0.009	
Log(AADT) (X_{i12})	***0.573***	0.147	3.900	0.000	0.285	0.862	57.3
Model Constant	-5.241	1.189	-4.410	0.000	-7.571	-2.911	
Over-dispersion	0.481	0.086			0.338	0.683	

One more model was set for a level deem very high levels of illuminance defined as 16 lux and above for highways, 21, 15 and 11 lux as minimum levels for major, collector and local, correspondingly. Results from this model are shown in Table 12. From the results, it seems plausible to argue that as one increase the levels of illumination, nighttime collision frequency drops for standard illuminated road segments (Table 13). Nothing can be concluded for nonstandard roads; at various levels of illuminance its correlation to collision frequency remains at about the same levels.

Levels of significance for standard illumination on Table 13 dropped presumably when compared to the two previous analyses. This is because with higher levels of illuminance a less number of observations is found inside the standard category as shown by Table 14.

Table 13 Correlation Coefficient at Various Levels of Illuminance - (CI%)

Level	Low	Medium (95%)	High (94.1%)	Very High (88.8%)
Standard	N.S.	0.599	0.465	0.405
Non-standard	0.496	0.433	0.479	0.480

Table 14 Observed Segment Numbers Based on Pedestrian Conflict Area Categories

Illumination Level Based on Pedestrian Conflict Area Type	Number of Segments (Percentage %)
Low	245 (25%)
Medium	197 (20%)
High	141 (14.4%)
Very High	116 (11.8%)

Table 15 reports the Log-likelhood values for each regression as well as the Log-Likelihood ratio (LR) of the chi square distribution.

Table 15 Regression Models Statistical Analysis

	ZINB (Medium)	ZINB (High)	ZINB (Very High)
Number of Observations	**981**		
Nonzero observations	**260**		
Zero observations	**721**		
Inflation model	**Logit**		
Log Likelihood	**-762.93**		
LR chi2 (12)	**5,976**		
Probability > Chi2	**0.0000**		

4.4.2 MTQ Grid Warrant System and Statistical Evidence

This research has tested some of MTQ warrant grid system variables. Levels of illumination together with some operational, road environment and geometry variables had been correlated to number of collisions.

From the results one can argue that presence of intersections is significant, slippery is significant (presence of snow, rain or icy conditions), combined curvature and slope also explains more accidents, average speed negatively correlates with accident frequency but is very weak. Traffic volume in AADT was also significant in explaining more accidents. Finally number of lanes and land use could not be found to explain higher accident frequency.

An analysis of the grid system shows that there exist a preference towards illuminating intersections, urban sites and those with higher volumes of traffic. This is explained by having two out of five grids dedicated only to interchanges and intersections (grids G4 and G5, *Transport Quebec*, 2012). On the other grids, one can observe variables such as land use, number of lanes, level of service (based on volume to capacity ratios) and proportion/proximity to development. Therefore, is seems reasonable to argue that rural roads would likely not be illuminated (dark) because fewer accident occur at such sites, meanwhile urban locations or interchanges/intersections will benefit from lighting. Therefore a correlation is expected between dark roads and rural land use, in this research a correlation matrix found a correlation value of 0.68 between both variables. Aggregating all levels of illumination into one category and testing its correlation with urban/suburban sites proofs that there is a strong correlation (0.68) which supports the argument that lighting as per current warrant system favours urban locations. Even more, looking at a variable that aggregates all urban land uses and rural intersections and correlates this with lit sites shows a correlation of 0.66.

Any road illuminated under the warrant system will fall within the standard classification. Evidence in this research found that accident frequency at standard illuminated roads and non-standard illuminated sites resulted in higher frequency of collisions as compared to dark sites. This could be explained by the fact that the grid system favours lighting at urban sites and intersections and when compared to non-illuminated sites (mostly rural) where lower collision rates are observed. Another explanation comes from an omitted variable bias. The fact of not involving important predictors such as human factors as well as other site attributes (e.g. lane width) may have impacted the regression coefficients of the predictors. Depending on the magnitude of the bias, it may actually change the sign of the coefficient which can explain why illuminated sites were found to increase nighttime frequency collision instead of a decrease as previous researchers have found. Again, it should be pointed out that, this study is a cross-sectional analysis and previous research is mostly longitudinal. This means that, in this study, standard and non-standard illuminated sites are being compared to dark sites and in previous research the analysis had looked at the same site before and after the provision of lighting. Another argument comes from the fact that dark sites observed perfect uniformity because there is no variation in lighting conditions, this in turn means that they are very consistent, i.e., the drivers eyes do not have to go through reiterative cycles of adaptation (contraction and dilatation of pupil) from variation in lighting levels, but rather remain with the same peripheral vision resulting in a better ability to identify objects.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research presents a method for the collection and processing of roadway illumination in order to use it into statistical analysis of roadway safety at nighttime. The guidelines provide practitioners with easy to follow steps in the collection and preparation of roadway lighting measurements and its consolidation into typical spatial databases.

It has been proposed to break segments into small length of about 100 meters for road portions as opposed to that traditionally recommended in typical safety analysis where the length of the segment is integrated into safety performance functions. This is due to the fact that point data needs to be used to estimate average illuminance and uniformity ratios. Also variations of lighting parameters can be better captured by smaller segments, as well as the easiness to identify hotspots. At the end, small segments have really helped in better characterizing the data, although other methods could be used to estimate an optimal segment size.

A model with operational, geometrical and lighting variables has been developed to estimate the effect of lighting parameters on explaining accident frequency. The model included number of lanes, presence of intersections, average posted speed, type of land use, surface condition of the road (slippery or dry), average AADT, standard deviation of lighting, uniformity and nighttime collision count.

A Zero-Inflated Negative-Binomial model was used due to the over-dispersion characterization of count data and the observed high number of zero nighttime collisions. As expected higher traffic volume, presence of intersection, slippery road surface conditions and complex geometrical alignments all significantly explained higher rates of road collisions. Weather related road condition correlates to both atmospheric circumstances and possibly visibility in addition to the coefficient of friction and the ability of the driver to maintain control. This in addition to complex alignments possibly resulted in vehicles abandoning the road or crashing with each other. The contribution of variables such as the presence of intersections or higher volumes of traffic is explained by increases in likelihood of a collision.

A small negative correlation was found between posted speed and collision frequency, possibly explained by the gap between vehicles. Those segments located at non-standard sites resulted in an increased likelihood of road collisions, explained by a significant reduction of collisions at non-illuminated road segments. It was demonstrated that variations in the levels of lighting also affect collision frequency. Higher levels of lighting (simulated through increased interval minimum value for a group called standard) explain fewer accidents than non-standard sites. This suggests that existing definition of cut-off point (for standard illumination) need to be reviewed in order to align existing lighting standards with the statistical evidence found.

A large database is advisable in order to obtain more variation in lighting levels, possibly including other highways and more segments from transitioning stages at suburban and industrial locations.

5.2 Recommendations

Future research can look into segment size selection by following an optimization analysis with two contradicting objectives: minimize the overall number of sites observing zero nighttime road collisions and maximizing the number of collisions per site to better identify hotspots. The need to minimize the number of sites with no collisions comes from the desire to prevent a zero inflated analysis.

The role of uniformity was not deeply studied, nor that of luminance and the role of glare in its classical forms of disability and discomfort glare. This study was limited to nighttime collision frequency. Further studies should look into the role of lighting and collision severity in addition to frequency. It appears that non-standard lighting is less effective than standard lighting above certain levels of illuminance. Levels of lighting below the standard lighting actually performs poorer than standard lighting with possible negative consequences in terms of collision frequency. It would be advisable to expand the database considered in this study to incorporate a wider range of road segments from several locations that may exhibit different levels of environmental variables such as total amount of rain, or total number of hours with good visibility.

Future studies should look into the role of glare in explaining crash frequency and severity, considering not only glare at the site of the registered crash but also by looking into the exposure to glare on the overall driver experience while at a specific facility.

Future research should look into the role of commercial lighting in road collisions, and attempt to develop better indicators of uniformity in order to prevent loosing segments because they are at the transition point between lit and unlit locations.

In overall it is recommended to measure luminance and incorporate such measurement into the analysis, as well as the role of wet pavements, the presence of snow on the ground or fog in the environment. Variables affecting human ability to perform should be incorporated if available.

Provision of lighting as defined by IESNA (2005) should include a maximum level of illumination in addition to the minimum requirement. Both levels should be defined based on statistical evidence of lower number (severity) of road collisions, keeping in mind that excessive illumination may result in glare. Levels of illuminance should be further studied.

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