A METHOD TO CALIBRATE ROADWAY LIGHTING WARRANTS AND LEVELS WITH CRASH-HISTORY

Mustafa Al-Dulaimi

A Thesis Submitted in Partial Fulfillment of the Requirements of
Doctor of Philosophy
of
Civil and Environmental Engineering

In the Graduate Academic Unit of Civil Engineering

Department of Civil, Building and Environmental Engineering

Concordia University
Montreal, Quebec, Canada

July 2015

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: **Mustafa Al-Dulaimi**

Entitled: **A Method to Calibrate Roadway Lighting Warrants and Levels with Crash-History**

and submitted in partial fulfillment of the requirements for the degree of:
Doctor of Philosophy (Civil Engineering)

Complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

Dr. Gerard Gouw – Chair

Dr. Eric Hildebrand – External Examiner

Dr. Adel Hanna – BCEE Examiner

Dr. Ciprian Alecsandru – BCEE Examiner

Dr. Amin Hammad – External to the Department

Dr. Luis Amador – Supervisor

Approved by

Chair of Department or Graduate Program Director

Dean of Faculty

Date

ABSTRACT

A method to calibrate roadway lighting warrants and levels with crash-history

Mustafa Al-Dulaimi,

Concordia University, 2015

Every year hundreds of night time road collisions result in fatalities and injuries in Canada. Roadway lighting is considered as the main countermeasure to prevent nighttime crashes. Provision of lighting follows two industry standards in North America: one for the warrants and the other for minimum recommended levels. The warrant system assigns scores to highway segments based on geometrical, operational and functional characteristics as well as the collision history through a night-to-day crash-ratio. Transportation agencies in North America had manifested their interest in simplifying the warrant system; eliminating elements and/or modifying lighting values, however, there is a need for a method to support lighting decisions over its effectiveness as a countermeasure. This thesis presents a novel method to calibrate lighting warrants and to identify effective levels of lighting in order to reduce the severity and frequency of night-time collisions. This new method uses an evidence-based mechanism to connect lighting warrants with statistical analysis of collisions in order to adjust the scores of the warrant. It also connects the estimation of lighting levels with evidence-based statistical analysis of crash-history in order to identify recommended levels of luminance, illuminance and uniformity variations. The method expands the industry standards by providing the decision maker with two alternate non-exclusive approaches supported over collisions' frequency and severity criteria. A large-scale case study for highways in Quebec was used to calibrate the warrants and identified recommended levels of luminance of at least 1.5cd/m^2, maximum uniformities of illuminance of 1.5 and of luminance of 8 times to prevent severe and frequent collisions. A case study of Arthabaska region

in Quebec found that levels of luminance should be increased for every functional classification of roads that values of uniformity must be reduced, and that levels of illuminance increased to reduce severe collisions. The novel methods developed in this research will provide province/state transportation agencies and municipalities with the capability of not only allocating lighting when is needed and justified, but also of selecting the optimal levels that result in effective reductions in nighttime road collision frequency and severity, signifying safer roads for the society at large.

ACKNOWLEDGMENTS

This dissertation was completed in August 2015 at Concordia University, Montreal, Quebec, Canada. First, I would like to express my deep gratitude to Dr. Luis Amador for his kind encouragement and support during the entirety of my PhD study. Under his guidance, I gained invaluable experience in performing scientific research and learned how to overcome various types of research problems.

Second, I very much appreciate the Ministry of Transportation of Quebec (MTQ) for kindly providing me with and letting me use the data that they have extensively collected for a long time.

Last but not least, I express my deepest acknowledgement to my supportive mother, my adorable wife, my kids, my sisters and their families. Without their support, I would certainly not be able to finish this interesting but challenging research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AS/NZ	Australia, New Zealand
CIE	International Commission on Illumination
COMT	Council of Ministers for Transportation and Highway Safety of Canada
DOT	Department of Transportation
E	Expectation (mean)
EXIF	Exchangeable image format
FB	Full Bayesian
FHWA	Federal Highway Administration
GMC	Glare control mark
GPS	Geographic Positioning System
IESNA	Illuminating Engineering Society of North America
JAGS	Just Another Gibbs Sampler
JIS	Japanese Illumination Society
KM	Kilometer
KPH	Kilometer per hour
LED	Light Emitting Diode
MCMC	Markov Chain Monte Carlo
MOT	Ministry of Transportation
MPH	Miles per hour
MTQ	Ministry of Transportation of Quebec
NCHRP	National Cooperative Highway Research Program
NS	Non-Significant
OLS	Ordinary Least Squares
OpenBUGS	Open source Bayesian Using Gibbs Sampler
PDO	Property Damage Only
PT	Scores (points)
SAAQ	Automobile Insurance Company of Quebec
TAC	Transportation Association of Canada
TI	Threshold Increment
TRB	Transportation Research Board
UAE	United Arab Emirates
UE	European Union
UK	United Kingdom
USA	United States of America
VAR	Variance
WHO	World Health Organization
WinBUGS	Windows Bayesian using Gibbs Sampler
ZINB	Zero Inflated Negative Binomial
ZIP	Zero Inflated Poisson

CHAPTER 1 - INTRODUCTION

1.1 Background

Road accidents negatively affect the lives of thousands of individuals and causes negative socioeconomic impacts on the society such as fatalities, injuries, labour loss and reduction of competitiveness (de Leur, Thue. and Ladd 2010). Collisions damage road infrastructure and traumatize families; carrying over heavy social consequences (WHO 2013). Roadway collisions are ranked eighth worldwide among causes of fatalities in the world, and this number is expected to increase in the coming decades (WHO 2013). About 1.24 million road users have died annually worldwide (WHO 2013). Moreover, road fatalities contribute to approximately one third of fatalities in Canada (Government of Canada 2012). In 2011, the number of injuries and fatalities had reached a total of 181,855 and 2,227 respectively on Canadian roads (WHO 2013). In high income developed countries, the largest percentage of road deaths is associated with collisions of motorized vehicles (WHO 2013). This number reached 81.6% for Canada in 2011 (WHO 2013). More than half of the Canadian road fatalities occur in rural areas (57%), whereas the majority of injuries (75%) occur in urban areas (Government of Canada 2012). In Quebec, 67% of the fatalities involved motorized users and the number of collisions is expected to grow as more people become motorized (SAAQ 2012). During 2012, the province registered 74,574 car accidents, 39,105 cases of injuries, and 436 fatalities on its road network (SAAQ 2012). As observed before, the number of fatalities on Quebec and Canadian roads is higher for motorized users, a trend that is being observed worldwide (SAAQ 2012). Only 18% of the road fatalities involved non-motorized road users (*i.e.*, pedestrians and cyclists) in the Province of Quebec in 2012 (SAAQ 2012).

According to the World Bank (2004) nighttime vehicle collisions can be mitigated through the installation of adequate roadway lighting. Lighting not only serves to control the number of road related collisions but also the speed of the vehicles (IESNA 2005). The International Commission on Illumination agrees in the role of lighting to reduce "the toll of death and injury" (CIE 2007). However, the reality for many countries is that lighting is provided on very few roads because it is very expensive to provide and maintain the infrastructure for lighting the entire network. Additionally, environmental considerations also discourage unnecessary lighting. Only 35% of Quebec's roads (1208 out of 3,452 kilometres of highways) count with artificial illumination (COMT 2013). This number considers only highways under MTQ's jurisdiction and does not count grid roads at rural locations under municipal jurisdiction. The cost of initial investment, energy consumption, and maintenance is only justifiable when it translates into a reduction of nighttime road collisions of more than two times that of day time crashes, or when a combination of factors deem a significant reduction in night time accidents (Walton 1974, AASHTO 2005). Many studies have shown lighting to be an effective countermeasure to reduce night time road accidents (CIE 1992). Before and after studies have shown reductions in road collisions ranging between 13 to 75% at sites where artificial lighting has been improved or upgraded (Yanmaz-Tuzel and Ozbay 2010). According to a comprehensive literature review conducted by the *Commission International de l'eclairage (*CIE 1992) and Rea *et al.* (2009) in some instances the number of accidents occurring at nighttime could be close to those happening during daytime. CIE (1992) and Rea *et al.* (2009) also identified that night-time accidents are more severe and involve more fatalities when compared to daytime accidents. According to the authors, it appears that darkness of a non-illuminated road reduces a driver's ability to manoeuvre and respond adequately to hazardous situations, due to reduced visibility which impairs visual capability (CIE 1992). Transportation agencies are responsible for determining when to provide lighting and how much lighting to design for. North America follows a warrant system first proposed by Walton (1974). This system uses scores to assess each road depending on its geometric, functional, and operational elements; the decision of lighting follows for roads obtaining 60 points or more. However, there is a disconnect between such decisions and whether or not lighting is beneficial for reducing collisions on the road under consideration. In 2003, Texas Department of Transportation adapted and extended the warrants (CTC and Associates LLC 2013), creating additional criteria and assigning custom values to the scores, and other states have recently followed. A review of the modified guidelines of several states revealed that most of the modifications are changing the existing scores with new values. This fact suggest that there is a need for local calibrations of warrant scores. Interviews with Quebec's MTQ revealed that the application of the warrant system criteria sometimes results in unexpected decisions, which is evidence of lack of calibration to local circumstances. In addition, even when lighting is provided, the proposed levels should be designed in such a way that lighting becomes an effective countermeasure, reducing the number and severity of collisions.

1.2 Problem Statement

There are no methods to calibrate the warrant to local circumstances of road lighting and the design levels. Many transportation agencies had recently used expert criteria to simplify the existing methods and suggested modified values to the scores; however, this approach lacks a necessary connection between lighting warrants and crash-history which should be the basis for local calibrations. On the other hand, IESNA's lighting levels are only reference minimums and there is no method capable of identifying recommended levels from a crash-experience perspective.

1.3 Research Objective

1.3.1 Overall goal

The overall goal of this thesis is to create methods to calibrate lighting warrants and to identify recommended lighting design levels which effectively serve to countermeasure night-time road-collisions.

1.3.2 Specific objectives

i. Establish a connection between warrants and design levels with crash-history.
ii. Connect warrants and design levels with crash-history.
iii. Develop and test a method to locally calibrate lighting-warrants.
iv. Develop and test a method to identify effective lighting levels.

1.3.3 Tasks

i. Collect illuminance and luminance data, prepare databases, and use statistical models to analyse the role of lighting indicators on night time collisions' severity and frequency.
ii. Conduct a critical review of lighting warrants around the world and identify the state of the art and practices, revise the state of the practice in North America and recommend changes.
iii. Identify mechanisms to calibrate roadway lighting warrants and lighting levels from a crash-history perspective.
iv. Use the mechanism to propose methods to conduct local calibration of warrant scores and identification of beneficial road lighting levels.
v. Test the methods through case studies that illustrate the ability to explain less frequent and severe nighttime collisions
vi. Write a protocol that summarizes the unified method.

1.4 Scope and Limitations

1.4.1 Scope

This research was funded by the Ministry of Transportation of Quebec (MTQ), the *Fond Quebecois de la Recherche sur la Nature et la Tecnologie,* and the *Fond Quebecois de la Sante* through a grant aimed to revise the grid warrant score system and adapt it for the province of Quebec. MTQ provided the road collisions data from 2007 to 2011. This data involves at least one motorized vehicle crashing with a motorized or non-motorized user or object. MTQ also provided data for geometric and functional characteristics. Roads for Arthabaska included local, collectors, arterials and highways with posted speeds ranging between 40 to 100 KPH. Roads for Quebec included only highways with posted speeds ranging between 70 to 110 KPH. Roadway lighting measurements were collected on the field. Lighting measurements for illuminance and luminance were collected for about 2,500 km on Quebec major highways & Arthabaska region.

The aim of this research is not to study the impact of variables on road collisions, but to use this type of analysis to propose two methods. The research proposes methods for local calibration of warrant scores, and for the identification of lighting levels. It uses Quebec and Arthabaska as case studies explaining changes to AASHTO warrants and IESNA levels. However, the methods proposed are general enough to be applicable anywhere in the world.

1.4.2 Limitations

Many circumstances limit the ability to collect data (weather, safety, data storage, et cetera). For illuminance, observations were recorded at every 15 meters with the aid of a logger; however, measurements cannot be taken if there is precipitation. For luminance, pictures were taken every 500 meters, lights of the vehicle were turned off and camera positioned to capture the drivers' perspective, which required taking several safety measures. Longitudinal uniformity was estimated for each segment (not measured). Transversal uniformity was not part of this research. No colour characterization was performed for the luminaires (the equipment was unable to measure it).

It has been assumed that observed lighting has not changed across time and that it is representative of that observed at the time of the collisions. This subdivides in two assumptions: first that improvements (or downgrading) had not been observed; second, that the amount of lighting from the source is the same. However, other researchers (Jacket and Frith 2013) suggest that the amount of light varies as much as 15% throughout the lifespan of the lamp.

The effect of some environmental variables on night time collisions will be left outside the scope of this research (snow, rain, fog, dust et cetera). The equipment was only capable of capturing the unified glare index and not the other glare indicators.

Data for pedestrians was not available, and it was unable to be included in the analysis. Practitioners planning to adapt the methodology presented herein must add such information to further break down the analysis in order to estimate recommended values of lighting parameters, not only per functional classification, but per level of pedestrian activity.

1.5 Research Significance

This research makes the following contributions:

i. Proposes a calibration method for roadway lighting warrants, providing departments of transportation and local municipalities with the ability to justify lighting decisions with expected reductions on nighttime collisions based on statistical analyses of crash experience. The revised scores are based on available data which better suits agencies' needs. The creation of this currently inexistent method will benefit agencies in North America and around the world, as is applicable anywhere as long as crash-data is available.

ii. Develops a method to identify effective levels of roadway illumination (illuminance, luminance and uniformities) according to the local/regional crash-experience, such that minimum values of illuminance and luminance and maximum uniformity variation do correspond to reductions of the frequency and severity of roadway collisions. This task has never been done before.

iii. Databases useful for lighting research have been created with about 2,500 kilometres of highways with illuminance data. About 800 km of them with both illuminance and luminance. Such a massive database outweighs any other previously created. This work signifies the largest lighting safety database in the world. This will serve for future research on safety and lighting.

iv. Demonstrates the use of Full Bayesian hierarchical analysis for validation and on a secondary plane to reproduce the ideas behind latent class mixture methods for the analysis of road collisions through safety risk groups. However, deeper exploration was left for future research.

In addition to the new methods, this research will improve the existing ones because surrogate variables could be used. The number of variables reduced to those available and the decision could be justified through improvement on nighttime collisions frequency and/or severity which is currently absent.

The overall research provides with a unified protocol for roadway lighting. This protocol will provide agencies at any level of government with an evidence-based justification of lighting to support their decisions, which in turn will minimize their liability position.

1.6 Organization of the Thesis

This thesis is presented in seven 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 safety and its statistical analysis. Chapter 3 presents the methodology employed for the collection, processing and analysis of the data. Chapter 4 explores the understanding of lighting and safety through a pilot study of the Arthabaska region in Quebec. This chapter has been submitted as a conference paper to the 12th World Conference on Injury Prevention and Safety Promotion in September 2016 in Finland. Chapter 5 presents the method for calibration of road warrants. It illustrates the method on a case study of hundreds of kilometres of highways 20, 40, 55, 105 and 132 in the province of Quebec. It has been submitted for publication to the Journal of the Transportation Research Board of the National Academies. Chapter 6 presents the method to identify recommended levels of lighting, and it contains two case studies: one for Arthabaska region and another one for highways in Quebec. It has been submitted for publication to the Journal of the Transportation Research Board of the National Academies. Chapter 7 presents the conclusions and recommendations for future research work. Because of self-contained nature of chapters 4, 5 and 6 as papers, some of the contents maybe a reiteration of material previously discussed on the thesis.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

Roadway lighting is provided as a countermeasure to reduce nighttime collisions, but it also has secondary purposes, such increasing pedestrian safety by reducing crime (DMD & Associates Ltd. 2009). Research on the safety benefits of lighting investigated crime rates before and after implementing nighttime lighting, showing nearly significant reductions for control areas in the US and significant reductions in UK (Rea *et al.* 2009). The following sections present the basic concepts of artificial roadway lighting, its use as collision countermeasure, and current warrant and design standards used in Canada.

Three major areas are discussed thoroughly in this chapter: statistical analyses for road safety, the role of artificial lighting as a countermeasure for nighttime collisions, and the state of the practice on lighting warrants and design levels. The first section describes concepts related to statistical analysis used in road safety. The second section provides a brief review of lighting and the different indicators used to measure it. The third section covers nighttime road collisions and the role of lighting. The fourth section provides a description of lighting warrants and design guidelines. A revision of world practices and a critical review of the state of the practice of warrants in North America are used to justify the gap in knowledge due to inexistent research in this area and an urgent need from the state of the practice.

2.2 Statistical Analyses in Road Safety

Using an appropriate regression model to correlate independent variables with an outcome is important to provide reliable statistical results. There are many statistical regressions that can be used to predict an outcome associated to road safety. Road safety outcomes are collisions which are random integers that typically got aggregated by looking into several years at a time and therefore turn into count variables. Widely used ordinary least squares model is not applicable to count collision data because this data is highly abnormal with zero inflated means (Zhou and Hsu, 2009); rather count models such as Poisson or negative binomial must be used (Isebrands *et al.* 2010).

The typical form of a count model is given in Equation 2.1 (Bullough, Donnell and Rea, 2012). It depicts the relation between the outcome (collisions), and the explanatory variables (road characteristics among others). The model also includes an error term that takes into account the impact of unobserved variables. This form involves the use of a natural logarithm; however, because many observations of the response exhibit zero value, it is typically transformed to an exponential model such as that shown in Equation 2.1.

$$Y_i = AADT_i{}^{a} \; * \exp(\beta_0 + \beta_1 x1_i + \cdots + \beta_k x_{ki}) \qquad [2.1]$$

Where:
k:variable number (1,2,3,….)
β_k *:Coefficient of explanatory variable* x_k
Y_i*:Frequency or severity of night-time collisions on segments i*
$AADT_i$*: Average Annual Daily Traffic of segments i*
X_{ki}*: Explanatory variable i*
α*: Coefficient of AADT at segment i*

2.2.1 Poisson and negative binomial regression models

Poisson and negative binomial models have been used to analyse roadway safety given their properties that enable them to handle count data. The main assumption behind the Poisson model is that the mean μ is equal to the expected value and to the variance VAR(Y) of the outcome as shown in Equation 2.2. This is not always the case mainly because of unobserved heterogeneity which can result from missing important site characteristics, randomness, and a high number of zero counts, causing over-dispersion of the data and therefore resulting in variances much larger than the mean. The Poisson model is not applicable in those cases when the data is over-dispersed, mainly because it underestimates the standard error. Count data often exhibit over-dispersion making negative binomial the ideal choice.

$$\mathrm{Var}(Y) = E(Y) = \mu \qquad [2.2]$$

Where:

Y = Accident frequency or severity
μ = Average number of accident (mean)
VAR(Y) = Variance of Y
E(Y) = Expected value of Y

2.2.2 Zero-inflated Poisson an negative binomial

If the count of zero (Equation 2.3) for the response is very high in the sample under study, a zero-inflated Poisson (ZIP) (Equation 2.4, 2.5, and 2.6) or negative binomial model (ZINB) should be used, (Equation 2.7 and 2.8) depending whether or not there is over-dispersion (Mullahy 1986). The general framework for the ZIP model has been explained elsewhere (Lord and Miranda-Moreno 2008) and is presented in Equations 2.3 to 2.6. The response Y is dependent on μ_i which is a function of a vector of site attributes, hence, it is a function of traffic flow (AADT) and the other characteristics of the road (x) and their accompanying coefficients (β). In these Equations ε_i is an unknown parameter representing the proportion of zeros that is added to the Poisson distribution. The error term ε_i can also be determined as a function of some site attributes that were not considered in the model in question and can be defined by using a logistic link function $\varepsilon_i = \frac{e^{\omega z_i}}{1+e^{\omega z_i}}$, where ω is a parameter vector and z is a vector of an unobserved site characteristics. 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.

$Y_i = 0$, with probability ε_i, and [2.3]

$Y_i \mid \mu_i \sim$ Poisson (μ_i), with probability (1- ε_i) [2.4]

Equations 2.3 and 2.4 follow the following distributions respectively

$f(y_i \mid \mu_i, \varepsilon_i) = \varepsilon_i + (1- \varepsilon_i)$ Poisson(μ_i) for $y_i = 0$, and [2.5]

$f(y_i \mid \mu_i, \varepsilon_i) = (1- \varepsilon_i)$ Poisson(μ_i) for $y_i = 1, 2, \ldots$ [2.6]

Although the ZIP distribution can handle the problem of excessive zeros, it is inflexible in the sense that it cannot represent important unobserved attributes or randomness that may also affect the mean number of accidents (*i.e.* unobserved heterogeneity). To address this issue, ZIP has been extended to the zero-inflated Negative Binomial model, which assumes that the mean number of accidents is also random, by introducing a multiplicative random term (Hauer 1997).

An alternative model to standard/regular negative binomial is the zero-inflated negative binomial regression model if over-dispersion is observed (Mei-Ling *et al.* 2004). The ZINB is an extension to the ZIP. This regression model deals with both the high number of zero counts and over-dispersion (Mei-Ling *et al.* 2004). This model assumes that the zero count results from two different processes. For instance, in the case of road safety, there might be a high number of zero accidents because of two reasons. The first reason can result from the fact that there are no reported accidents because of the road segment's observed and unobserved characteristics (1-ε_i) in Equation 2.7. The second reason that might explain zero crash frequency is that the accident was not reported (ε_i) in Equation 2.8. There is also a zero-inflated Poisson model that can be used if and only if the variance of the outcome is equal to the mean. The variance and the mean of the outcome have to be compared to determine which one to use. It is important to mention that over-dispersion (α) for ZINB regression also stems from splitting the zero count generation process into two parts, in addition to what was mentioned earlier (Mullahy 1986 and Greene 2003). The ZINB model has the following probability distribution (Equations 2.7 and 2.8):

$$f(y_i \mid \mu_i, \varepsilon_i, \alpha) = \varepsilon_i + (1- \varepsilon_i) \text{ Poisson}(\mu_i, \alpha) \text{ for } y_i = 0, \text{ and} \quad [2.7]$$

$$f(y_i \mid \mu_i, \varepsilon_i, \alpha) = (1- \varepsilon_i) \text{ NegBin}(\mu_i, \alpha) \text{ for } y_i = 1, 2, \ldots \quad [2.8]$$

As in the ZIP model, ε_i represents the probability of being in the zero-state and is also analysed as a function of a vector of covariates z_i.

2.2.3 Full Bayesian analysis (FB) for road safety

An alternative approach to classical statistical analysis is that of Full Bayesian Analysis combined with some estimation algorithm, like the Gibbs sampler or any other Markov Chain Monte Carlo simulation which enables the estimation of parameters via sampling of the space and, guided by initial priors and the information contained in the observed data. In this research, this approach used to validate the results obtained via classical statistical methods (*i.e.* those supported over maximum likelihood estimation). Three elements are at the core of any Bayesian analysis: (1) a prior distribution of the parameters of interest, (2) a likelihood distribution from the existing data, and (3) a posterior distribution to be estimated. In Bayesian estimation it's necessary to provide a point of departure (called prior) to each parameter. Typically priors are based on previous studies or previous knowledge; they can also be directly obtained from professional engineers or technicians with vast experience in the area. The posterior inference comes from a mix of the prior and the likelihood.

Full Bayesian regression analysis poses a superior framework for estimation when dealing with models that follow a hierarchical structure in which parameters are dependent of certain factors which are themselves parameters as well (Congdon 2010). This is dependent of certain probability density functions (hyper-priors) of one or more parameters of the model, which are in turn dependent on a series of other parameters (called hyper-parameters). Such hyper-parameters also follow a particular prior distribution, so that different levels of hierarchies can be set up in the analysis. This idea will be briefly explored in the analysis of sites by level of risk introduced in chapter four of this research work. However, Full Bayesian regression will be used for validation. The process of estimation requires the preparation of thousands of iterations in order to achieve a stationary state form, from which the expected values of the posteriors can be estimated. Such values represent the estimated parameters that accompany the causal factors of the regression model. For this, Full Bayesian analysis takes advantage of simulation approaches such as Markov Chain Monte Carlo (MCMC) methods (Gamerman and Lopes 2006). The simulation follows the estimation of values from different points of departure called chains, which proceed until the paths of the values cross and reach a stable range called convergence. Convergence can be visualized by checking the historical trace of the chains. Typically, the first few thousand (and sometimes million) iterations must be dropped off the analysis, as they belong to an initial state in which the estimation has not converged. Checking the significance is another challenge in Full Bayesian analysis. The most common way is by simply observing the spread on the estimated statistical distributions of the parameters and making sure that the values of the distribution do not cross over zero; for instance if one seeks 95% confidence in the results of a given parameter, then the values of such parameter at the 2.5% and 97.5% points should both be positive (in the event of a positive contribution of the causal factor to the response) or negative (on the contrary).

Several softwares exist for Bayesian estimation, among others: R (Albert 2007), JAGS (2014), WinBUGS (2014) and OpenBUGS (2014). All of them utilize a MCMC simulation approach for Bayesian inference, the difference lays on the algorithm: while many use a GIBBS sampler others follow more general forms of the Metropolis Hastings algorithm.

Choosing the appropriate prior for Bayesian Regression has been a matter of debate (Lunn *et al.* 2000 and Bishop 2007). The likelihood is generally derived from the available data and the prior from either expert criteria or independent studies. Priors can either be informative or non-informative. When little is known about the phenomena that is being modelled, non-informative priors are preferable as they result into a more reliable posterior derived from observations (*i.e.*, the likelihood). When there is insufficient knowledge about the phenomenon to be analysed, informative priors are recommended if there is certainty that such knowledge is incorrect. Priors get mixed with the likelihood (as explained before) producing an improved estimate of the posterior from a reduced variance. By obtaining such posterior it is possible to balance the associated risk of either having biased priors or unusual observations (from limited time series data, in particular).

2.2.4 Latent Class or Markov mixture models (LCM)

Most existing research has used traffic volume as the main factor to explain observing zero accidents at many road segments; that is, low volumes of vehicles commonly result in no crashes. However, a new technique called latent class has recently captured the attention of researchers (Persuad *et al.* 2009). This technique acknowledges the fact that observations across sites may belong to different populations. Hence having mixed observations presented as one isn't adequate and that the structure of the data should reflect such membership to disentangle the results into separate analyses. Such a method strongly mirrors that of a nested or hierarchical analysis in the Full Bayesian literature (Persaud, *et al.* 2009).

This technique abandons the dependency of the zero inflation and through an identification of the level of risk of the segment produces an analysis that takes into consideration the explanatory power of the causal factors according to the level of risk at hands. Two precursor studies by Malyshkina, Mannering and Tarko (2009), and by Malyshkina and Mannering (2010) introduce this novel method and were dedicated to assess the suitability of Markov switching negative binomial models and of zero-state Markov models in their application to vehicle accident frequencies. Their studies found that instead of heavily depending on the zero inflation the models should rely more on a categorization of risk and on an analysis of the explanatory factors at each level. The most recent study was conducted by Peng and Lord (2011) through an application of the latent class to analyse longitudinal data. The analysis of trends was used to characterize the relative importance of risk factors on explaining accidents and estimated the contribution of geometrical and operational factors per level of risk.

2.3 Roadway Lighting

2.3.1 Photometric quantities

Photometry is the science of measurement of light in terms of its apparent brightness to the human eye (IESNA 2008). It is distinct from radiometry, which is the science of light measurement in terms of absolute power. Photometric quantities such as lux, lumens, and candelas serve as reasonable indicators reflecting variables that characterize visual responses (Lennie, Pokorny and Smith 1993), including reaction times.

According to the CIE (2007), road lighting standards are set by considering:

1. Luminance and Illuminance
2. Luminance-based uniformities and Illuminance-based uniformity
3. Glare
4. Threshold increment and color of the light source

This research uses luminance, illuminance, and their variations. Glare was initially explored but limited to the ability of the equipment; only the unified glare indicator was available. Other aspects of lighting were not included as the equipment was not capable of its measurement.

2.3.2 Illuminance, luminance and uniformity variations

Illuminance is the amount of light arriving at the surface of the pavement (Figure 2.1). It is measured in units of light flux (lux). Luminance is the amount of light as perceived by the driver; it depends on the road surface and environmental circumstances (wet, dry). It is measured in candela per square meter (cd/m^2) and is typically measured using a photometer (which costs tens of thousands of dollars) or, most recently, a calibrated commercial camera, with its white balance and exposure settings calibrated to match the pixel grey-scale brightness to luminance targets (Jackett and Frith, 2013, Cai and Li 2014). According to Rea *et al.* (2009) for roads that are mainly used by non-motorized road users, illuminance should be used as a lighting criterion, whereas, luminance should be used for motorized roads with vehicles moving at high speed. Neither overall nor longitudinal uniformity has been identified as significant predictors of collision rates reductions in previous studies (OPUS 2012). Uniformity refers to the longitudinal and transversal variation of lighting (luminance or illuminance) as shown in Figure 2.1. Lower values of uniformity (starting on one) correspond to homogeneously lighting circumstances. Higher values refer to large variations, such as those seen on the longitudinal uniformity of Figure 2.1. Two ratios are commonly used for luminance-based uniformity: the maximum over minimum and the average to maximum. The maximum to minimum variation can tolerate larger variations as it looks at the brightest and darkest points from a driver's perspective and it can be used to measure glare. Average to minimum luminance variation will likely have values of one in order to have consistently lit environments. For illuminance, the uniformity variation refers to the ratio of average over minimum and could lead to values starting at one (Figure 2.1) and large values for segments where the amount of light on the surface varies significantly. One common issue is that of segments transitioning from zero to some level of illuminance, resulting in very large ratios. This situation can be fixed by removing them from the analysis. Similarly, non-lit roads with mean and minimum illuminance of zero pose a mathematical problem, solved by assigning a very low value of illuminance (0.01Lux).

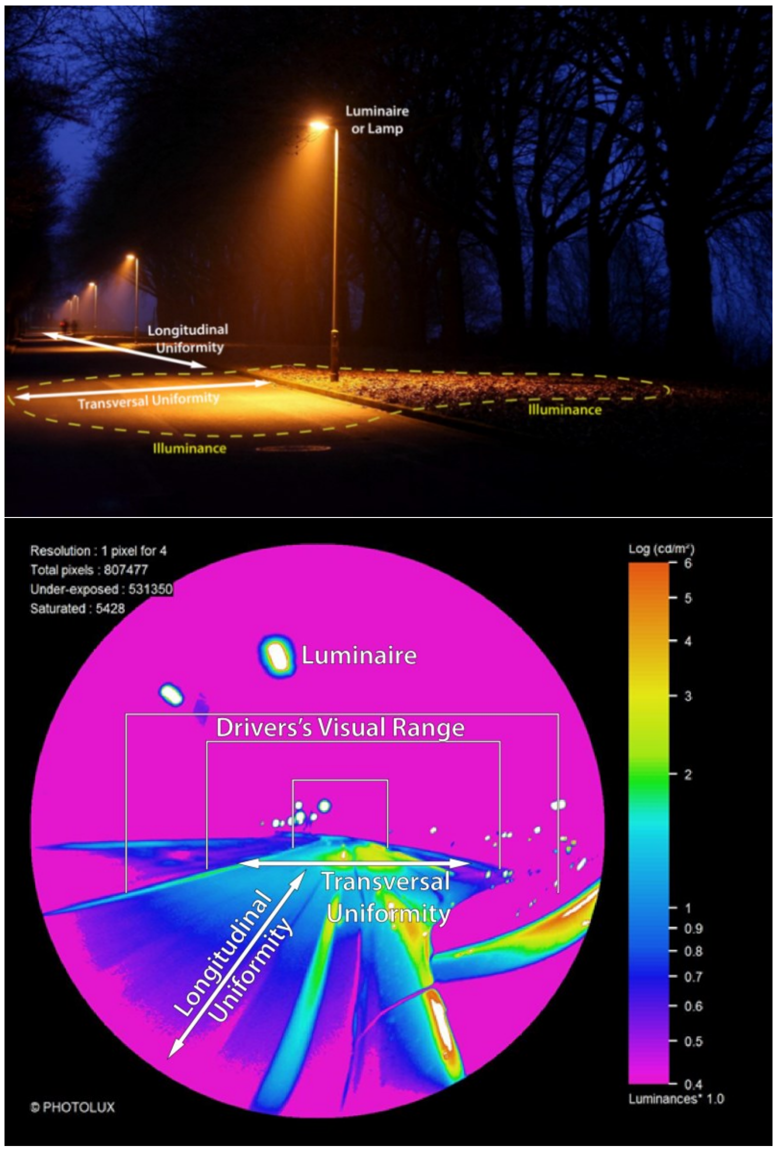

Figure 2.1 Top: Luminance and its Variables, Bottom: Illuminance and its Variables
(Source: desktopwallpapers4.me 2015)

According to IESNA (2005) glare is defined as visual impairment or difficulty of seeing objects from the abrupt change in light contrast. This could come from the presence of a bright source of light or luminaire (Figure 2.1). Contrast is the difference in luminance between a target and its background, which is relative to the average luminance of the immediate environment (CIE 1976). Two types of glare have been defined: disability glare and discomfort glare (IESNA 2005). Several formulas have been developed throughout the years by different researchers to estimate glare. These equations were formulated by taking into consideration the low adaptation level to exterior lighting, the pulsating action experienced by the driver due to the presence of luminaires which emit high intensity of light close to the driver's visual range of sight (Figure 2.1), or that is coming out from headlamps.

This research employs the unified glare ratio because it was the only one the camera and software were able to estimate the unified glare ratio is defined in Equation 2.9.

$$UGR = 8\log\left[\left(\frac{0.25}{L_b}\right)\sum \frac{L^2\omega}{p^2}\right] \qquad [2.9]$$

Where L is the luminance from one luminaire, ω is the solid angle of the luminaire from the viewer's position, p is the Guth index which increases as the line of sight of the viewer moves away from the luminaire.

The role of the Threshold index has been discussed by Armas and Laugis (2007). They essentially explain that, there is a value called adaptation luminance at which an object and its surroundings require a minimum level of contrast for it to be visible. In the event of glare veiling luminance, the eye of the driver is forced to adapt to higher levels of luminance making the object invisible. To counteract this adverse effect one needs to increase the luminance contrast.

2.4 Roadway Lighting and Road Safety

2.4.1 Road safety and night time collisions

Highway features consistency is an important element in road safety (COMT 2013). In fact, TAC (2004) and TAC (1999) lay down the foundation of road safety on the cornerstone of consistency. The environment to which drivers are exposed impacts their behavior and their response on the road. Inconsistency in road features tends to increase the frequency and the severity of road crashes, depending on the complexity of the road environment. Severity refers to the degree of damage to the human body suffered by the driver and/or the passengers. A consistent road environment provides the driver with enough clues to take timely decisions. Consistency is one of the most transcendental concepts because it explains collision risk. Proper driving visibility is linked to consistency. According to TAC (2004), 90% of the information used by drivers is visual. In this sense, drivers should be able to recognize all signals and information from the road environment in order to avoid errors and collisions. Road crashes can be generally explained at sites where multiple decisions need to be done in a short amount of time. Complex operating environments, in which a variety of road users interact, could be crowded with information overwhelming the driver and impeding timely processing and decision making. The lack of proper lighting may aggravate these circumstances, given late detection of hazards or clues expected to condition the driver's response. Even when the environment is not complex, lack of proper illumination can still result in limited visibility, which may lead to late responses, given insufficient time to process the information (TAC 2004) and sometimes resulting in road collisions. Visibility at night time is also dependent on driver's age. Places with large concentration of elder drivers (Rea, Bullough and Zhou 2009) may require adjustment to the amount of illumination provided and to improve glare control measures like median panels (IESNA 2005).

Previous research had shown that higher speeds result in less frequent (due to increased gap between vehicles) but more severe collisions (CIE 1992). On the other hand, traffic volume is one of the explanatory variables that have a significant impact on crash frequency (TAC 2004). Higher frequencies of road collisions are expected during peak hours and at roads with higher volumes (with all other variables held constant). With this being said, collisions are never caused by a single factor. A combination of factors are always related to each collision, where at least four causal factors and the sequence of events are reported to the police.

Some of the most recognized variables which have been traditionally linked to higher frequency of collisions are traffic volume, presence of intersections, undivided roads, and complex alignments with limited sight distances, dark locations, and disability glare.

2.4.2 Lighting and night-time road collisions

The question of whether roadway lighting reduces or increases the risk of crashes is one of the most studied and debated subject in road safety. Such an issue can be addressed by incorporating road lighting with the purpose of increasing visibility (Bulldough, Rea and Zhou 2009, Cobb *et al.* 1979). TAC (2004) and Oya, Ando and Kanoshima (2002) acknowledge that the provision of roadway lighting as a countermeasure results in a 10 to 40% decrease in observed collision frequency and up to 65% of fatal crashes. An effectiveness of 37% reduction on crash rate with 95% significance has been found by Isebrands *et al.* (2010).

The effectiveness of roadway lighting also suggests that nighttime collisions result in more severe crashes and that provision of lighting contributed to the reduction of their frequency (TAC 2004, CIE 1992, IESNA 2006).

The whole purpose of lighting is to increase visibility (Bullough, Rea and Zhou 2009). Because of the versatile use of lighting (DMD & Associates 2009), lighting can be used to provide just enough visibility in some cases and in others, a higher level of lighting might be needed to provide safety to the road user.

Several studies have been conducted for examining the relationship between roadway lighting levels and safety, Zhou and Hsu (2009) investigated how maintained illuminance levels impact safety of pedestrians. They found higher frequency of pedestrian crashes at sites with low level of lighting, and similar findings did Isebrands *et al.* (2010) for Minnesota. Yannis, Kondyli and Mitzalis (2013) found that road lighting contributes to reduce accident frequency and especially reduce the number of persons killed and seriously injured in a study conducted with data from urban and rural roads in Greece (Elvik 1995). CIE (1992) found that the presence of lighting was statistically significant in reducing the number of collisions. Also, lighting was found to be statistically significant in decreasing the number of motorized crashes in all three studies that considered freeways interchanges.

Another review done by IESNA (1989) looked into three studies that investigated the impact of lighting on crash frequency in freeways. A decrease varying between 17 to 40% in road collision was found when illuminated freeways were compared to unlighted ones.

Box (1970) conducted a theoretical cross-sectional study investigating 203 miles of illuminated and non-illuminated freeways in the regions of Toronto, Denver, Chicago, Atlanta, Dallas, and Phoenix. Box (1970) assumed that nighttime traffic accounts for approximately 25% of the total volume on an urban freeway and that nighttime traffic volume is one-third of that observed during the day. The study found a 40% reduction for all types of crashes nighttime. Another study done by Box (1970) investigated the relative effectiveness of different light levels. The night-to-day crash ratio associated with low illuminance values, fluctuating between 0.3 and 0.6 horizontal *fc* (3 to 6 *lux*), was statistically different from night-to-day ratios observed at higher illuminance ranges (0.8 to 1.1 *fc* and 1.3 to 1.5 *fc*). Surprisingly, the set of higher lighting levels was observed to have higher crash ratios; whereas, roads with low illuminance levels had lower crash ratios than dark freeways. According to Box (1970), higher crash rates observed at sites with high illumination values might have been caused by glare, but this hypothesis was not tested. Several explanations can be found in the literature as to what higher levels of lighting result into more collisions. CIE (1992) suggest that to achieve the higher light levels, fixtures will have to be placed closer to one another thereby decreasing the uniformity ratio. Having more light poles on the road, by placing them closer to each other might also simply provide more objects with which a vehicle could collide (Wilde 1994).

Wilde (1994) studied the impact of light upgrades for a 'before' period of two years and a one year 'after' period for a six lane, 5.3 mile length urban freeway. The results indicated that lighting upgrades were beneficial to safety. The night-to-day crash ratio observed were 3.0:1 and 1.3:1 for the before and after periods respectively in section A, and 3.1:1 and 2.1:1 night-to-day crash rate ratios for section B. (Wilde 1994). A cross-sectional study done by Lamm, Kloeckner and Choueiri (1985) on a suburban freeway in Germany investigated the impact of the presence of lighting fixtures and reductions in lighting levels. Many difficulties related to data interpretation were encountered during this study (which was conducted from 1972 to 1981) mainly because of changes that couldn't be controlled for during the period of study. Some of these factors have been correlated to reductions on observed accident frequency because they correspond to actual evolvement of maturity practices at the country level (Amador and Willis 2013). The major drawback of this study as well as many others such as Bruneau and Morin (2005) is that it assumed that lighting is maintained to national standards during the study period (that is an average luminance of 1 cd/m² and a minimum-to-maximum uniformity ratio of 0.7). The study found that the provision of lighting from dusk to dawn in the after period has been found to decrease night-time collision rates when compared to the before period. A decrease in the period of illumination was observed to increase accident frequency significantly when compared to roads illuminated for longer periods during the night (Lamm, Kloeckner and Choueiri 1985).

Five year cross-sectional studies, from 1985 to 1990, conducted by Griffith (1994) looked into the effect of lighting on urban freeways with continuous and interchange only lighting. Crash rates were broken into seven categories: 1) all crashes, 2) serious crashes, 3) injury crashes, 4) property crashes, 5) property damage only (PDO) crashes, 6) interchange area crashes, and 7) non-interchange area crashes. It was observed that freeways with continuous lighting were found to have statistically less night-time collisions when compared to freeways with interchange only lighting. A reduction of 16% in collision frequency was observed on segments that are continuously lighted and located between interchanges. Both sections had the same distribution of total vehicle miles travelled which was also true for the traffic volumes. Moreover, Griffith (1994) assumed that all other exogenous causal factors that might have an impact on road collision frequency were the same for the sections given that they are adjacent to each other. It was observed that PDO collisions on lighted interchange-only segments were 19% higher than continuously lit freeway sections; no significant differences were observed for other types of severities. An 18% higher collision frequency was observed for road segments only illuminated at the intersections as compared to the continuously illuminated ones. PDO crashes were found to be 32% higher at non-interchange parts of the freeway with interchange-lighting-only when compared to similar areas but with continuous lighting. The differences in serious injury and total injury crashes were not significant between these sections.

A study conducted by Bruneau and Morin (2005) investigated the impact of different lighting positions situations. Partial and complete interchange-only lighting settings and continuous lighting on Canadian rural freeways were looked at in this study. A sample of 213 freeway sections, with 800 km length and 4 lanes, along with an eight year crash data (1990 to 1998), was considered by taking into account the different types of severity being total collisions, PDO collisions, and fatal and injury crashes. Smaller crash ratios were observed for continuously illuminated freeway segments. The crash ratios were 33% ($p < 0.001$) and 49% ($p < 0.05$) for continuous and interchange-only lightings respectively when compared to unlighted similar sites. When compared to dark sites, a significant 33% ($p < 0.05$) reduction in the total collision frequency is found for freeway segments with continuous lighting. Also, a similar result (32%) was obtained for continuously lit segments when compared to interchange-only illumination. No significant difference was found between complete and partial interchange lighting. Variation in traffic volume doesn't result in any changes in the aforementioned results. A significant decrease in PDO crashes was found when continuous lighting segments were compared to interchange-only illuminated sections and dark freeway segments, with 35% and 43% respectively. More severe night-time road crashes, such as injuries and fatalities, were inconclusive when compared to the aforementioned different light settings.

In 1973, Sabey and Johnson, conducted a before-after study on forty-three trunk (national) roads in England investigating the effect of light upgrade or provision, following national standards practiced at that time. The roads were classified based on posted speed limit. They found that, in general, crashes were reduced after new lighting was provided. Sabey and Johnson (1973) showed that for 70 mph roads, the estimated savings (from reduced crashes) turn out to be approximately three times the annual cost of lighting.

Another type of investigation was done by Monsere and Fischer (2008) where they looked at the effect of downgrading and/or removing lighting units on highway segments. A significant 29% increase in the number of collisions occurring during night-time was observed at locations where lighting was reduced when compared to similar road segments with the original lighting levels. Interestingly, a 23% decrease in severe daytime road collisions were observed at site where lighting was reduced ($p < 0.05$).

Another study conducted in the Netherlands by Wanvik (2009), investigated whether the presence of lighting on roadways had an impact on injuries resulting from road accidents. A 50% decrease in nighttime injuries was observed in illuminated roadways when compared to non-lit ones. Collisions involving non-motorized road users were observed to be less in numbers for illuminated roads when compared to dark sites. Also, bad weather conditions seem to increase the number of non-motorized accidents in the same sites with the same lighting levels.

A before-after study conducted by Cornwell and Mackay (1972) examined the impact of roadway lighting upgrades in urban and rural routes on the frequency of motorized collisions, which was observed to significantly decrease in both areas. Results obtained were such that a slightly larger decrease in road crashes (30%) was observed in rural roads when compared to urban routes as a result of improvements done to existing lighting levels. Similar results were found by Box (1989) in a before-after study where light provision significantly reduced the number of nighttime crashes (30%). The impact of lighting presence in intersections was investigated within the same study as well. It was found that 15% more night-time collisions occurred at unlighted intersections when compared to illuminated intersections. Also, in terms of urban and suburban intersections CIE (1992) found that previous studies always indicate that lighting is beneficial to safety.

A before-after study of illuminance at intersections conducted by Oya, Ando and Kanoshima (2002) has showed a clear benefit of lighting at major urban intersections, with a statistically significant reduction in the after period for light levels at or above 30 lux, but not for lower lighting levels.

In 2008, Monsere and Fischer looked into the impact associated to decrease in lighting levels on freeway interchanges in Portland. They looked into the impact of reducing lighting levels from "partial plus" to partial lighting, and from full lighting to partial lighting. The authors defined the concept of "partial plus" as the level between full and partial lighting. A reduction of the level of lighting from full to partial was found to be statistically significant, $p < 0.05$, in decreasing daytime crashes and increasing nighttime accidents. Such a decrease in the level of illumination is found to decrease all daytime accidents by 2% and to decrease injury characterized collisions by 9%. On the other hand, an increase of 2% is observed in all night-time accidents, and a higher observed percentage of 12% for injury accidents. A further reduction in the level of lighting (*i.e.* from "partial plus" to partial lighting) was observed to decrease significantly all of daytime and nighttime injury collisions as well as all night-time collision frequency by 14%, 40% and 35% respectively.

Bruneau and Morin (2005) concluded that standard and non-standard levels of lighting contribute to less frequent collisions; however, their definition of standard is not based on photometric or illuminance measurements but rather on the presence of a lamp attached to a lighting pole (standard) or a utility pole (nonstandard). This has been criticized by Rea *et al.* (2009) from the lack of considerations on spacing height and actual levels of illuminance.

Even though lighting is widely accepted as a countermeasure, the cost of its provision is very high because it involves the construction and maintenance plus the energy that is consumed. Some cities have installed dimmers to reduce the consumption of energy. Other cities like Dubai have recently decided to turn off street lighting at straight segments of local streets (not curves nor intersections) with very low traffic flow (The National UAE, 2014). A similar policy had been implemented in UK where about 75% of the municipalities are implementing a similar policy (Dailymail 2010), other cities such as Edmonton in Canada are timidly testing the technology (City of Edmonton 2014) through a pilot project in the community of Woodcroft. European companies are actively promoting the use of dimmers and other technology to save energy on their roads (E-streetlight 2014). The major drawback when applying this system is the possible reduction of security when the light turned off, which could results in an increase in the rate of nighttime crime at those locations.

Investigation of more realistic roadway lighting and driver scenarios was recently conducted through the aid of computerized software (Rea, Bullough and Zhou 2009). This software can account not only for fixed lamps but also for other cars' headlamps and commercial lighting. Its results showed that low and high speed intersections should be illuminated; older drivers in particular benefit more when illumination is given to high speed roads.

Most researchers have looked into the impact of light provision or upgrading. Many used terminology such as "good lighting" which often refers to the national standard at the time of evaluation (Rea *et al.* 2009). It appears that uniformity might be problematic and that further research might be necessary to know its true impact on road collision; other studies have been unable to find explanatory power on it (Jackett and Frith 2013).

Scott (1980) observed that roadway luminance and night-to-day crash ratios are statistically related, where an increase in average luminance of 1.0 cd/m^2 causes a 35% decrease in nighttime crash ratio. In his experiment, a mobile lab with a closed-circuit television system recorded the field of view from the driver's perspective. Average road surface luminance, overall uniformity, and average luminance level of the area surrounding the roadway data were extracted from the videotape. A data logger recorded veiling luminance (disability glare) and both horizontal and vertical illuminance at the road surface and at 0.3 m above the road surface, respectively. However, night measurements were made late at night to minimize the influence of vehicle forward lighting. Average road surface luminance and surrounding luminance were found to be highly correlated with horizontal and vertical illuminance, while metrics of disability and discomfort glare were not. Using data on average road surface luminance, overall uniformity, and surrounding luminance, Scott (1980) fitted each possible combination to see how incorporating each variable affected a model to predict night/day crash ratios. While overall uniformity alone was not strongly related to the crash ratio, its addition to models already containing either of the luminance measures did significantly improved the goodness of fit.

With respect to the average road surface luminance, it was found that a range of pavement luminances between 1.2 and 2 cd/m² resulted in significantly lower night/day crash ratios (about 20% to 30% lower) compared to lower ranges of luminances (between 0.3 and 0.9 cd/m² and between 0.9 and 1.2 cd/m²). The data also revealed a monotonic trend in terms of lower crash ratios with increasing surrounding luminance. With regard to uniformity it was found that increased uniformity of illumination was associated with higher nighttime crash risk, but the range of uniformity levels was not large and therefore not likely to be useful in predicting degrees of uniformity outside the range that was studied.

The most recent study of safety and lighting was conducted by Jackett and Frith (2013) in urban streets in New Zealand. The study lacks a random sample selection and instead is based on an arbitrary selection of sites with at least 10 collisions (injuries and PDOs). In addition, streets were chosen only if they exhibit similar levels of lighting along their length. Not surprisingly the study finds that uniformity ratios are not a significant variable. The study uses night-to-day-ratios as response which in a sense captures the relative deficiency on lighting from a frequency perspective. This study also looks into the color of the light source. Even though this study is a first step in the right direction, given that they use the calibrated camera, it lacks from the suggestion of methods to unite safety statistical analysis and warrant or lighting levels and is content only with the study of accident rates reductions with increments on luminance.

2.5 Roadway Lighting Levels Identification

2.5.1 International roadway lighting regulations

Lighting systems in different regions of the world are compared in this section. The aim was to identify opportunities for improvement in North America's lighting levels. The design guidelines used in Australia-New Zealand, Europe, and Japan were compared to IESNA RP-80 (2005) used in North-America (USA and Canada). Australia-New Zealand follow AS/NZS1158 (AS/NZS. 2010), while Europe follows UE 13201 (CEN. 2004) and Japan follows JIS Z 9111 (JSA. 1988) as shown on Table 2.1 below.

Table 2.1 Comparison of Roadway Lighting in Developed Regions of the World

Element	North America	Europe	Japan	Australia/Nz
Illuminance	Per functional classification and presence of non-motorized vehicles, uses pavement reflectance.	Per traffic flow, operating speeds, type of users and environmental characteristics. Includes a surrounding value just outside edges of road.	For road with pedestrians and intersections (average maintained), for segments consider Illuminance-based uniformity	For intersections. Functional classification based on operational characteristics (Jackett, Consulting and Firth 2012)
Luminance	Per functional classification and presence of non-motorized vehicles	Per traffic flow, operating speeds, type of users and environmental characteristics	For type of vehicles, depending on characteristics leading to functional classification	Specific consideration for straight segments and curves less than 100m and intersections
Longitudinal Uniformity	Per functional classification and presence of non-motorized users. Two ratios for luminance, max to min and average to min.	Wet and dry circumstances for the classes defined for luminance/Illuminance. One ratio: average to min.	Dry only, per functional classification	Yes per subcategory
Transversal Uniformity	Not considered	Considered per road category (AADT)	Per road functional classification	Yes per subcategory
Glare	Veiling Luminance ratio	Threshold Increment: light from luminaire shining on drivers eyes	Glare control mark	Threshold Increment
Other – specific elements	Pavement type, four design approaches	Face recognition(presence of pedestrians), color rendering	Modification of values when environment around road is dark (land use)	Does include underpass, tunnels and tree lining roads. Luminaire Asset Management maintenance. Control upward waste lighting (sky glow).

The system followed by Australia and New Zealand is somewhat similar to that followed by North-America (USA and Canada) in the sense that pavement reflectance is considered and roads are categorized according to their functional characteristics. New Zealand and Australia have a very similar system with specific considerations for straight segments, curves of less than 100m radius and intersections. This could be interpreted as a need to further count with specific detailed values, and as seen in the following section, will translate into the need to count with a calibration method. In terms of levels, IESNA (2005) defines four different design methods based on illuminance, luminance, and control mark. Meanwhile Australia and New Zealand also define four design approaches: luminance and illuminance computer design, curve spacing chart, and design rule for isolated intersections. Austroads guidelines control upward waste of lighting (sky glow) which is not done by IESNA (2005).

Europe follows a more complex system in which each road is required to be characterized in terms of the traffic volume, speed, main allowed and not-allowed users (including non-motorized), geometry (including type of junctions, interchange spacing, conflict areas, lane separation, conflict areas and traffic calming needs), and environment and external influences (land use, main weather type). Europe's approach can be thought of as a system with an eligibility requirement based on the aforementioned characteristics. This also represents an opportunity to incorporate such initial filters in the warrant of roadway lighting.

Another interesting fact is that the European guidelines consider the transitioning between different lighting situations, and provide specific guidelines of how to move between them. In terms of levels and its values, Europe follows a more conservative scheme with lower uniformity variations and higher average illuminance for complex/dangerous circumstances or locations. For instance, European guidelines may go up to 50 lux, while IESNA's maximum average recommended value is 34 lux at intersections. There is, however, a problem with having higher average values, which is that there is a higher likelihood of having uniformity issues or glare.

The European norm considers the prevalent type of weather (dry or wet) when deciding the need to provide illumination and for the amount and characteristics of the lighting to be provided (wet uniformity). This kind of consideration seems to go best in line with Canada's needs. IESNA's regulations are simpler and more straight forward than European ones. However, this translates into an excess in generality of North America's lighting practices, and an opportunity to count with a calibration method. The other learning element found in this critical review is that of an eligibility filter to be incorporated at the beginning of the decision making process for the warrant of roadway lighting. It is interesting to notice how Japan utilizes illuminance-based uniformity for roads with no pedestrians (*i.e.* highways). A similar conclusion is found in the results of this research.

2.5.2 North America's roadway lighting regulations

There are two types of guidelines in North America; one for the warrant of roadway lighting (AASHTO 2005) which is based on a grid system, and one for the allocation of lighting (IESNA 2005) based on minimum recommended levels of luminance and illuminance, and maximum permissible uniformity variation ratios (Table 2.3 and 2.4). This research is concerned with the local calibration of the grid system and the identification of lighting levels. The Warrant system consists of five grids (G): highway segments (G1), highways plus intersections (G2), national, regional, collectors and local roads (G3), freeway interchanges (G4) and intersections (G5). The system is based on scores from a multitude of geometrical, operational, and functional factors as well as security considerations; Table 2.2 illustrates the grid G1.

There is another system originally proposed by the NCHRP Report 152 (Walton 1974) which applies an analytical cost benefit approach (Preston and Schoenecker 1999). Even though the grid system comprises many elements, it fails to include severity; it also does not consider current lighting levels, as could be the case when non-standard lighting levels may be present on the road. In such cases, an increase on the level of lighting may turn out to be the solution to reduce nighttime collisions.

Table 2.2 Grid Assessment System for Quebec (Transports Quebec. 2012)

Evaluation Grid (G1)									
Evaluated Element									
Length of Segment					Level (1, 2 or 3)				
Description of Analysed Criteria		Real Value	Classification Points (PT)					Score (PD)	Scored Value = PD*PT
			1	2	3	4	5		
Geometry									
1	Total number of lanes		≤4	5	6	7	≥8	0.15	
2	Lanes width		>3.6	3.4 to 3.6	3.2 to 3.4	3.0 to 3.2	<3.0	0.30	
3	Median Width		>12	7.5 to 12	3.5 to 7.5	1.2 to 3.5	<1.2	0.30	
4	shoulder width		>3.0	2.5 to 3.0	1.8 to 2.5	1.2 to 1.8	<1.2	0.30	
5	Slope (from 0 to 7)		>6:1	6:1	4:1	3:1	<3:1	0.30	
6	Horizontal curve radius		>3500	1750 to 3500	875 to 1750	575 to 875	<575	4.90	
7	Vertical gradient		<3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 7.0	>7.0	0.25	
8	Frequent interchange distance		>6.5	5.0 to 6.5	3.5 to 5.0	1.5 to 3.5	<1.5	1.85	
Subtotal									0
Operational									
9	Level of Service (Night-time)		A	B	C	D	≥E	3.05	
Subtotal									0
Environment									
10	% of Developments		0	0 to 24	25 to 50	50 to 75	>75	1.85	
11	Distance to developments (e.g. residential, commercial, or industrial buildings)		>60	45 to 60	30 to 45	15 to 30	<15	1.85	
Subtotal									0
Security (Accidents)									
12	Night-to-day accident ratio		<1.0	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	>2.0 (see Note 1)	4.90	
Subtotal									0
Notes: 1.Provision of lighting 2. Current speed: 80kph (95% of night-time operational speed if available, otherwise use the posted speed) 3. Development is defined based on the presence of commercial, industrial, or residential buildings. 4. Use the most deficient geometrical characteristics for road segments.						Grand Total			
						Required Scoring to provide lighting			60

Table 2.3 Illuminance Criteria Recommended by Type of Road (IESNA 2005)

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

IESNA RP-80 (IESNA 2005) recommends the use of the illuminance criteria (Table 2.3) for intersections and of the luminance criteria given on Table 2.4 for road segments. The analysis presented in future chapters of this thesis supports the view that illuminance is inadequate for road segments, but finds its uniformity to be important.

In terms of lighting levels, the Transportation Association of Canada (TAC) and the province of Quebec follow those suggested by IESNA (Transports Quebec 2012). There are two types of lighting systems as discussed by Rea, Bullough and Zhou (2009); extended and localized, whereas extended refers to a continuous system, and localized implies only one lamp at a given point, commonly a rural intersection.

Table 2.4 Luminance Criteria – Recommended Levels (IESNA 2005)

Road and Pedestrian Conflict Area		Average Luminance (L_{avg}) (cd/m^2)	Uniformity Ratio L_{avg}/L_{min} (Maximum Allowed)	Uniformity Ratio L_{Max}/L_{min} (Maximum Allowed)	Veiling Luminance Ratio L_{Vmax}/L_{avg} (Maximum Allowed)
Road	Pedestrian Conflict Area				
Freeway Class A		0.6	3.5	6.0	0.3
Freeway Class B		0.4	3.5	6.0	0.3
Expressway	High	1.0	3.0	5.0	0.3
	Medium	0.8	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Major	High	1.2	3.0	5.0	0.3
	Medium	0.9	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Collector	High	0.8	3.0	5.0	0.4
	Medium	0.6	3.5	6.0	0.4
	Low	0.4	4.0	8.0	0.4
Local	High	0.6	6.0	10.0	0.4
	Medium	0.5	6.0	10.0	0.4
	Low	0.3	6.0	10.0	0.4

A comparison of the grid systems was prepared in order to find out the most significant factors influencing the decision process of lighting provision across different kind of sites (*i.e.*, intersections, road segments, et cetera) and is presented on Table 2.5. Shaded cells represent those factors with a large impact on the corresponding grid. In general across the grids, night-to-day ratio is the most utilized factor across all grids followed by external lighting, curvature and level of non-motorized activity. Others, such as slope, interchange frequency and et cetera are also considered.

Table 2.5 Comparison of Warrant Grids and Largest Contributing Factors

Criteria	G1: Highways	G2: Highways+inter sxns	G3: National, Regional, collectors, local	G4: Freeway interchange	G5: Intersections	Parameter unique to grid #
Geometry						
Total number of lanes	x	x	x	x		
Lanes width	x	x	x	x		
Median Width	x			x		
shoulder width	x	x				
Slope (from 0 to 7)	x	x				
Horizontal curve radius	x	x	x	x	x	
Vertical gradient	x	x	x	x		
Frequent interchange distance	x					G1
Visibility Distance		x	x		x	
Opening within median			x			G3
Private entrance/exit			x			G3
Parking			x			G3
Type of interchange				x		G4
Route Channelization				x	x	
Lateral Lane				x		G4
Visibility Distance (from transversal road to the intersection)				x		G4
Angle of offset intersections					x	G5
Number of approaches					x	G5
Angle of approach					x	G5
Channelization					x	G5
Operational						
Service Darkness level (traffic time for darkness)	x			x		
Frequency between interchanges and intersections	x					G1
Turn lane						
Median Width		x	x			
Average speed or posted speed limit		x	x		x (major road,	
Level of Non-motorized activity (e.g. cyclists, pedestrians) during highest nighttime period		x	x			
Intersections with traffic lights			x			G3
Left turn lane			x			G3
AADT both directions					x	G5
Nighttime pedestrian flow per hour					x	G5
Network classifications involved					x	G5
Environment						
Distance to developments (e.g. residential, commercial, or industrial buildings)	x	x	x	x		
% of development		x	x			
Zone type		x	x			
External lighting (other than road lighting)		x	x			
Median with border		x	x			
Presence of development				x		G4
Lightning of transversal roads				x		G4
Highway lightening				x		G4
Development lit within a radius of 100m from the intersection					x	G5
Security (Accidents)						
Night to day Accident ratio	x	x	x	x		
Average Annual nighttime accidents or rate for last 3 years (accidents only related due to poor lighting)					x	G5

Note: Cells highlighted in grey have high scores

2.5.3 A critical review of the state of the practice in North America

The first predecessor of North America's lighting warrants was proposed by Walton in 1974 through a national cooperative research program project aimed at the establishment of a standardized method for warrants of highway lighting. In this report (NCHRP-152) Walton proposes the use of a warrant system based on a score system that considers the geometric, functional and operational characteristics of any highway segment under consideration. Additionally, appendix D of NCHRP-152 presents the possibility of using a cost-benefit analysis as an optional alternate to the score system. Table 2.6 illustrates the historical progression of lighting warrants.

Table 2.6 Historical Progression of Lighting Warrants in North America

Year	Title	Author	Relevance
1974	Warrant for Highway Lighting	NCHRP-152	Foundation, suggested use of benefit cost on its appendix
1976	Roadway Lighting Design Guide	AASHTO	Warant system
1978	Lighting Handbook	FHWA	Federal Government
1979	N.Y. State DoT policy on Highway Lighting	New York State	Adopt AASHTO warrant
1983		FHWA	Addendum
1984		AASHTO	Addendum
2003	Texas DoT Highway Illumination manual		Creates additional warrant criteria
2005		AASHTO	Latest version
2006	Guide for the Design of Roadway Lighting	TAC	Adopt AASHTO warrant
2009	Guidelines for Roadway Lighting based on safety benefits & Cost	NCHRP-05-19	Terminated prematurely, argue not all states data on benefits (before-after studies)
2010	Minnesotta DOT Roadway Lighting Design Manual	Minnesota DoT	Creates additional warrant criteria
2012		New Jersey	Creates additional warrant criteria
2013		CALTRANS	Investigates uses of additional criteria, or simpler method
2015?		AASHTO	Expected revision, apparently warrant remains unchanged

In 1976 the American Association of State and Transport Officials (AASHTO) launched the official guidelines for roadway lighting, followed by the Federal Highway administration in 1978, both of them based upon the NCHRP-152 (Walton 1974). In 1979 the state of New York adopted the guidelines and many other states followed throughout the years. Minor modifications were introduced to the AASHTO guidelines in 1984 and the FHWA in 1983. It was in 2003 when Texas Department of Transportation became the first DOT that questioned the guidelines and extended them by creating additional warrant criteria, other states followed. AASHTO published the latest version of its lighting guidelines in 2005. In 2006, TAC in Canada created its own version based on the aforementioned publication with no significant changes. According to a 2013 report of California DOT, it is expected that AASHTO will publish a revised version this year, but no changes in the warrant system are anticipated as much of the attention has been devoted to the role of new technology such as LED and to develop regulations for the automatic dimming of street lights.

A review of the guidelines developed by several states from 2003 to date (Figure 2.2) revealed that most of the additional criteria is a simple modification of the existing factors by changing the score values or reducing the number of elements used in the warrant. This fact suggests the need for local calibrations of such elements. Interviews with Quebec MTQ revealed that the application of the current warrant system criteria sometimes resulted in unexpected decisions, which is another evidence of the lack of calibration to local circumstances. Two other elements were found in the review of DOTs guidelines: first there is a need to verify that the proposed levels of lighting are effective in reducing the number and severity of road collisions as suggested by Oregon DOT. Second there may be a need to count with a filtering system that enables experts to conduct an initial identification of the sites possibly requiring lighting. For instance, some states suggest the need to light all urban areas; perhaps such disposition could be used as an initial filter of eligibility and the locally calibrated warrant system would be applied afterwards.

Type of change	Proposed by	My Conclusions
Complex Geometry configuration	Illinois, Minnesota, Oregon (**higher levels**)	It is on Grid. ***Need to be calibrated*** ***Need to revise levels***
Custom Nigh to Day Ratio (NDR)	New Jersey, Minnesota, Pennsylvania, Washington State	It is on Grid, ***Need to be calibrated***
AADT	Texas, Minnesota	It is on Grid as LOS, ***Need to be calibrated*** ***Surrogate for LOS***
Interchange spacing	Texas, Florida, New Jersey	It is on Grid, ***Need to be calibrated***
Land Use	Texas, Pennsylvania, New York, New Jersey	It is on Grid ***Need to be calibrated*** ***Surrogate for Development***
Eligibility	Texas	**NOT** on Grid. ***Could be added as filter***

Figure 2.2 Justification for the need of a calibration method

The need for a local calibration is the main result from this critical review of the DOT's current practices. Its detailed explanation is presented in chapter three. Finally, it is of interest to mention that there is an alternate method for the warrant of lighting based on benefit-cost analysis. Such a method, however, suffers from one major drawback. It requires the estimation of lighting benefits, which in turn implies the need to count with before-after studies to be able to estimate the reduction in accidents. Not all states count with such information, however it is impossible to rule-out such type of analysis from a theoretical perspective. The approach was initially proposed in 1974 by the NCHRP-152 and revised by the NCHRP-1509 (Rea *et al.* 2009) which was prematurely terminated.

2.5.4 The state of the art and advancing the state of the practice

The state of the art and the practice match almost perfectly in the field of lighting warrants and levels. With the only difference of the research conducted by Rea *et al.*(2009) which is at the upper front of the state of the art. Rea *et al.* (2009) proposes the use of a benefit-cost approach to justify lighting decisions. This method has not been yet implemented by practitioners and the project was actually prematurely terminated. A critical review of his propositions reveals that his method is difficult to implement in practice because it requires the estimation of benefits employing among others before and after studies which are data hungry and imply the use of longitudinal data (Figure 2.3). This doctoral thesis adapted the ideas of Rea *et al.* (2009) and instead proposes the use of evidence-based analyses that in the kernel also capture the safety effects of lighting decisions by estimating the explanatory power of several variables over two types of responses (frequency & severity). Figure 2.3 presents the improvements to the state of the practice incorporating the method presented in this research and keeping the use of the benefit-cost approach as an alternate method to justify lighting decisions. As can be seen, the eligibility requirement was incorporated in lighting warrants as an initial filter and the need was suggested to conduct a local calibration of the grid system. This calibration is divided in two: one for current roads (with the inclusion of the night-to-day accident ratio) and another one without it for new highways. It is important to note that the use of a benefit-cost analysis could be employed in either case. It is also crucial to emphasize that the use of custom-tailored criteria, as currently found in the state of the practice, is arbitrary and subjective and hence unjustifiable because it lacks a connection to the root of the problem; nighttime collisions. A locally calibrated grid and design levels can adequately identify when to count with lighting and what levels are required to effectively reduce nighttime crashes.

Proposed by	Type	Based Upon	Critiques
Walton NCHRP-152 1974	Warrant based on scores	Functional, Operational, Geometric & collision ratio (nigh-day)	• Difficult to estimate % and distance to development • May not make sense
Rea, NCHRP 0519 2005-2009	Benefit-Cost	Estimation of benefits and cost	• Difficult to quant. benefits • Requires before-after • For specific sites
State DOTs 2002 - 2012	Custom tailored Criteria	AADT levels, NDR value, LandUses and Interchange spacing	•
Aldulaimi, FQRNT- MTQ-FQRS 2013-2015	Evidence-based Local Calibration	Statistical Analyses → Adjust scores & levels	• **Could use surrogates** • **Reduced Size Warrants** • **Only uses available data** • **Connected to causes** • **Expected to be effective**

Figure 2.3 Advancing the State Of The Art on Lighting Regulations

2.6 Summary of Literature Review

As seen on Table 2.7, studies for lighting can be traced back to the 1970's with Box looking into crash rates and levels of illumination. Many others followed up until today, with Jacket and Frith (2013) finally suggesting that crash-rates could be used to estimate levels of lighting. Measuring lighting has been one of the major challenges; given the difficulties, few researchers have studied this field. It was only recently that digital cameras became capable of being calibrated to measure luminance. The majority of the studies conducted until today were done in developed countries such as USA, Canada, Germany, Greece, Australia & New Zealand, France, and Japan. They look at two major areas, effectiveness of lighting and relationship between different characteristics of lighting and road collisions. Highway features consistency is an important element in traffic safety and inconsistency in road features tends to increase the frequency and the severity of road crashes (COMT 2013), (TAC 2004) and (TAC 1999). Traffic volumes, presence of intersections, undivided roads, complex alignments with limited visibility, presence of animals, and dark locations and disability glare are the most recognized explanatory variables that have significant impact on crash frequency. However a combination of variables is always related to each accident (TAC 2004) (Sullivan 2009). Many conducted studies and reports acknowledge that the provision of lighting would increase visibility and considered it as a countermeasure to reduce the collisions frequency & severity.

Some of these studies found that higher frequency of pedestrian crashes are observed at sites with lower levels of lighting (Zhou and Hsu 2009) (Yannis, Kondyli and Mitzalis 2013).

International focus on lighting has shifted to energy consumption, light pollution, and the use of new technologies. Most researchers concentrate their attention in understanding the role of lighting and finding better methods to measure the effectiveness of lighting indicators. Only one recent study has suggested the need to connect crash-history with levels of lighting. Nobody has looked into developing a method to calibrate lighting warrants to crash history.

The literature review reveals some minor differences of design guidelines used in Australia-New Zealand (AS/NZS1158), Europe (UE 13201), and Japan (JIS Z 9111) as compared to IESNA RP-80 used in North-America. One of the important learning outcomes was that illuminance is used in sites with the presence of pedestrians (intersections) and luminance on sites with the presence of vehicles (luminance). However illuminance-based uniformities are used on sites with vehicles. Also the existing literature on lighting revealed that contrast differences between the brightest and darkest spots is related to amount of glare. These two facts are important for the interpretation of the results of this research. From the perspective of statistical models, it was learned that zero-inflated negative binomial was the most adequate method applicable to the cases studies of this thesis and that Full Bayesian regression modelling could be used for validation.

Table 2.7 Summary of Literature Review

Year	Author(s)	Type study, size, location	Findings
1970	Box	Cross Sectional, 203 miles (US, Canada)	Effects of lighting levels, night-to-day ratios
1972	Cornwell and Mackay	Before and After	Lighting upgrades, urban and rural
1973	Sabey and Johnson	Before and After	Lighting effectiveness
1976	Walton (NCHRP 152)	Cross sectional	Warrants and Cost Benefit method
1979	Cobb *et al.*	Cross-sectional	Lighting increase visibility
1985	Lamm, Kloeckner and Choueiri.	Cross-Sectional (Germany)	Impact of reductions on lighting levels
1989	IESNA	Several	Comprehensive literature review of lighting
1992	CIE	Several	Comprehensive literature review of lighting
1994	Wilde	Before-After	Impact of Lighting upgrades
1994	Griffin	Frequency and Severity	Continuous and intermittent (at interchanges)
1995	Elvik	Greece	Lighting as countermeasure
1999	Preston and Schoenecker	USA	Cost benefit method for lighting
2002	Oya *et al.*	Before and After	Urban intersections and lighting
2002	Ando and Kanoshima	Cross sectional	Lighting countermeasure
2004	Transportation Assoc. Canada	Several	lighting countermeasure
2005	Bruneau and Morin	Cross-sectional (Canada)	Impact of standard lighting
2006	IESNA	Several	Literature review of lighting and safety
2007	Armas and Laugis	Threshold Index	Luminance adaptation
2008	Monsere and Fisher	Before-after	Downgrading lighting
2009	Bulldough, Rea and Zhou	Simulation environment	Lighting increase visibility
2009	Zhou and Hsu	Levels of lighting	Illuminance and pedestrian collisions
2009	Sullivan	Cross-sectional	Lighting and animal vehicle collisions
2009	Wanvik	Netherlands	Lighting effectiveness, bad-weather
2009	Rea	USA	Cost benefit method for Warrants
2010	Isebrands *et al.*	Cross-sectional	Lighting effectiveness
2011	Hiscocks	Calibrated Camera	Calibrated Camera
2013	Yannis, Kondyli and Mitzalis	Cross-sectional	Lighting on Frequency and Severity
2013	Jackett and Frith	Cross Sectional (270 Km - New Zealand)	Effects of lighting levels, crash-history
2014	Nabavi *et al.*	Cross sectional	Looked at intersections in Montreal

2.6.1 Drawbacks and what is missing

The following is a summary of drawbacks and what is missing:

- Most of the studies were limited to small segments of roads, and some looked into road corridors. However, it was not possible to find a full scale study for the role of street lighting as a countermeasure for nighttime collisions of an entire province, state or country.
- The majority of previous experimental work was conducted with manual illuminance meters that is data logging in the past, which was done manually. Recent incorporation of global positioning systems into equipment capable of measuring data characteristics and its connection to handheld computers have recently enabled researchers to create large databases at the network level. There is a lack of research on large scale experiments containing geo-referenced luminance and illuminance.
- There are warrant systems and design guidelines followed by North America and other developed countries. However, there doesn't exist a method that calibrates the warrant system to give more importance to those factors that explain more frequent or severe accidents and the adequate levels for a design that is effective in reducing the accident frequently and severity.
- Many agencies and municipalities have modified the warrant system but this has been based on expert criteria and no method has been proposed to scientifically do this. No calibration for the guidelines, based on a statistical analysis, has been proposed.

CHAPTER 3 - METHODOLOGY

3.1 Introduction

New methods to calibrate the warrant system and identify recommended lighting levels are developed in this chapter. The chapter is divided into four main sections. The first section explains the procedure for data collection and processing, leading to the creation of spatial databases used in the statistical analyses. The second section includes details of the statistical analyses. The third section explains the connection between statistical analysis, the warrant system, and lighting levels. Finally, the last section presents two novel methods. The new methods used to calibrate the warrants and estimate levels use the database to feed statistical analyses responsible for the estimation of recommended levels and score values for the warrants as seen in Figure 3.1.

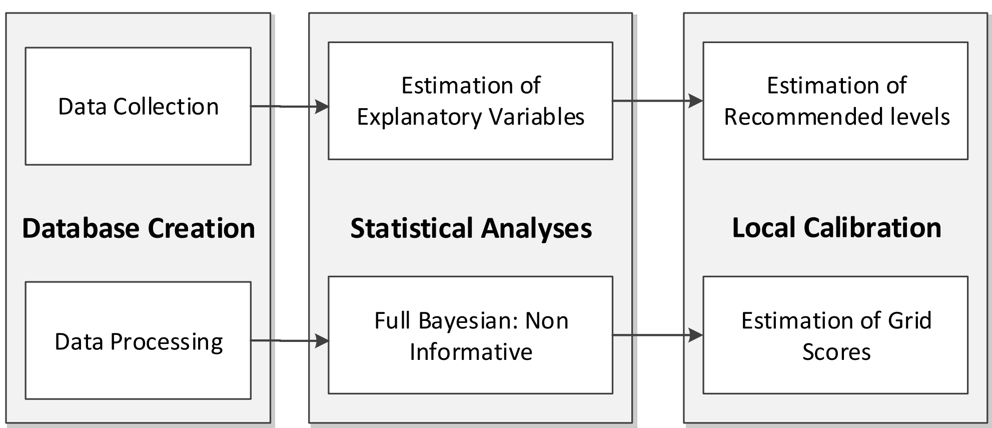

Figure 3.1 Overall Methodology

3.2 Creation of a Database for Safety Analysis and Lighting

Two databases were created for this research; the first one for the Arthabaska region and the second one for major highways throughout the province of Quebec (routes 20, 40, 55, 105, and 132). The first database was aimed for a pilot study in order to test the methodology. The Quebec network database was used for a case study to demonstrate the application of the method for local calibration. Roadway lighting measurements of illuminance (in lux) were collected for both regions. The first dataset is for a pilot study with a sample of approximately 95 km randomly selected roadways corresponding to several segment classifications in the Arthabaska region of Quebec. The second dataset is of approximately 2,500 km of highways along the main axis of Quebec's road network and will be used in the calibration of the grid system to local conditions for the entire province of Quebec.

The primary task of the data collection is to map roadway accidents and roadway lighting into road segments that already contained other attributes such as surface condition at the time of the accident, presence of heavy vehicles, geometry (horizontal and vertical curves), presence of intersections, number of lanes, posted speed, et cetera. Base maps for Quebec roads as well as roadway accidents were provided by the Ministry of Transportation of Quebec (MTQ). Roads used in this analysis corresponded to different functional classification, namely highways, arterial, collector and local roads. Each road was broken into 100m segments and both a count of accidents and an index of severity (as explained later) were created based on the record of accidents from the past 5 years. Minimum, maximum, standard deviation and average amount of illuminance (in lux) was assigned to each segment.

This research used segments of 100 m for the Arthabaska region in order to capture the precise location of intersections and of lighting levels and uniformity variations. This is contrary to previous research which did not go to such levels of detailed information and accuracy. For the case study of Quebec highways, this research used segments of 500m following conversations with MTQ that revealed possible inaccurate spatial location of collisions. Larger segment sizes seem to be ideal for the aggregation of accidents in order to avoid having a large number of segments with zero accidents. On the contrary, having too long of segments will prevent the ability to identify hotspots, which was not the aim of this research.

3.2.1 Data collection

Data for illuminance was collected while driving a vehicle and using two devices: *spectrosense* (Figure 3.2) and a GPS with the application *MyTracks* to assist the GPS. It is recommended that the driver starts and finishes at a stationary position for the data collection in order to have the same recorded geographical coordinates on both devices. The sensors connected to the *spectrosense* device were placed on the top of the car to capture illuminance. The car was driven at preferable constant speed to obtain illuminance measurements at constant intervals. The logger collected both illuminance and coordinates for about 50 minutes with a rate of 1 observation per second. A cell phone with an assisted GPS unit was used in parallel to have an extra set of coordinates to be used only if the spectrosense GPS failed.

For Arthabaska, 95 km of lighting data was collected covering the entire region for both illuminance and luminance and used for a pilot study later described in this thesis. For the Province of Quebec, the main highway network (routes numbered under 132) consisted of 9,225 km, so a 27% sample was selected (2,500 km) at the beginning of the research and data for illuminance was collected twice during winter and summer. Several tests were conducted in order to reduce the sample size without modifying the results given the high degree of difficulties encountered to collect lighting data. It was found that 800 km were enough to replicate the results obtained with

2,500 km. Data for luminance for this reduced sample of 800 km (1,600 segments of 500 meters) were collected between January and March 2015. Many difficulties were faced given the adverse weather conditions, safety concerns, and time of data collection. Winter data was selected given the adverse circumstances that motorists experience and increased likelihood of collision as observed in the crash history.

Figure 3.2 SpectroSense2+ Logger and Setup for Data Collection

Data for luminance was collected using a professional digital camera with a special lens filter (fish eye type, as shown in Figure 3.3), and specialized software capable of estimating average luminance (as perceived by the driver) and unified glare (Photolux 2012). Data collection followed the parameters established by JIS-Z-9111 (1988) in terms of the location of the camera (midpoint between luminaires), angle (2 degrees from horizontal sight of driver), height (1.5m), visual environment (capturing distance between 60 and 160 meters ahead, 90 m for intersections) and other specifications related to data collection already predefined in the system (seven continuous shots, with a variation of aperture and other photograph characteristics predefined and calibrated by the software provider).

Figure 3.3 Digital Camera with a Special Filter (Fish Eye Type) for Luminance

3.2.2 Data processing

Once finished collecting measurements, the data was then transferred to a computer where it was processed. As explained in Figure 3.5, there were three major steps in the processing: one related to the illuminance data, a second one dealing with the road network map, and the third with the accident database. The final purpose was to join lighting and collisions to the network's segments.

For luminance, the Photolux software processed pictures by reading the information stored in the header of the picture using the EXIF format (Photolux, 2012). This information included the aperture, time of exposure, and sensitivity. Photolux computes the exposure used on the picture to assign a value of luminance to each pixel which eventually results in a luminance map. This map represents the amount of luminance in candela per square meter and can be used to estimate the unified glare. Figure 3.4 illustrates the Photolux camera capabilities. The flowchart shown in Figure 3.5 illustrates the steps done for data collection of illuminance and luminance, data processing, and data analysis.

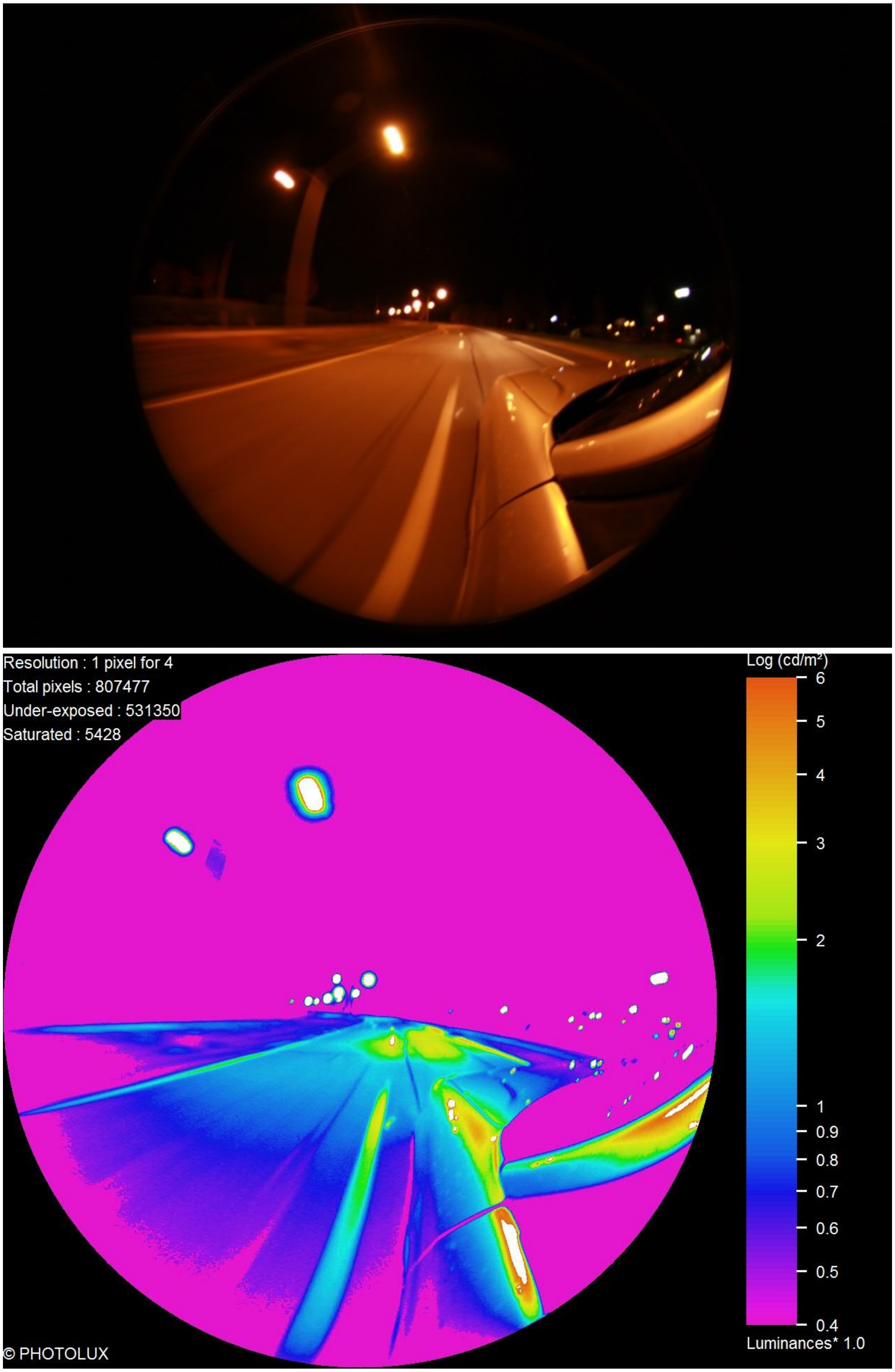

Figure 3.4 Luminance Map Generated by Photolux.

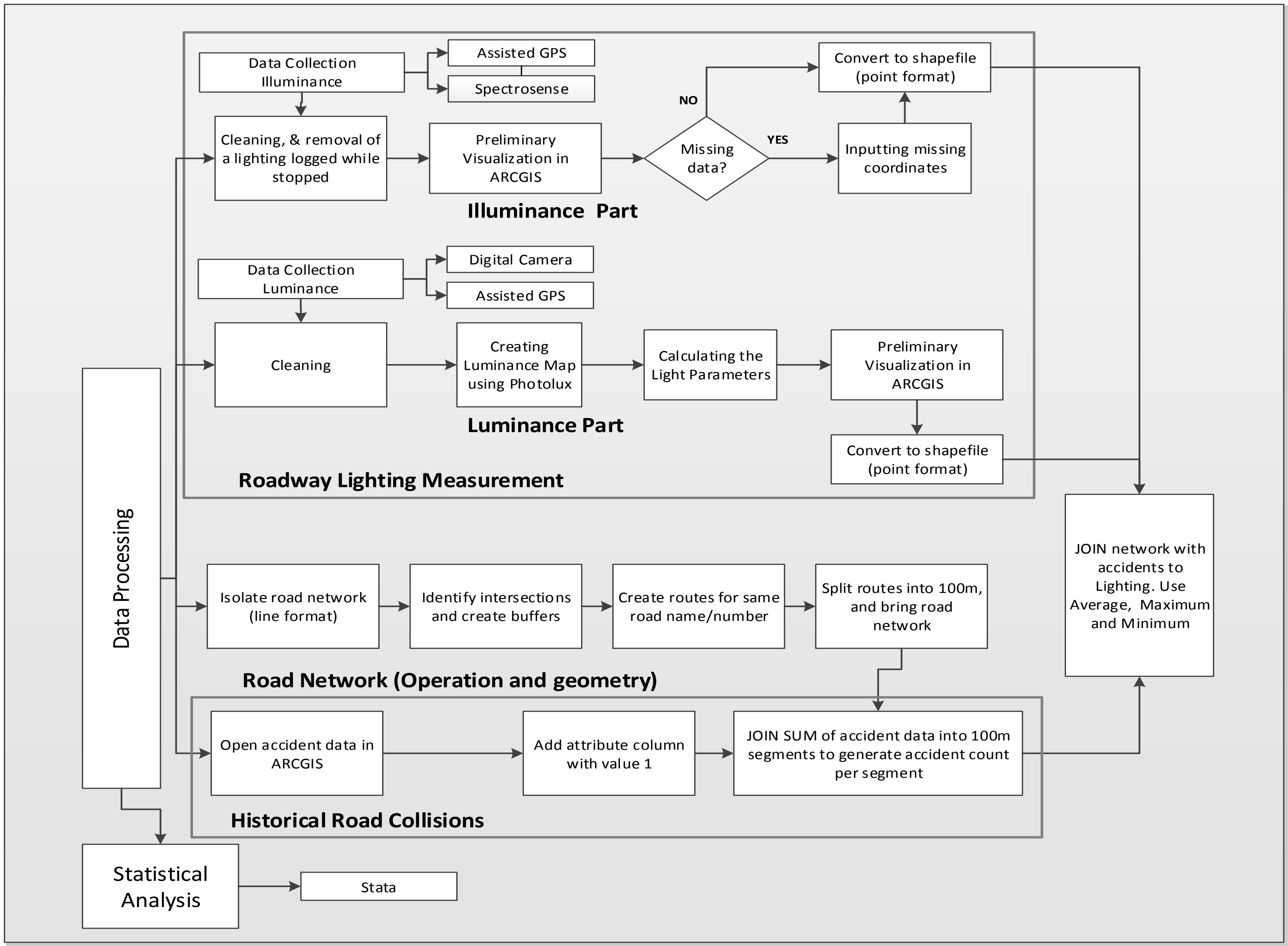

Figure 3.5 Data Collection, Processing, and Analysis (Illuminance & Luminance) Flowchart

3.3 Statistical Safety Analysis

3.3.1 Creation of a severity index

An economic value in Canadian dollars (C$) has been given to each type of road collision. The value came from a comprehensive collision cost study prepared by De Leur *et al.* (2010).

A new indicator for severity is proposed in this research, it is based on a semi-monetized expression of collision severity that has been normalized in order to avoid large values of over-dispersion that happens when direct monetary value is used as the scaling factor on the model. The indicator has been built in two steps: first the monetized collision value at a particular segment is used to obtain a scaling factor by normalizing everything in terms of major injuries. Secondly, normalized values are multiplied by 100 in order to move extremely small values away from zero and obtain a scale similar in orders of magnitude to that of accident frequency. Used values and factors are shown on Table 3.1.

Table 3.1 Severity Monetary Values and Index Weight to Build a Severity Index

Collision Severity	Economic Value ($)	Scaling Factor	Index Weight
Fatality	5,416,000	3.9	390
Major Injury	1,385,000	1	100
Minor Injury	30,581	0.0216	2.16
PDO Major	15,000	0.0108	1.08
PDO Minor	2,000	0.0014	0.14

3.3.2 Selection of the type of regression

Statistical analysis will be used for two initial models that will examine the correlation between accident frequency and severity with roadway lighting. The type of regression to be used in these statistical analyses depends on the type of data. Figure 3.6 shows the logical process followed to test for this; the first thing that one needs to identify is the distribution type of the response. If the distribution is continuous, then ordinary least squares (OLS) regression model can be used which is not the case. The next step would be to check if this dependent variable is inflated and has a high number of zero counts. If this is the case, then a zero inflated regression model should be used. If non-zero mean is observed in the predictor, then the analysis can be run using regular Poisson or Negative Binomial models. If the variance is greater than the mean, then Negative Binomial should be used. This is because the Poisson regression model assumes that there is no over-dispersion (*i.e.* mean = variance), whereas Negative Binomial takes into account over-dispersion. This criterion is also applicable when deciding on choosing zero inflated Poisson model or zero inflated Negative Binomial regression model.

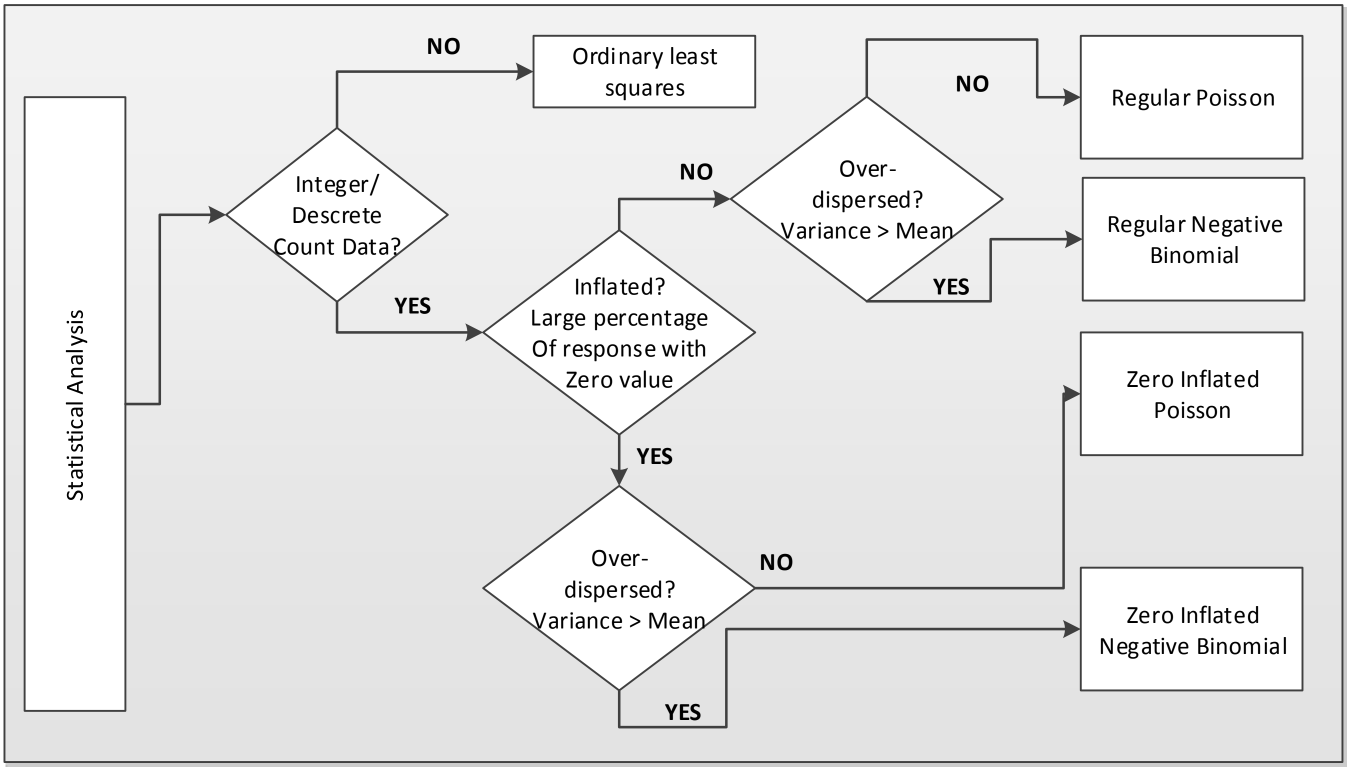

Figure 3.6 Statistical Analysis Flowchart

3.3.3 Division of road segment by levels of risk

A risk index can be based on the segments' deficiency or on other factors. Even though deficiency can be estimated from geometric characteristics, it may fail to capture other circumstances relative to unobserved operational or functional characteristics. This research proposes the use of a risk factor based on predicted number of collisions calculated as the value of each coefficient (of the explanatory variables) multiplied by the observed level of each variable. The coefficients are directly obtained from a statistical analysis which uses collision frequency as response and available road elements as causal factors. As such, the risk index will be based on the following factors, shown on Table 3.2.

Table 3.2 Weights Used In the Creation of a Risk Index

Predicted Frequency	Coef.
lnAADT	0.10
Number of lanes	0.11
Presence of Intersection	0.40
Average Lux Illuminance	0.00
Number of Heavy Trucks involved in Collisions	0.43
Wet Pavement	0.28
Snow Pavement	0.29
Iced Pavement	0.54
Slope	1.50
Average Posted Speed	0.02
Suburban	0.32
Urban	1.25
Standard Illumination	0.50
Presence of Animals	0.58
Functional Class	0.33
Total Width	0.04
Right Shoulder width	-0.24
Presence of Pedestrians	-0.34
Land Use	-0.23

The risk index will be used to create three levels of risk, as suggested by Peng and Lord (2011): low, medium and high. A longitudinal analysis for such groups was prepared to verify that the groups followed the expected trends (Figure 3.7). It was expected that the low level group experienced the lowest number of accidents and observed zero or declining trends across time, that the individuals at the medium group observed stagnant or slowly increasing trends of accidents, and that those at the high level observed growing levels and higher number of accidents. All these were confirmed by the data obtained and presented in Figure 3.7.

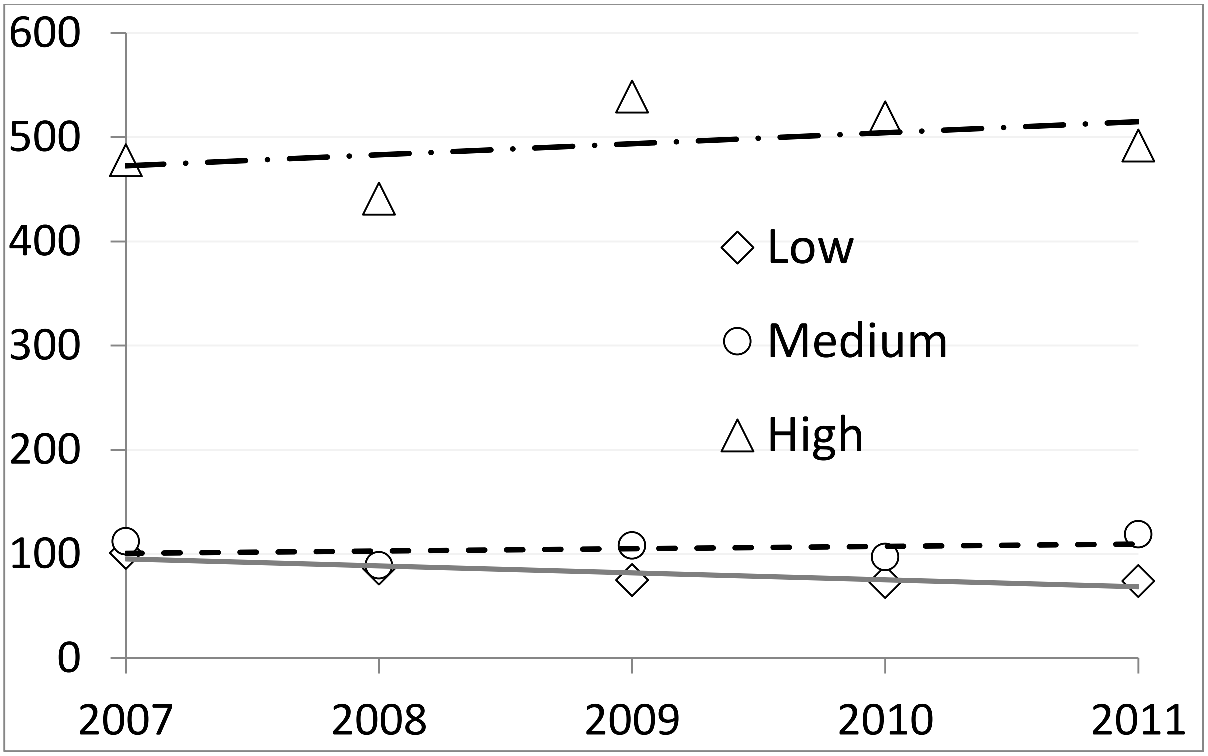

Figure 3.7 Longitudinal Analysis of Accidents

A mapping of the location of the segments also revealed good agreement with prior expectations of having higher risk segments concentrated at intersections of urban areas as shown in Figure 3.8.

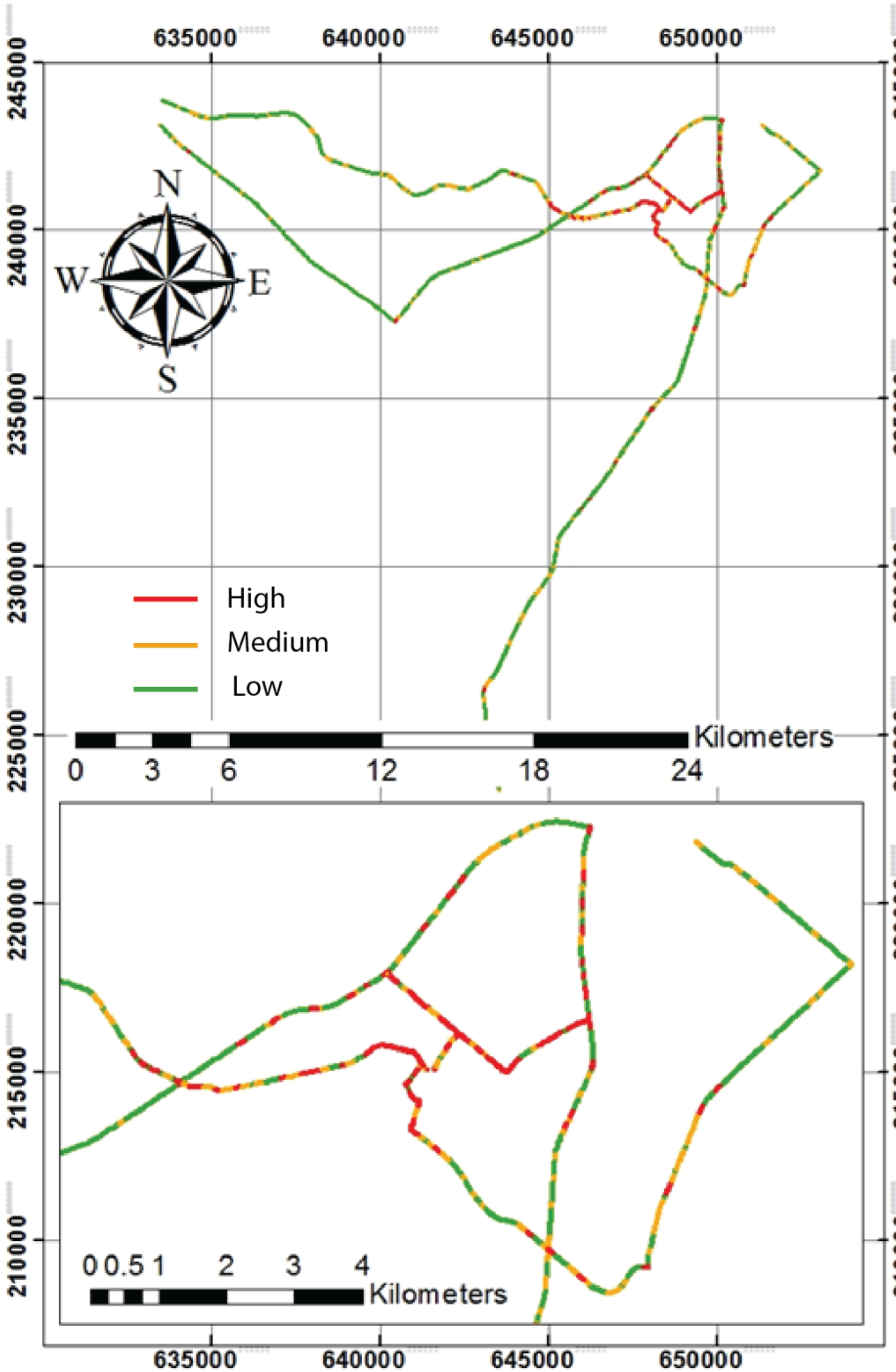

Figure 3.8 Risk Indicator for the Arthabaska Network.

3.3.4 Validation using a F. B. Non-informative model

A maximum likelihood statistical analysis was validated by a Full Bayesian regression analysis with non-informative approach. A comparison of the values of the coefficients for the explanatory variables of both analyses will be used to validate the use maximum likelihood approach to conduct a local calibration of the grid system's weights, as further explained in the following section. It is expected that for a pilot study of the same data, both analyses should reach similar values of the coefficients of the explanatory variables, meaning that their contribution to explain collisions is the same. Having surpassed such tests, the results from either approach could be used for the local calibration of weights.

3.4 Connecting Warrants and Design Levels with safety analysis

One of the main drawbacks of current lighting warrants and design levels is the lack of a connection to the observed crash-history and in particular the ability to use such a connection to locally modify the scores of the warrants and the levels of roadway lighting. The idea is that the warrant serves to identify the need to provide lighting when such measure is expected to reduce nighttime collisions frequency and severity. Similarly, there is no point in providing lighting at levels unable to reduce the number and severity of nighttime collisions. The two methods proposed in this thesis serve to identify scores for the grid and levels for the design of roadway lighting by connecting statistical analyses of safety to both lighting standards.

3.4.1 Warrants and crash-history

As seen in section 2.5.2, the warrant system consists of a grid system with scores given to geometric, functional, operational, and crash-history elements. These elements could be interpreted as causal factors and treated as such through a statistical analysis. Then the value of the coefficients from the statistical analysis can be interpreted as the contribution of each factor (element) to explain collisions, if the response is the number (or severity) of nighttime collisions, then the coefficient is explaining the factors contribution to nighttime collision frequency (or severity). Only factors with p-values below the desired level of confidence will survive the analysis and used in a local calibration as explained in future sections. For instance, a negative coefficient will be interpreted as an effective reduction on collisions (frequency or severity), with an increase on the corresponding factor value. Factors such as number of lanes and width of the shoulder, among others, are expected to have such behavior. Other factors would explain higher levels of collisions with higher values of the factor (for instance, traffic volume).

A critical review of several departments of transportation's policies revealed a trend of their guidelines to reduce the number of factors used in the grid. This thesis proposes the ability to do so by running a statistical analysis with those factors available to the analyst, which will result in a grid with only those significant factors.

3.4.2 Lighting levels and crash history

A similar proposition can be made for connecting lighting levels and crash history. However, lighting levels should be explained through their ability to be effective countermeasures. If a lighting level is too low, its effect on reducing collisions (frequency or severity) may be null or insignificant from a statistical analysis. The connection of lighting levels and crash-history is also done through statistical analyses, however many analyses are required in order to identify the minimum recommended levels. The idea is to run analyses for various levels of any given lighting parameter; for instance, in the case of luminance, very low levels (say 0.1 cd/m2) may not explain reductions in collisions (frequency or severity). At some point there has to be a level such that luminance explains less frequent and/or severe collisions. To identify such a level, one needs to use a dummy variable for the given lighting indicator. A dummy variable will help categorize those segments of roads (ramps, intersections, et cetera.) that exhibit the desired level (or better) by giving them a value of 1, while deficient roads below the tested lighting level will be given a value of zero. A statistical analysis containing all other explanatory variables (linearly independent) and the dummy variable will establish the contribution of each factor to explain the response, similarly to as explained above If a variable has a negative value, then any increase on such variable results in a reduction of the response. Hence, if the statistical analysis provides a negative value for the dummy variable (and the p-value is below the desired target) then one will interpret such level of lighting used to categorize the data through the dummy as an effective countermeasure for nighttime accidents. Analyses will run until the sign of the dummy changes from positive (not an effective countermeasure) to negative (an effective countermeasure). At which stage, the sign change point is interpreted as the minimum recommended level of the lighting indicator being analyzed.

One final point is necessary regarding the connection of lighting levels and crash history; each time we change and test for a better lighting value, the sample of observations (with such level or above) reduces, hence, it is plausible that at some point the p-value will start dropping from a lack of enough observations.

3.5 Local Calibration of Lighting Warrant Scores

The warrant grid system contains two major dimensions: (1) classification points and (2) scores. The classification points assign a degree of deficiency to each road element. The scores give the contribution of each element to explain nighttime collisions. Walton (1974) conducted a series of interviews and used questionnaires to establish the scores and identify the classification points. The current warrant system utilizes both elements to obtain an overall estimation of the degree of deficiency of the road during nighttime, and presumes that lighting is an effective element that can be used to ameliorate (improve) the degree of safety.

The calibration of the warrants could consider either or both dimensions. This thesis explores the connection of the warrants to the crash history, and the approach selected transforms the warrants to become an evidence-based method. The most practical way to do this is by estimating the relative explanatory power of each element on the warrants in explaining nighttime collisions. Hence, it becomes natural to use statistical analyses at the core of the calibration and to apply the calibration to the scores, which directly provides the contribution of each element to explain nighttime collisions and allows the reduction of the number of elements based on the available data.

The approach used in this thesis is to calibrate the scores of the warrant system using the expected contribution of available causal factors on nighttime collisions. The method normalizes and re-scales parameters to obtain scores of a grid containing geometric, operational, environment and crash-history factors. The new grid contains only significant factors identified by the analysis. In this regard it better serves the needs of departments of transportation with limited available data. Figure 3.9 summarizes the calibration method proposed in this research. The first step was to prepare a consolidated database containing geometrical, operational and environment characteristics, as well as crash-history of the road. Then data was analyzed in a statistical regression in order to estimate the beta coefficients that accompany each possible explanatory variable. Statistically significant values are normalized and scaled in order to estimate the recommended scores for the local calibration. Calibrated grids could be produced for frequency and/or severity of collisions (Figure 3.9).

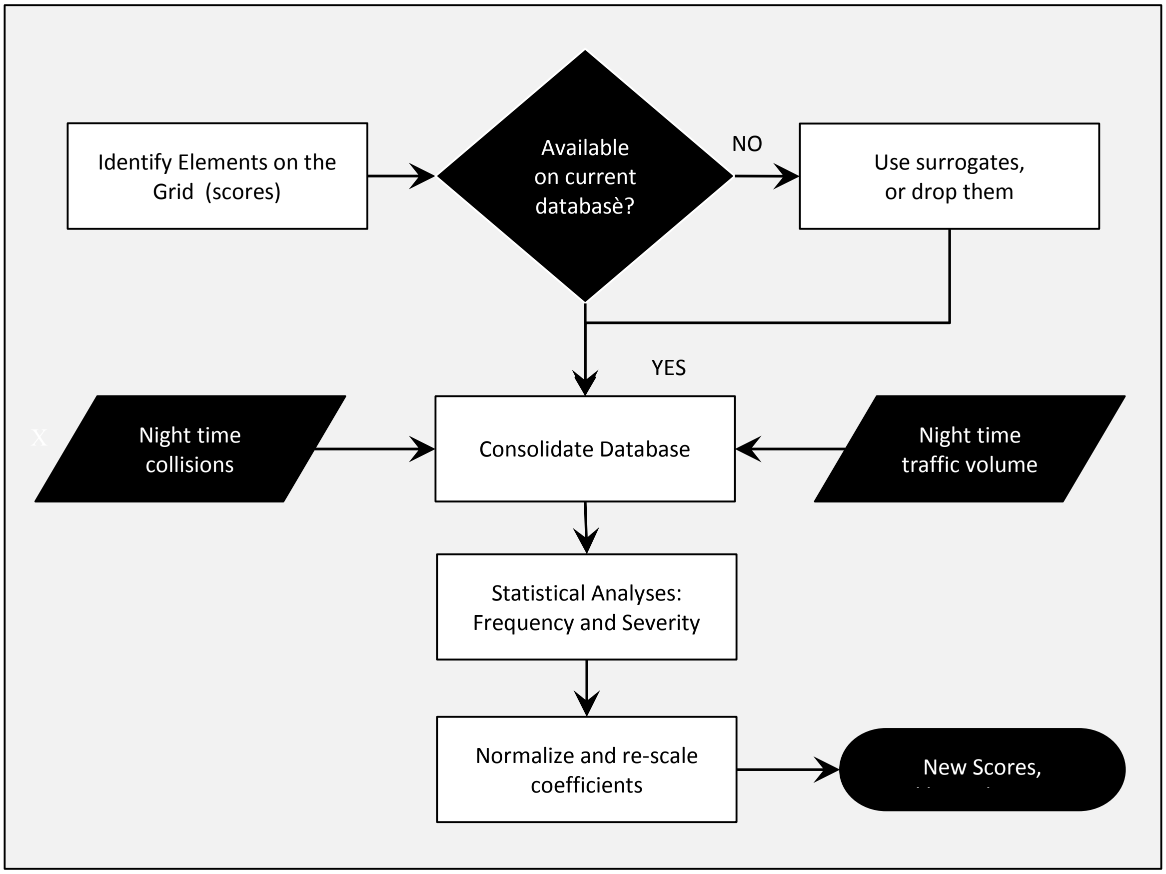

Figure 3.9 Method to Calibrate the Lighting Score Grid System

The normalization establishes relative weights on a zero to one basis for all the available coefficients (Figure 3.10). The re-escalation transforms the weights into scores that are multiplied by classification points with values between one and five. Hence, the maximum theoretical summation of scores multiplied by points reaches up to 100 points. Given the 100 points and 5 levels, all scores together could not go beyond a maximum of 20 points. Hence, each factor (previously normalized) is multiplied by 20 in order to obtain the final value of the new score for the grid of the warrant system (Figure 3.10). It is important to notice that the warrant system consists of 5 grids and that each grid is applicable to a specific element of roads. This subdivision follows a functional classification and type of road site (intersections, segments, et cetera).

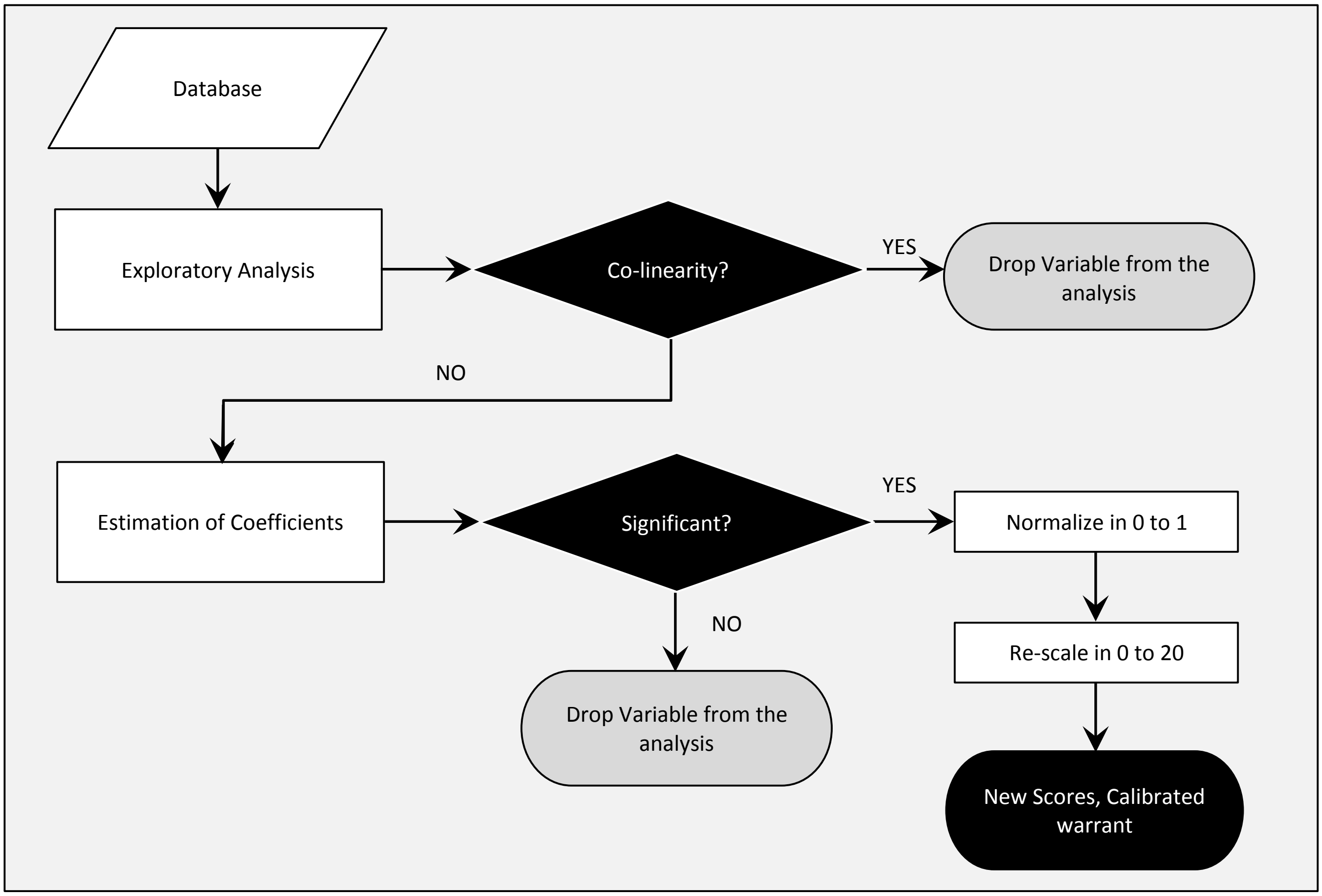

Figure 3.10 Calibration Mechanism

The other possible approach to calibrate is to change the classification points. This could be done in two ways: (1) adjusting the interval values that categorize the deficiency level of each element or (2) abandoning the global values used for the classification points (one to five) and using individualized values per road element. The adjustment of the deficiency levels will require a very large amount of data containing observations at all ranges in order to calibrate them. It is easier to preserve the nature of the intervals to be associated with deficiency levels. The connection of the crash-history to the classification points is complicated, but possible; it will require the individualization per road element, changing first the upper limit according to the explanatory power and then adjusting the interval limits to match the degree of contribution, which could follow any form, not necessarily linear as in today's grid. But, it will be impractical for decision makers, because it will further subdivide the grid, overcomplicating it for practitioners.

3.6 Estimation of Recommended Levels of Lighting

The estimation of recommended levels starts with the preparation of a consolidated database containing road characteristics, nighttime traffic volume, crash-history and lighting. The estimation can be further broken down into two types of analysis (severity and frequency) and five variables from which recommended level needs to be learnt. The first two values estimate minimum maintained levels of illuminance and luminance. Then, the estimation of maximum accepted variation in the form of three uniformity indicators could be considered. Minimum recommended levels of illuminance or luminance take the form of a dummy level variable. Several statistical analyses containing the level of the variable in turn at the time are prepared; the data is separated into two groups according to the compliance with a minimum average level of either illuminance or luminance. The estimated coefficients of such variables will indicate if the variable is capable of explaining less severe and/or less frequent roadway collisions. The analysis will continue until a point at which the level-variable shows a capability to explain less severe or frequent collisions, and at that moment, the minimum average recommended value of either illuminance or luminance will have been found. A similar approach will follow for the estimation of maximum recommended variation of uniformity: a level-variable is used to divide the data in two groups and this level variable is used to measure the ability to have less frequent/severe accidents.

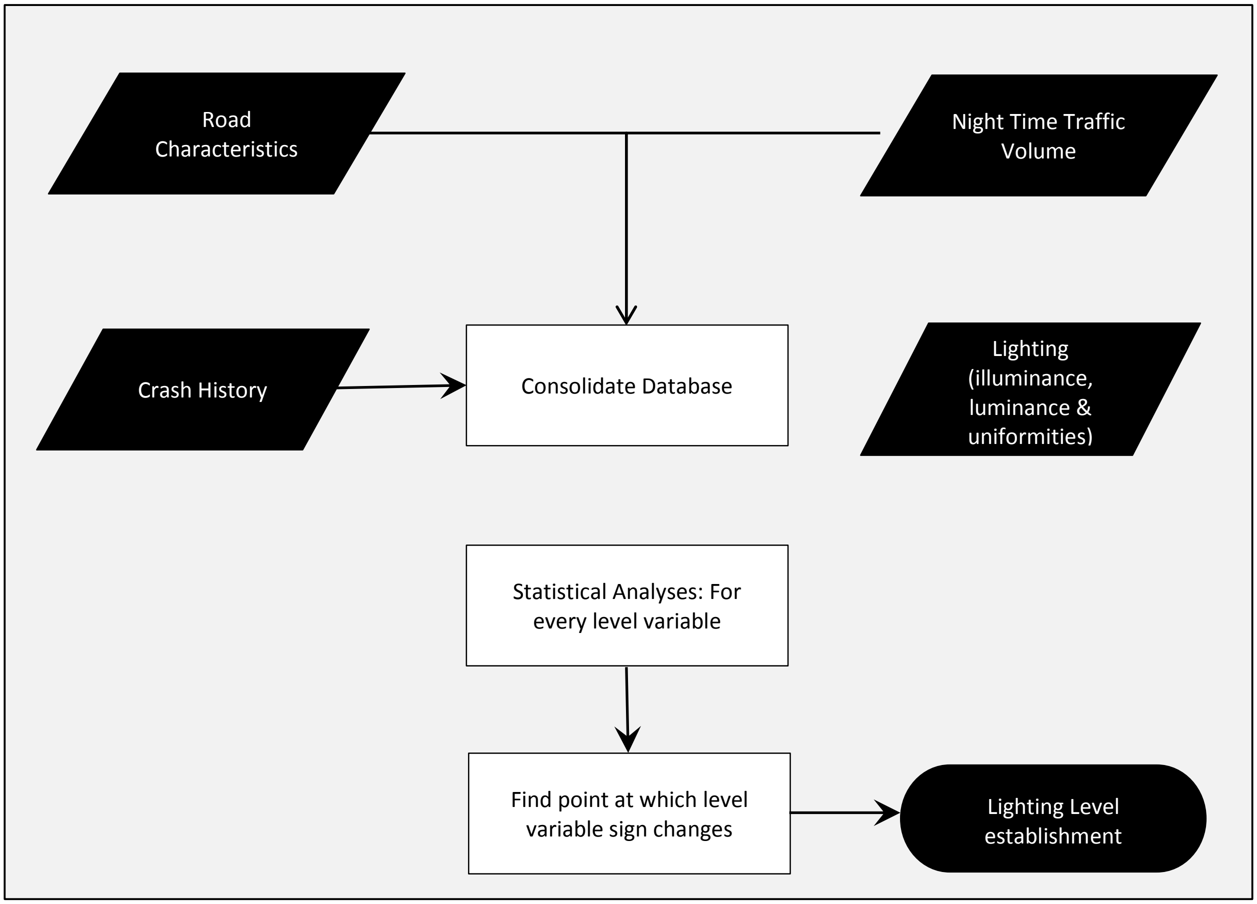

Figure 3.11 Method to Estimate Adequate Levels of Lighting

This procedure (Figure 3.11) is repeated per functional classification of roads; that is, a value of minimum average illuminance and luminance and values of maximum permitted uniformity variation are given for each type of road. Additionally, values could be further broken down into lighting per intensity of pedestrian activity, however this is not done in this research.

3.7 Protocol of a Unified Method for Lighting Warrants and Levels

This research proposes the need to unify both the warrant system and the recommended levels. This need comes from the fact that the warrant determines which sections to lit, the levels respond to the amount of lighting to be provided. From the state of the practice perspective, it is clear that both approaches come from separate industry standards (AASHTO 2005 and IESNA 2005). However, from a state of the art viewpoint, they should be treated together and, as proposed herein, connected to the crash-history in order to justify evidence-based lighting decisions.

The unified method is nothing more than the culmination of this research thesis. The method is applicable to municipal governments, regional authorities, and provincial/state agencies. The method provides the decision maker with an identification of warrants and levels for its jurisdiction. First, roadway lighting data must be collected; this data will be unified to existing crash and road characteristics data to generate a database for the analysis (Figure 3.12). The methods explained before will be used to calibrate the scores of the warrant's grid for each type of entity (Figure 3.12). The approach given before for lighting levels will be used to identify recommended levels per functional classification of roads.

At the end, the designer or decision maker will have a calibrated grid with recommended levels of minimum maintained luminance and illuminance (whichever is applicable for the type of road entity) and of maximum permissible uniformity variation for luminance and illuminance (whichever is applicable for the type of road entity). This will enable them to make an informed decision to provide roadway lighting as a countermeasure.

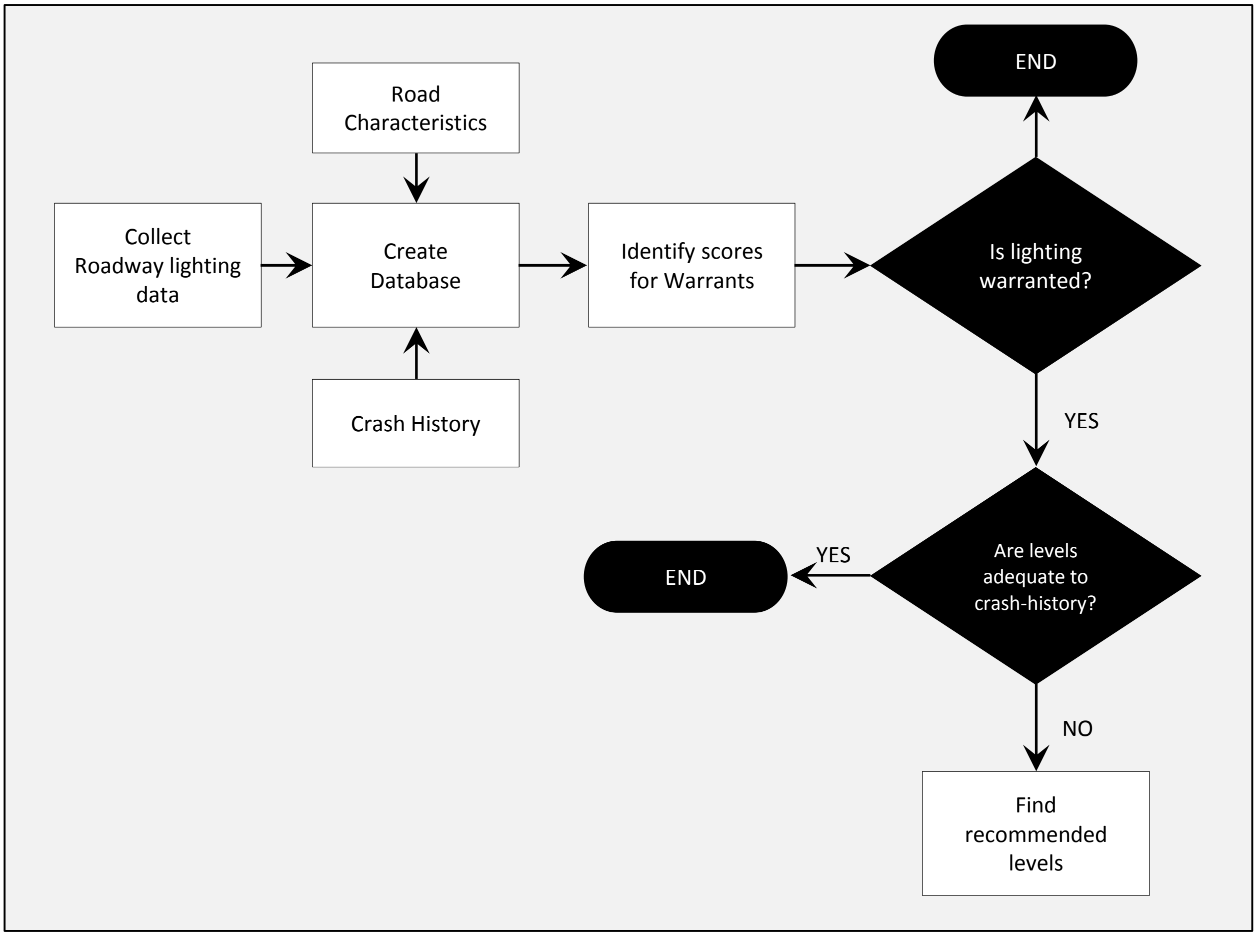

Figure 3.12 A Unified Method for Lighting Warrants and Levels

CHAPTER 4 - UNDERSTANDING LIGHTING AND SAFETY: A PILOT STUDY OF ARTHABASKA REGION

4.1 Introduction

Road collisions can negatively impact thousands of individuals. In 2011, road fatalities were ranked eighth worldwide, making road injuries one of the top ten leading causes of death worldwide (WHO 2013). The majority of existing research has focused on intersections and interchanges (Abdel-Aty *et al.* 2005, Santiago-Chaparro *et al.* 2010, Lord and Persuad 2000, Lovegrove and Sayed 2006). Few researchers had concentrated into road segments (Jonsson, Ivan, and Zhang 2007), perhaps because more collisions are actually observed at intersections (Barua, Azad, and Tay 2010). Collision frequency typically responds to higher volumes of traffic (Baek and Hummer 2008, El-Basyouny and Sayed 2010, Hadayeghi, Malone and De Gannes 2006), the presence of complex geometries (El-Basyouny and Sayed 2010), and combinations of horizontal and vertical curves in particular (Eassa and You 2009, Hummer, Rasdor and Findley 2010). Slippery surfaces have been found to explain a higher number of road collisions (Bullas 2004, Gilfillan 2000, Karlaftis 2002). Urban sites seem to receive more attention than rural ones (El-Basyouny and Sayed 2010), with constant efforts spent on improving their safety and special focus placed on intersection retrofitting (Feldman, Manzi, and Mitman 2010). Some of these studies looked into traffic calming measures as possible solutions (Zein *et al.* 1997). Typical studies focused on motorized vehicles, particularly cars, although other research focused primarily on motorcycles (Haque and Chin 2010). Some researchers have looked into pedestrians and their role in road safety (Lyon and Persuade 2002), taking into consideration their presence and interactions with motorized users. This is especially true for nighttime road collisions, for which current guidelines (IESNA 2005, TAC 2006) have established the decision criteria for warranting lighting and specified its levels as those found on grids G3 and G5 (Transports Quebec 2012) on the basis of pedestrians' presence.

Research has proven that many severe accidents occur at nighttime (Isebrands *et al.* 2010, CIE 1992), particularly involving pedestrians (Zhou and Hsu 2009).The typical countermeasure for nighttime collisions is roadway lighting (Rea, Bullough, and Zhou 2009). Studies have observed significant reductions in nighttime collisions at road segments to which lighting was provided as a countermeasure, with effectiveness ranging between 10 to 40% of all crashes observed and up to 65% of fatal crashes (TAC 2004). Previous research has found a roughly 37% reduction of crash rates (Isebrands *et al.* 2010). This is also supported by a report by CIE (CIE 1992) that found a large number of studies before 1992 which revealed that nighttime accidents resulted in more severe accidents and that lighting did help reduce their frequency. Several studies have been conducted to examine the relationship between roadway lighting levels and safety. Some researchers (Isebrands *et al.* 2010, Zhou and Hsu 2009) investigated how maintained illuminance levels impact safety of pedestrians, finding a higher frequency of pedestrian crashes at sites with low level of lighting. Others found that road lighting contributes to reduce collision frequency and especially reduce the number of persons killed and seriously injured (Yannis, Kondyli, and Mitzalis 2013).

The majority of studies on lighting refer to illuminance of a single site. Illuminance portable technology has recently been developed (Cai and Li 2014). Measurement of luminance for road safety studies of nighttime crashes is recent. Luminance portable technology does exist but has been impractical for collecting massive amounts of data (Elvik 1995).

4.1.1 Motivation and Goals

The main motivation of this chapter is to explore the role of lighting as a countermeasure for nighttime road collisions involving motorized vehicles in road segments. Several aspects need to be studied or confirmed. First, whether severity and/or frequency is the best response to capture the causes of night time collisions in statistical analyses. Second, what indicator of lighting should be used for road segments, illuminance or luminance. Third, what geometric, functional, and operational characteristics of the segment should be used as causal factors. Fourth, to confirm that lighting is indeed a good countermeasure.

As expected, the main goals respond directly to each of the four previous aspects. In summary, this chapter identifies what response should be used, what factors were considered and what indicator of lighting was included, and finally, the effectiveness of lighting as a countermeasure as witnessed through a reduction in collision rates. Good understanding for the specification of statistical analyses will be developed.

4.1.2 Database

Part of the data used in the first part of this chapter was obtained from the Arthabaska region. These databases benefitted from the work of a team of students under the supervision of Dr. Nicholas Saunier of *Ecole Polytechnique*, that merged the spatial location from the emergency vehicle system to the one of the Ministry of Transportation, this signified the ability to count with a more precise spatial location of the accidents which in turn justifies the possibility to use segments of 100 meters. A total of 951 road segments of 100 meters were used in this pilot study. Some geometric and operational characteristics of the segments along with lighting measurements, accident counts, and a severity index were used for the analysis (Table 4.1). Geometry attributes included presence of intersection, number of lanes, complex geometry, posted speed, land use (*i.e.* rural or urban), and average AADT for a period of ten years. These attributes are also described ahead in Table 4.1.

Roadway lighting in the form of illuminance and luminance was collected for a network of around a 95 km of roads in the Arthabaska region in central Quebec (Figure 4.1). Illuminance measurements were collected using the *Spectrosense2+* machine by placing two light sensors on top of the roof of a passenger car along with the device's built-in GPS system. An additional assisted-GPS was used to input missing coordinates in those cases where the *Spectrosense2+* lose signal.

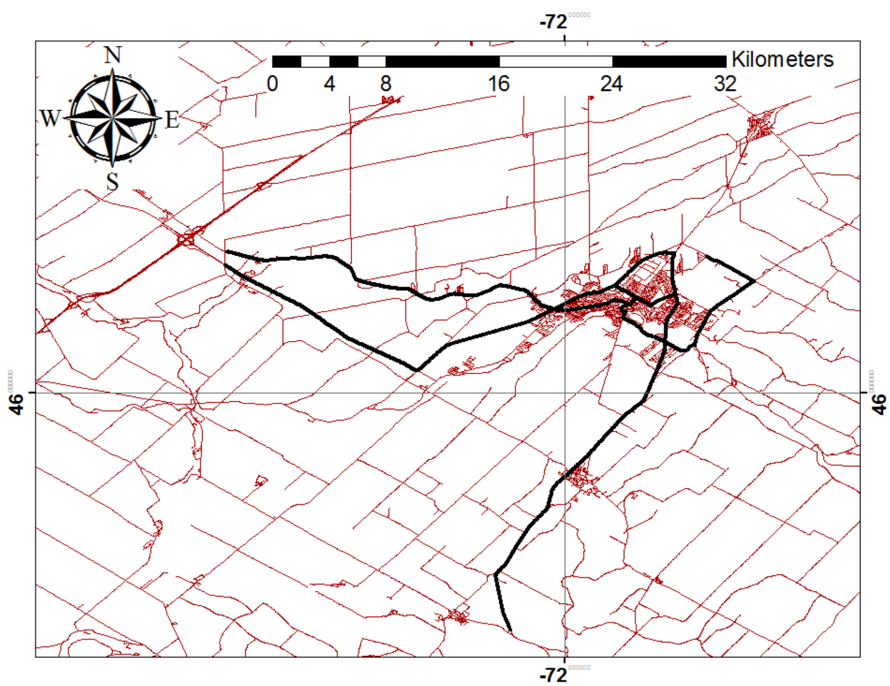

Figure 4.1. Arthabaska Region and Highways on this Pilot Study

A protocol for data collection is presented in Figure 4.2. Data collection begins and ends with the drivers being at a stationary position in order to have a known location and to allow the GPS to find signal; the driver then proceeds at near constant speed in order to have uniform point separation. Data collection is complemented by a cleaning process during the processing to remove measurements logged while stopped. *Spectrosense2+* and the assisted GPS have to be turned on and off simultaneously at the commencement and at the end of data collection respectively. The data then needs to be transferred to a computer system where it is processed. A preliminary visual inspection of the data is done using ArcGIS, where missing data can be easily identified. Coordinates from the assisted GPS are added in such cases. The complete cleaned illuminance dataset is then saved as a shape file which will be used at a later stage.

In terms of Luminance, data was collected using a professional digital camera (Nikon D70) with a special lens filter (fish eye type) and specialized software capable of estimating average luminance from ISO 400 photos as perceived by the driver and a glare indicator (Photolux 2012). Data collection followed the parameters established by JIS-Z-9111 (1988) in terms of the location of the camera (midpoint between luminaires), angle (2 degrees from horizontal sight of driver), height (1.5m), visual environment (capturing distance between 60 and 160 meters ahead, 90 m for intersections) and other specifications related to data collection already predefined in the system. Jackett and Frith (2013) further explained the calibration of a commercial camera required to translate photo pixels into luminance values. One indicator of glare was tested; the unified glare ratio.

Photolux software was used to process pictures by reading the information stored in the header of the picture using the EXIF format (Photolux, 2012). This information includes the aperture, time of exposure, and sensitivity. Photolux computes the exposure used on the picture to assign a value of luminance to each pixel, which eventually results in a luminance map. This map represents the amount of luminance in candela per square meter and can be used to estimate glare indicators.

A second subprocess takes care of adding the road network's operational and geometric characteristics and splits roads into one hundred meter segments. In addition, intersections were identified by creating buffers. Segmentation of the network followed a two-step process where routes were created and divided. The creation and splitting of the routes resulted in the loss of relevant segment-related attributes. Characteristics corresponding to each section are reincorporated into the splitted segments shapefile.

A third process uses a 20m buffer to allocate collisions into road segments in the form of collision frequency and by using specified weights (3.9, 1, 0.0216, 0.0108 and 0.0014 for fatality, major/minor, injury and major/minor PDO) creates a severity indicator scaled to match the order of magnitude of observed frequencies. Finally, lighting measurements, road network operational and geometrical characteristics, and accident frequency were joined together. The final database was used for statistical analyses (Figure 4.2).

4.1.3 Lighting variables used in the analysis

Values of uniformity followed those recommended by IESNA (2005) which defines uniformity of illuminance or luminance are shown on Equations 4.1, 4.2 and 4.3.

$$\text{Uniformity (illuminance)} = \frac{Average}{Minimum} \qquad [4.1]$$

$$\text{Uniformity 1 (luminance)} = \frac{Maximum}{Minimum} \qquad [4.2]$$

$$\text{Uniformity 2 (luminance)} = \frac{Average}{Minimum} \qquad [4.3]$$

According to IESNA (2005), the uniformity ratios are dependent on the functional classification of the road. The values provided in this table are the maximum allowable values that can be observed on road segments. Road segments in the database were classified as being standard by looking into the minimum illuminance and luminance values and functional classification in order to meet IESNA minimum recommended illuminance and luminance values. Uniformities for illuminance and luminance were used in the analysis as well. Average illuminance and calculated uniformity were the only light related variables used in the analysis. A dummy variable for lighting levels describing whether the light found on the segment is standard or non-standard was included as well. The natural logarithm of AADT has been chosen as a predictor to inflate the regression. This is because the number of crashes (or their severity) is related to traffic volume (AADT), *i.e.*, many segments with low levels of traffic registered zero collisions.

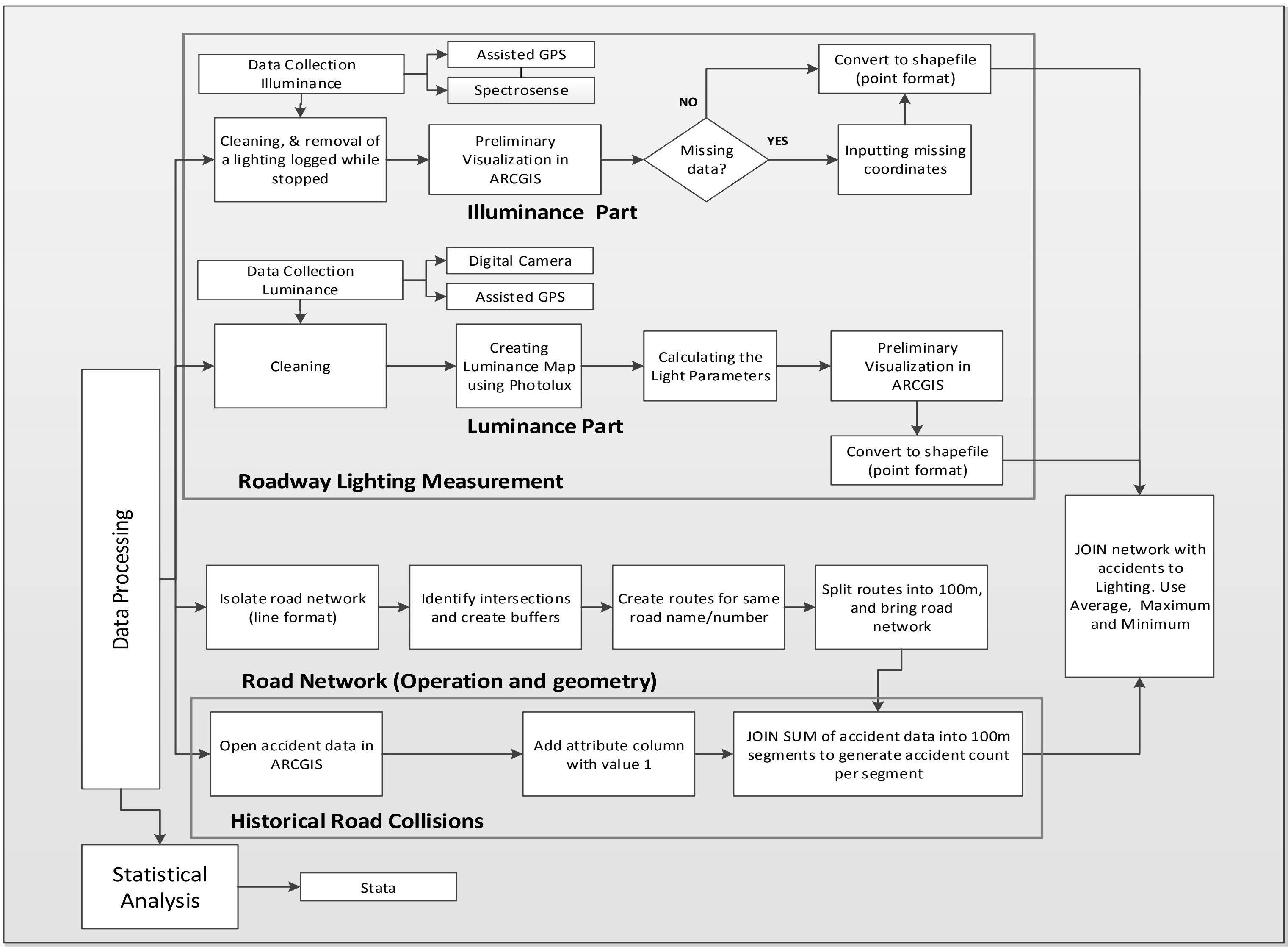

Figure 4.2 Flowchart of Data Collection and Processing

4.2 Methodology

This first stage of the analysis develops frequency and severity statistical models for roadway collisions in order to identify the recommended form of the response. The analysis is conducted in two parts: one for lighting in the form of illuminance and the other in the form of luminance. Maximum likelihood and Full Bayesian analyses were employed (the second to validate the results of the first) to identify the factors that are significant. The main tasks are shown on Table 4.1:

Table 4.1 Main Tasks

Method	Purpose
Statistical analyses of collision's frequency and severity	Identify best type of response
Statistical analyses of illuminance and luminance	Identify best indicator for lighting
Correlation Matrix	Identify causal factors to be used
Statistical analyses of daytime vrs. night-time collisions	Demonstrate lighting is countermeasure
Full Bayesian and maximum likelihood	Validation of results

4.2.1 Statistical Analyses

Different methods are available to estimate the parameters of a regression model. The most popular in safety analysis are the method of moments (Baglivo 2004), the method of maximum likelihood (Bedford and Cooke 2001), and Bayesian estimation (Gelman and Hill 2008). The method of maximum likelihood is widely accepted, and therefore used in this study. However, Full Bayesian counts with interesting properties and interpretive advantages (Mitra and Washington 2006) like the ability to handle structured data which could be exploited to replicate the ideas behind Latent class models and to abandon the need to inflate for zeros. Moreover Bayesian can combine expert criteria with local observations in order to calibrate models based on specific contributing factors for different engineering applications (Amador and Mrawira 2011). Bayesian estimation is structured based on prior, likelihood, and posterior. Prior distribution, which represents the initial knowledge about a parameter, can be selected as informative based on previous researches, literature, expert criteria, or experience. It can alternatively be specified to be non-informative. The likelihood is represented by data containing local observations. Finally, the posterior distribution can be obtained by mixing prior and likelihood. The Posterior distribution can be estimated through a stochastic Markov Chain Monte Carlo simulation framework using Gibbs sampler, which samples the space of the contributing factors and takes into account the randomness associated to these factors.

The analysis also runs parallel models with maximum likelihood as the main method and Full Bayesian in order to validate its results. However, Bayesian analyses will be the base of future research in order to develop a calibration method that separates road sites by levels of risk and then establishes calibrated lighting warrants.

A Zero-Inflated Negative-Binomial (ZINB) model is used to estimate the contribution of explanatory variables (including lighting) on collision frequency and severity. The ZINB is an extension to the ZIP, capable of dealing with the high number of zero counts as well as over-dispersion (Mei-ling *et al.* 2004). This model assumes that the high number of zero responses could come from two possible processes. One could be the result of good safety practices and adequate geometric design. The second could come from some collisions not being reported. The outcome Y studied herein follows a ZINB with distributions and the mean for the variance as recommended by Sharma and Landge (2013).

This chapter employs a safety performance function (SPF) that estimates the relationship between predicted crash frequency and a series of segment characteristics from four major areas, namely operational characteristics (AADT, speed, et cetera), geometry and built environment (land use, curvature, et cetera), environmental exposure (road surface condition), and roadway illumination. The SPF adopted in this study is presented in Equation 4.4 and follows the format recommended by AASHTO (AASHTO 2010). It should be noted that all segments measure 100m in length making possible to drop such factor.

$$Y_i = AADT_i^{\alpha} * \exp(\beta_0 + \beta_1 x1_i + \cdots + \beta_k x_{ki}) \quad [4.4]$$

Where:
k:variable number (1,2,3,….)
β_k :Coefficient of explanatory variable x_k
Y_i:Frequency or severity of night-time collisions on segments i
$AADT_i$: Average Annual Daily Traffic of segments i
X_{ki}: Explanatory variable i
α: Coefficient of AADT at segment i

4.3 Results

An increase in the number of collisions is expected for high traffic areas. Two models were run: classical analysis (maximum likelihood) using *Stata* and Full Bayesian using *OpenBUGS* (Table 4.3).

4.3.1 Road Collisions and illuminance

A zero inflated negative binomial model was analyzed using a maximum-likelihood commercial-software (*Stata*) and a Full-Bayesian free-source-software (*OpenBUGS)*. Two sub-models were prepared and results were obtained; one for accident frequency and one for accident severity. Their results were compared in Table 4.2 in order to validate and to withdraw conclusions regarding the preferred response.

The presence of an intersection, having a wet, icy or snowed pavement, along with the slope of the terrain and the presence of animals increase the number of roadway collisions. Higher average speeds resulted in slightly less accidents with an almost negligible contribution. More causal factors were capable of explaining accident severity; as such and in addition to the aforementioned variables, higher levels of average illuminance were found to explain less severe accidents. The presence of animals increase the frequency and severity of collisions. Tired and drunk drivers resulted insignificant for explaining collisions frequency and severity. Sites with standard levels of illumination were associated with more severe accidents as compared to sites with non-standard levels. This contradictory result aligns with the literature recommendation of not using illuminance as an indicator for road segments (only for intersections). This also suggests the possibility that the current standard is not helping to reduce the number of road collisions and may need to be revised.

Table 4.2 Comparison Maximum Likelihood (*Stata*) with Full Bayesian (OpenBUGS) for Illuminance

Parameters	Variable Name	Frequency			Severity		
		FB	Stata	Significant (90%)	FB	Stata	Significant (90%)
beta[3]	Number of lanes	-0.020	0.028		-0.309	0.213	
beta[4]	Presence of Intersection	**0.964**	**0.908**	**YES**	**0.623**	**0.757**	**YES**
beta[5]	Average Illuminance	0.003	-0.001		**-0.081**	**-0.055**	**YES**
beta[6]	Number of Heavy Trucks involved in Collisions	0.005	-0.102		-0.670	-0.391	
beta[7]	Wet Pav.	**0.454**	**0.459**	**YES**	**1.060**	**0.933**	**YES**
beta[8]	Snow Pav.	**0.319**	**0.308**	**YES**	**0.388**	**0.392**	**YES**
beta[9]	Iced Pav.	**0.544**	**0.549**	**YES**	**1.499**	**1.650**	**YES**
beta[10]	Horizontal Curve	-0.001	-0.023		0.041	0.198	
beta[11]	Slope	**0.274**	**0.307**	**YES**	**1.166**	**1.086**	**YES**
beta[12]	Average Posted Speed	-0.012	-0.010		**-0.082**	**-0.022**	**YES**
beta[13]	Suburban	-0.591	-0.498		-0.120	0.904	
beta[14]	Urban	-0.153	0.090		-0.542	0.294	
beta[15]	Standard Illumination	**0.578**	**0.695**	**YES**	**1.185**	**1.255**	**YES**
beta[16]	Nonstandard Illumination	**0.436**	**0.524**	**YES**	**0.511**	**0.598**	**YES**
beta[17]	Presence of Drunk Driver	0.031	-0.012		0.064	0.145	
beta[18]	Presence of Tired Driver	0.002	0.076		0.820	0.175	
beta[19]	Presence of Animals	**0.238**	**0.255**	**YES**	**0.585**	**0.590**	**YES**
beta[20]	Uniformity for illuminance (Avg to Min)	-0.001	-0.001		-0.004	-0.003	

4.3.2 Road Collisions and luminance

In this analysis, lighting took the form of luminance and glare (unified), for the same segments used in the analysis before. It was confirmed that segments with higher levels of traffic flow, on a slope, at an intersection, or exposed to slippery circumstances or the presence of animals (possibly poor fencing control) experienced a higher number of accidents. In terms of lighting, this analysis measured the role of luminance as perceived by the driver, glare, and uniformity variation (the higher the value the larger the lighting inconsistency). It was found that higher values of luminance resulted in less frequent and severe accidents (although at an 85 and 80% confidence), higher values of glare resulted in more frequent collisions and higher degrees of inconsistency in uniformity, resulting in more collisions. Tired and drunk drivers resulted insignificant for explaining collisions frequency and severity (Table 4.3).

Table 4.3 Classical Analysis (Maximum Likelihood) Analysis Results – *Stata*

No.	Variable	Frequency		Severity	
		Coef.	P-value	Coef.	P-value
2	Log AADT (Traffic Volume)	**0.29**	**0.09**	**0.39**	**0.08**
3	Number of lanes	0.05	0.63	**0.34**	**0.02**
4	Horizontal Curves	0.00	1.00	-0.01	0.96
5	Slope	**0.25**	**0.05**	**0.55**	**0.01**
6	Average Posted Speed	-0.01	0.14	**-0.02**	**0.01**
7	Intersections	**0.91**	**0.00**	**0.51**	**0.01**
8	Land Use	0.08	0.42	0.12	0.33
9	Average Luminance	-1.06	0.13	-1.23	0.19
10	Uniformity1 Luminance Avg to Min	0.13	0.19	0.10	0.48
11	Uniformity2 Luminance Max to Min	-0.03	0.21	0.00	0.97
12	Illuminance from Luminance	**0.32**	**0.08**	0.29	0.23
13	Unified Glare	**0.05**	**0.07**	-0.03	0.43
14	Animals	**0.23**	**0.03**	**0.74**	**0.00**
15	Tired driver	0.23	0.38	0.08	0.85
16	Drunk driver	-0.17	0.33	-0.30	0.36
17	Wet pavement	**0.52**	**0.00**	**1.22**	**0.00**
18	Snow pavement	**0.32**	**0.00**	**0.41**	**0.01**
19	Iced Pavement	**0.61**	**0.00**	**1.14**	**0.00**

4.3.3 Causal factor selection

The previous analyses were not concerned with the selection of factors and concentrated only on the identification of the ideal response(s) and suitable indicator(s) of lighting. This section is devoted to the identification of the causal factors to include in the analysis. The prior belief is that any factor in principle correlated to the response should be dropped. By correlated in principle, one means those who represent a specific characteristic of the response. For instance in the previous analysis, the presence of an animal at the time of the accident is a count of how many of the observed accidents involved an animal; similarly the impairment of the driver (tired or drunk) is also a mere count of accidents in which the driver presented as either of those circumstances. Finally, the surface of the pavement at the time of the accident is also a mere count of frequency of how many accidents occurred while the surface of the pavement presented some wet, icy, or snowy circumstances.

Table 4.4 Correlation Matrix for In-Principle Correlated Factors

	y = frequency	Animal	Driver		Pavement		
			Tired	Drunk	Wet	Snow	Ice
y = frequency	1						
Animal	0.31	1					
Tired	0.17	0.13	1				
Drunk	0.39	0.30	0.57	1			
Wet pavement	0.88	0.22	0.15	0.33	1		
Snow pavement	0.79	0.30	0.18	0.30	0.59	1	
Ice pavement	0.51	0.18	0.14	0.26	0.30	0.37	1

Table 4.4 shows a portion of a correlation matrix of such factors with accident frequency, while the other portion containing the remaining factors is shown on Table 4.5 given the large size of the matrix. As seen, most accidents presented a slippery circumstance, about half involved an impaired driver, and one third involved the presence of an animal on the road. They all result in high values

of correlation and should not be included in the analysis.

As seen in Table 4.5 there are three factors showing high values of correlation one of them (horizontal curve) with the response possibly because such measure (binary) only reflects the fact of whether the collision occurred at a horizontal curve segment or not. If this is the case, such geometric variable is inadequate and one containing the actual measure of the radius of curvature should be used. The other two variables showing high correlation are land use with speed (56%) and illuminance with luminance (68%). The reasons behind the second pair of highly correlated factors (illuminance and luminance) are very clear; the value of illuminance was estimated from the value of luminance, and hence only one or the other should be used. A negative correlation is observed between speed and land use, which means the more types of proximal land uses (urban and suburban) to a road segment, the lower the observed speed. This observation makes sense as the indicator of land use herein defined acknowledges the fact that homogeneous circumstances (only one type of land use) possibly results in higher speeds, and that transitioning segments will likely observe lower speeds.

Table 4.5 Correlations for the Rest of Causal Factors

	y nighttime	ln_aadt	lanes	curve	slope	speed	inters	Landuse	Lumen	unif_1	unif_2	illumin	glare
Y for nighttime	1												
ln_aadt	0.15	1											
lanes	0.27	0.37	1										
curve	**0.70**	0.12	0.14	1									
slope	0.41	0.12	0.16	0.43	1								
speed	-0.29	-0.08	-0.35	-0.22	-0.14	1							
inters	0.34	0.04	0.20	0.29	0.23	-0.39	1						
landuse	0.21	0.42	0.21	0.17	0.14	**-0.56**	0.28	1					
lumin	0.23	0.00	0.28	0.16	0.11	-0.40	0.18	0.19	1				
unif_1	-0.02	-0.25	-0.03	-0.02	0.01	-0.21	0.07	0.00	**0.71**	1			
unif_2	0.05	0.15	0.14	0.03	0.03	-0.24	0.18	0.21	0.08	0.16	1		
illumin	0.32	0.34	0.46	0.23	0.13	-0.38	0.18	0.29	0.68	0.02	0.08	1	
glare	0.02	-0.04	-0.23	0.06	0.04	0.07	-0.06	0.04	-0.27	-0.40	-0.15	-0.03	1

Table 4.6 Correlations for the Causal Factors on Daytime Analysis

	y daytime	lanes	intersec	total_width	shoulder_width	ln aadt	Speed	radius	median_bin	Landuse	slope
Y for daytime	1										
lanes	0.05	1									
intersections	0.18	0.04	1								
total_width	0.05	**0.89**	0.05	1							
shoulder_width	-0.03	-0.05	0.11	-0.01	1						
ln aadt	0.14	0.43	0.10	0.42	0.21	1					
speed	-0.10	0.13	-0.21	0.12	**-0.67**	-0.04	1				
radius curvature	0.02	0.20	-0.06	0.18	-0.15	-0.01	0.19	1			
median_binary	0.01	-0.06	-0.11	-0.02	0.32	0.11	-0.23	-0.11	1		
Land use	**0.71**	0.19	0.21	0.17	-0.02	0.14	-0.20	-0.01	-0.03	1	
slope	0.24	0.04	0.15	0.02	-0.02	0.06	-0.18	0.001	-0.04	0.41	1

4.3.4 Demonstrating that lighting is a countermeasure

The analysis, however, is based on an expanded version of the database which contained more segments (1600 segments) with geometric values for lane width, number of lanes, total pavement width, shoulder width, slope, horizontal curve radius, density of intersections/interchanges, and traffic volume. The data contained for land use on the database showed a high (0.71) correlation coefficient with the response (Table 4.6). The reason was that the fields of land use in the database reflected a count of collisions observed at the corresponding land use, so for this reason it was dropped from the analysis. The same correlation matrix (Table 4.6) revealed that total width was highly correlated to number of lanes. Only one value was kept for the analysis.

Lighting was represented by luminance and glare, collision severity was used as response. As seen in Table 4.7, both daytime and nighttime identify the same significant factors: number of lanes, density of intersections, traffic volume (AADT), posted speed, and slope. All coefficients are very close except the one for traffic volume which is about three times as important during nighttime. This could be explained by the fact that traffic volume has a greater impact on night time accidents. This is seen in the warrant score system of highway lighting by the use of a 2 to 1 night-to-day accident ratio. Both luminance and glare resulted significant and negative, which is to say that higher luminance and glare result in fewer collisions. This confirms that for the case study, lighting measured through luminance is an effective countermeasure. The result for glare contradicts prior expectations, thus glare should not be used.

Table 4.7 Day and Night Time Analyses

Daytime Collisions			Nighttime Collisions		
Factor	Coefficient	p-value	Factor	Coefficient	p-value
Lanes	**-0.48**	**0.03**	Lanes	**-0.50**	**0.01**
intersection	**3.11**	**0.00**	Intersection	**2.07**	**0.00**
shoulder	0.08	0.37	Shoulder	-0.04	0.55
Lnaadt	**0.16**	**0.00**	Lnaadt	**0.55**	**0.00**
Speed	**0.00**	**0.00**	Speed	**0.00**	**0.00**
radius_curve	0.00	0.46	Radius_curve	0.00	0.24
Slope	**7.27**	**0.00**	Slope	**7.23**	**0.00**
			Luminance	**-0.47**	**0.02**
			Glare	**-0.09**	**0.00**

4.4 Conclusions

This chapter presented a protocol to collect lighting data and developed understanding of the role of lighting in explaining nighttime collisions. This will be used in the upcoming chapters to develop a method to calibrate lighting warrants and design levels. In terms of the four major goals of this research, results from the analysis showed that accident severity is preferred over frequency, but one should keep in mind that they respond to different circumstances and it is the opinion of the author that both should be kept in the analysis. It was observed that illuminance returned inconsistent values for the statistical analysis of collisions on road segments, whereas luminance showed strong significance and improvement as a countermeasure. This result aligns with the literature that recommends the use of luminance for road segments (no pedestrians). Correlation analyses proved useful in identifying linearity between factors (same nature) or between factors and the response.

Miscellaneous initial results showed that, for the Arthabaska region in Quebec, the presence of an intersection, the presence of animals, and having a slippery/wet road surface produced more frequent and severe collisions. However, the correlation analyses force the drop of the presence of animals and slippery/wet roads as well as driver impairment. Roads with complex alignments resulted in higher collision rates. Traffic volume also explained higher collision frequency. Standard illuminated roads resulted in an increase of road collision frequency, a contradictory result. Average level of illumination (and being at an urban location) was only significant from a severity perspective, explaining less severe accidents with higher levels of illumination.

It was confirmed that Full Bayesian analysis was capable of estimating the impact of the explanatory variables on the response as it returned similar results to those obtained by the classical analysis. This is a key step for the validation of statistical analyses using Full Bayesian analysis. Future steps of this project include the development of a method to calibrate lighting warrants and estimate recommended design levels of lighting indicators. Such specifications will be based upon refined statistical analysis containing all the recommendations found in this chapter.

CHAPTER 5 - A CALIBRATION FOR THE WARRANT OF ROAD LIGHTING: CASE STUDY OF QUEBEC

5.1 Introduction

The Provision of Roadway lighting follows a warrant system established four decades ago. The current state of the practice finds many agencies in North America and the rest of the world simplifying the grid system to contain fewer elements already available to them and custom-tailor scores based on expert criteria. This tendency suggests the need for a method to conduct a local calibration of the warrant's grid supported by the local crash-history. This chapter presents a method to calibrate the scores of the warrant system utilizing only those elements available and significant from a statistical perspective in explaining less frequent and severe night-time collisions. A case study of the province of Quebec in Canada illustrates the application of the method. As explained later, only few factors survive the analysis and were found to be significant in explaining less frequent and severe accidents. Values of such factors were normalized and re-scaled to obtain the scores for grid G1 (highways). The number of lanes, width of the shoulder, density of intersections, traffic volume, and night-to-day crash ratios were calibrated to obtain two grids, one for severity and one for frequency. A modified grid without night-to-day ratios is proposed for new highways. The method to locally calibrate over statistical analyses proposes a strong foundation for lighting decisions better suited from a liability perspective.

The role of lighting as a countermeasure for night-time road collisions has been addressed by many researchers in the past (Zhou and Hsu 2009, Isebrands *et al.* 2010, Yannis, Kondyli and Mitzalis 2013, and Sullivan, 2009). In general researchers have found that certain levels of lighting is beneficial for reducing accident frequency (Elvik 1995, CIE 1992). The pilot study of the previous chapter confirms the positive effect of luminance in reducing road collisions.

Guidelines and regulations for recommended levels of lighting are proposed in IESNA (2005) and the warrant given by AASHTO (2005) and by TAC in Canada (2006). Many departments of transportation in the United States have developed custom values of specific geometric or operational characteristics following their disappointment with the current system and the fact that the warrant does not always agree with expert's criteria. This disagreement reveals, in the opinion of the author, the need to count with a local calibration method. However, no one has developed a method for local calibration of the warrants for highway lighting.

This chapter presents a calibration method for the warrant system. It addresses the grid (G1) of the warrant system. It estimates recommended values for the scores of G1, such that provision of roadway lighting is adapted to local characteristics of highway segments and ramps. It presents a case study of the road network for the province of Quebec. The method is similar to that presented in the pilot study; however, the model replaces two of the factors currently at the grid score system with surrogates. Severity and frequency were used as responses. The analysis was based on a maximum likelihood which enables the estimation of the parameters associated with each of the elements of the grid from the observed data.

5.2 Methodology

5.2.1 Exploratory statistical analysis

Two brief exploratory analyses were proposed. The first one was intended to confirm the findings of the pilot study; that is, identifying the best response and the set of causal factors that are linearly independent. The analysis was conducted on commercial statistical package *Stata* and made use of statistical regressions and correlation matrices. The other analysis illustrated the division of sites per levels of risk. The estimated value of each parameter was multiplied by the observed level of the corresponding variable and their products were added obtaining a prediction of the number of collisions. Sites were categorized in low, medium, and high levels given their predicted number of collisions. The breakpoints for the groups were established ad-hoc, based on the 33 and the 66-percentiles.

5.2.2 The calibration method

The calibration of the scores for grid G1 followed the normalization and re-escalation of coefficients obtained at statistical analyses. The process converted the weights obtained by the Maximum likelihood analysis into equivalent scores for the grid G1. The parameters values were presumed to be a good indication of the relative importance of each variable in explaining the response. Their values were converted into scores through a normalization and re-escalation that preserved their relative importance. The normalization computed the relative weight of each factor with respect to their total summation. The re-escalation stretched the scale to match a maximum theoretical summation of scores of 100 points. For this, a factor of 20 was used. It must be noted that the grid contains variables which are further given up to 5 times their weight; hence the weight of each variable was given by the normalized weight multiplied by a factor of 20 as shown in Equation 5.1.

$$PT_i = \left(\frac{P_i}{\sum_{i=1}^{N} P_i}\right) 20 \qquad [5.1]$$

Where:

PT_i: Proposed grid score value for variable $_i$

P_i: Parameter value obtained from the statistical analysis

This calibration method should be repeated for the other four site environments of the grid system (*i.e.*, intersections, interchanges, roundabouts et cetera). Future research could look into a method to handle multiple sites by having an indicator for the classification such that the analysis will identify a set of grid scores per category. This can be done through a hierarchical approach in which data is classified into groups and each coefficient carries an indicator of the group that it belong to, plus the coefficient's subscript index. Another way is by analyzing each group separately. Figure 5.1 illustrates the steps done for data collection of illuminance and luminance, data processing, and data analysis.

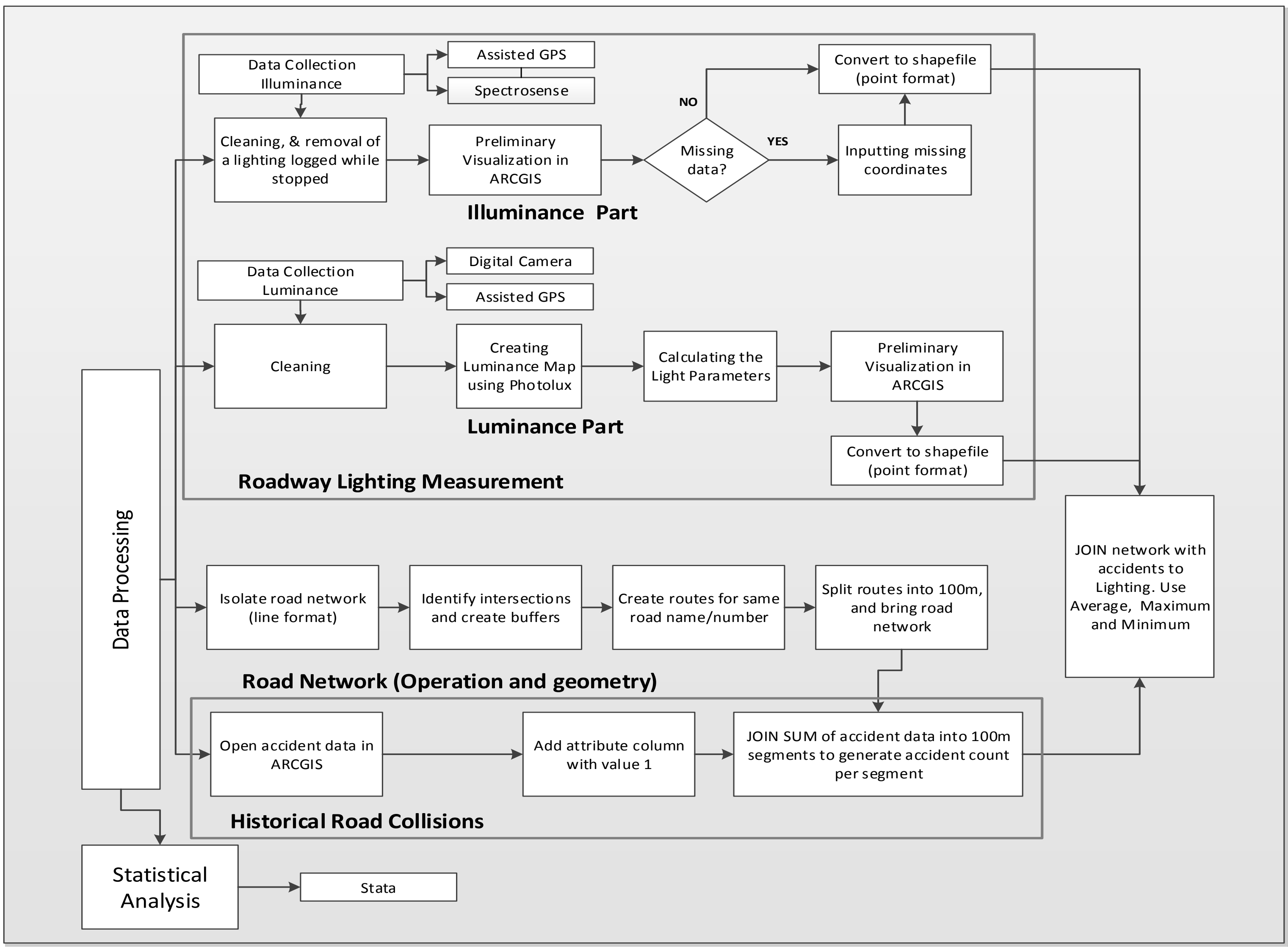

Figure 5.1 Data Collection, Processing, and Analysis (Illuminance & Luminance) Flowchart

CASE STUDY

A database was created by joining 2,500 km of roads surveyed at night time to measure illuminance with a Spectrosense 2+GPS. A luminance camera with GPS and luminance software (photolux) were used to collect data for a sample of 800 km from the previous database. Other functional, operational, and geometrical characteristics were added (Figure 5.2). The database was conceived to be representative of different land-use environments encountered through the province, and it extended in a longitudinal sense from West to East with several loops connecting back to the TransCanada Highway.

Additionally, the database was joined with the record of collisions and other accident related characteristics (impairment of driver, presence of animal on the road, condition of the pavement, time of the accident, among others).

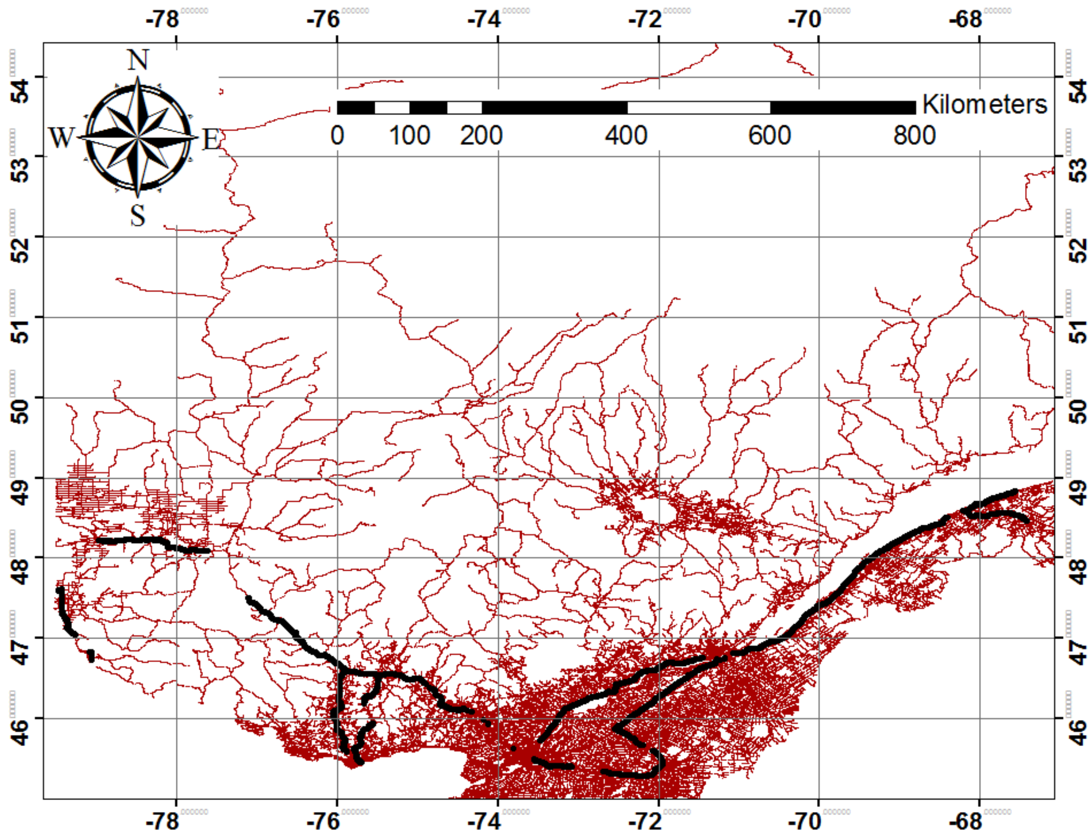

Figure 5.2 Selected Roads in Quebec Case Study

Table 5.1 gives a summary for the variables in the database used for this analysis. The effect of other geometric and operational variables was also included in the analysis in order to make inferences for the parameters of interest.

A total of 20 explanatory variables were tested. The nature of the variables was also presented; it ranged from binary (yes or no) to discrete and continuous. Some variables were compared versus a base level variable (for instance, lighting levels).

A safety function relating the outcomes and the explanatory variables was used in a zero inflated negative binomial model and a Full Bayesian multilevel model. The function used in the following analyses is presented in Equation 5.2. As seen, the model had many explanatory variables located on the power of the exponential in addition to AADT.

$$Y_i = AADT_i{}^{\alpha} * \exp(\beta_0 + \beta_1 x1_i + \cdots + \beta_k x_{ki}) \quad [5.2]$$

Where:
k:variable number (1,2,3,….)
β_k :Coefficient of explanatory variable x_k
Y_i:Frequency or severity of night-time collisions on segments i
$AADT_i$: Average Annual Daily Traffic of segments i
X_{ki}: Explanatory variable i
α: Coefficient of AADT at segment i

5.3 Exploratory Results of Safety Analysis

The natural logarithm of AADT has been chosen as a predictor to inflate the regression. This is because the number of accidents is related to AADT. An increase in the number of collisions is expected for high traffic areas as opposed to road segments with low AADT. In general the analysis test for determining the significance of several operational and geometry related variables, as well as lighting indicators, is presented below for each specific analysis. The adequacy of severity has been explained before in this research and it comes from the fact that collision frequency per segment does not fully capture the nature of the outcome.

5.3.1 Finding the best response: frequency and/or severity

A maximum-likelihood zero-inflated Negative-Binomial regression was conducted in order to gain better understanding of the contribution of available factors. This analysis also serves to estimate the predicted number of accidents for each segment based on its own observed characteristics. Significant factors are shown in bold font in Table 5.2 below.

The values of the coefficients obtained by the statistical analysis of collision frequency (Table 5.1) were used to estimate the expected number of accidents per segment. This number was used to categorize roads into three levels of safety: low, medium and high.

Table 5.1 Summary of Statistical Analysis

Sr. No.	Variable	Name	Frequency			Severity	
			Coef.	P>z		Coef.	P>z
2	lnAADT	Ln(aadt)	**0.10**	**0.00**		**0.12**	**0.00**
3	Number of Lanes	x3	0.11	0.13		-0.01	0.84
4	Presence of Intersections	x4	**0.40**	**0.00**		**0.10**	**0.01**
5	Average Lux illuminance	x5	**0.00**	**0.03**		0.00	0.64
6	Presence of Heavy Trucks	x6	**0.43**	**0.00**		**0.14**	**0.00**
7	Wet Pavement	x7	**0.28**	**0.00**		**0.09**	**0.00**
8	Snow Pavement	x8	**0.29**	**0.00**		**0.03**	**0.07**
9	Iced Pavement	x9	**0.54**	**0.00**		**0.14**	**0.00**
10	Horizontal Curve	x10	0.00	0.58		**0.00**	**0.02**
11	Slope	x11	**1.50**	**0.00**		**-0.35**	**0.00**
12	Average Posted Speed	x12	**0.02**	**0.00**		0.00	0.18
13	Suburban	x14	**0.32**	**0.00**		**0.18**	**0.03**
14	Urban	x13	**1.25**	**0.00**		0.11	0.14
15	Standard illuminance	x15	**0.50**	**0.00**		**0.23**	**0.00**
16	Presence of Animals	x16	**0.58**	**0.00**		**0.15**	**0.00**
17	Uniformity illuminance Average to Min.	x17	0.00	0.26		0.00	0.61
18	Length	x18	0.00	0.611		0.00	0.85
19	Road Functional Class	x19	**0.33**	**0.00**		**0.11**	**0.02**
20	Total Width of road	x20	**0.04**	**0.02**		**0.07**	**0.00**
21	Right Shoulder Width	x21	**-0.24**	**0.00**		**0.03**	**0.07**
22	Presence of Pedestrians	x22	**-0.34**	**0.03**		**-0.84**	**0.00**
23	Driver Workload	x23	**-0.23**	**0.00**		-0.03	0.37

5.3.2 Using levels of risk: Full Bayesian Multilevel Modelling

The previous Full Bayesian model was nested by levels of risk estimated through the coefficients and the actual values of each factor. Two Full Bayesian nested analysis were estimated for 22 coefficients and only those significant at the 95% are shown in Table 5.2.

Table 5.2 Results from Full Bayesian Analysis

Sr. No.	Variable Name	Risk	Beta	Frequency	Severity
2	lnAADT (Traffic Volume)	Low	2	3.47	4.87
		Med	2	3.50	4.81
		High	2	-1.62	2.93
3	Number of Lanes	Low	3	NS	NS
		Med	3	-1.72	NS
		High	3	NS	NS
4	Presence of Intersections	Low	4	NS	NS
		Med	4	NS	-1.68
		High	4	NS	-1.64
5	Average Lux illuminance	Low	5	NS	NS
		Med	5	0.00	NS
		High	5	0.00	NS
6	Presence of Heavy Trucks	Low	6	NS	NS
		Med	6	NS	NS
		High	6	0.31	0.83
7	Wet Pavement	Low	7	NS	NS
		Med	7	0.33	0.79
		High	7	0.19	1.79
8	Snow Pavement	Low	8	NS	NS
		Med	8	NS	NS
		High	8	0.50	NS
9	Iced Pavement	Low	9	NS	4.99
		Med	9	NS	NS
		High	9	0.88	NS
10	Horizontal Curve	Low	10	-4.00	-3.94
		Med	10	NS	0.00
		High	10	NS	NS
11	Slope	Low	11	NS	NS
		Med	11	2.03	4.77
		High	11	1.51	0.72
12	Average Posted Speed	Low	12	NS	NS
		Med	12	0.03	0.08
		High	12	NS	0.08
13	Suburban	Low	13	NS	NS
		Med	13	-3.92	NS
		High	13	-6.23	NS
14	Urban	Low	14	NS	NS
		Med	14	NS	NS

Sr. No.	Variable Name	Risk	Beta	Frequency	Severity
		High	14	-6.77	NS
15	Standard Illuminance	Low	15	NS	NS
		Med	15	1.08	3.83
		High	15	1.11	2.12
16	Presence of Animals	Low	16	7.85	7.14
		Med	16	0.16	NS
		High	16	0.45	1.36
17	Uniformity Illuminance Average to Min.	Low	17	NS	NS
		Med	17	NS	NS
		High	17	NS	NS
18	Total Length	Low	18	NS	NS
		Med	18	-0.06	-0.09
		High	18	NS	NS
19	Functional Class	Low	19	NS	NS
		Med	19	-6.57	NS
		High	19	1.54	NS
20	Total Width of road	Low	20	NS	NS
		Med	20	NS	-0.68
		High	20	NS	-0.317
21	Right Shoulder Width	Low	21	NS	NS
		Med	21	-2.78	NS
		High	21	-0.14	NS
22	Presence of Pedestrians	Low	22	NS	NS
		Med	22	NS	4.38
		High	22	2.36	NS
23	Land Use	Low	23	NS	NS
		Med	23	1.02	NS
		High	23	NS	-6.72

It is not possible to argue in favor of only one aspect; either frequency or severity lead to different angles of the problem at hand and should be used in the analysis. At this stage is important also to acknowledge that a correlation between factors, as well as and factors and the response, should be explored. Finally, any measure of lighting should be dropped from the calibration. Both aspects are addressed in the upcoming sections of this chapter.

5.3.3 Identifying the causal factors

A correlation matrix (Table 5.3) was prepared for the coefficients available after removing several collinear variables (presence of animals, drunk driver, trucks and weather-related pavement surface). A similar number of factors were identified to the one produced in chapter four. The matrix confirms the linear independency of selected variables suggested by the analysis conducted in the pilot study. Table 5.3 presents the values of a reduced matrix containing only the factors kept for the analysis.

Table 5.3 Correlation Matrix for Road-Segments

	Y_Night	Lanes	Intersection	Shoulder	Lnaadt	ND_Ratio	Speed	Radius	Slope
Y_ Night	1								
Lanes	0.03	1							
Intersection	0.18	0.04	1						
Shoulder	-0.02	-0.05	0.11	1					
Lnaadt_Night	0.17	0.41	0.10	0.22	1				
ND_Ratio	0.09	-0.04	0.03	0.02	0.02	1			
Speed	-0.12	0.13	-0.21	-0.67	-0.06	-0.13	1		
Curvature	0.02	0.20	-0.06	-0.15	-0.02	0.04	0.19	1	
Slope	0.28	0.04	0.15	-0.02	0.07	0.32	-0.18	0.00	1

The coefficient on the slope was slightly higher than the other variables, and its correlation to the night-to-day-ratio of accidents along with further verification of the database confirmed the fact that this value reflected a count of accidents occurring at a segment with a slope and did not represent the actual slope of the road in the longitudinal direction. Another abnormal value is that of shoulder and speed, which could not be explained. A similar matrix for highway ramps is presented in Table 5.4.

Table 5.4 Correlation Matrix for Ramps

	Y_Night	Lanes	Intersection	Shoulder	lnAADT	ND_Ratio	Speed	Radius	Ramp
Y_Nighttime	1								
Lanes	0.08	1							
Intersection	0.10	0.02	1						
Shoulder	0.03	-0.15	0.10	1					
lnAADT	0.23	0.09	-0.12	0.18	1				
ND_ratio	0.10	-0.09	0.02	0.05	-0.02	1			
Speed	-0.21	0.11	-0.30	-0.60	-0.16	-0.16	1		
Radius	-0.03	0.21	-0.13	-0.15	-0.02	0.12	0.23	1	
Ramp_Length	0.07	0.14	0.06	-0.01	0.15	0.11	-0.06	0.14	1

In summary, the exploratory results suggested the fact that not all variables currently contained on the grid (G1) are required from a statistical-perspective. This means that only those that surpassed the test of correlation should be used. Furthermore, only those deemed significant will be used on the final calibrated grid (G1). The preparation of a local calibration of the warrant was based on the available data which is statistically significant in explaining collisions and will facilitate the work of transport officials in producing local adaptations.

5.4 Calibration of Warrants Scores for Quebec's Highways

5.4.1 Existing roads

Four analyses were prepared by frequency (Table 5.5) and severity (Table 5.6): two for highway ramps and two for road segments, It was found that both types of facilities share some causal factors but their values differ. From a frequency perspective (Table 5.5), the presence of an intersection proximal to a ramp resulted in a very large and significant value, and the traffic volume (AADT) during the night and the night-to-day accident ratio also resulted in positive contribution to more frequent accidents. In a minor role speed resulted significant, however its coefficient was very close to zero. For road segments, the same trend previously depicted for ramps was observed, while having more lanes or wider paved shoulders resulted in less frequent collisions.

From a severity perspective (Table 5.6), ramps observed less severe collisions when equipped with wider shoulders and more severe collisions with more traffic flow (AADT) higher night-to-day accident ratio and higher values of speed and smaller radius of horizontal curvature. For road segments, less severe accidents are observed with more lanes and wider shoulders, and more severe collisions are observed with higher density of intersections (more frequently spaced), higher traffic volume (AADT), higher night-to-day accident ratios and higher speed. Again, the contribution of speed was negligible as its coefficient was close to zero.

Table 5.5 Coefficients of Ramps and Segments – Frequency Analysis

RAMPS	Coef.	P-Value	SEGMENTS	Coef.	P-Value
Lanes	-0.05	0.90	Lanes	**-0.54**	**0.08**
Intersection	**2.13**	**0.00**	Intersection	**3.46**	**0.00**
Shoulder	-0.04	0.75	Shoulder	**-0.43**	**0.00**
ND_ratio	**0.65**	**0.00**	ND_ratio	**0.60**	**0.00**
Speed	**0.00**	**0.00**	Speed	**0.00**	**0.00**
Radius	0.00	0.85	Radius	**0.00**	**0.09**
lnAADT	**1.25**	**0.00**	lnAADT	**0.45**	**0.00**
Ramp_Length	0.00	0.84			

Table 5.6 Coefficients of Ramps and Segments – Severity Analysis

RAMPS	Coef.	P-Value	SEGMENTS	Coef.	P-Value
Lanes	0.57	0.27	Lanes	**-0.84**	**0.06**
Intersection	0.13	0.87	Intersection	**1.87**	**0.00**
Shoulder	**-0.66**	**0.00**	Shoulder	**-0.56**	**0.00**
ND_ratio	**0.23**	**0.03**	ND_ratio	**0.31**	**0.00**
Speed	**0.00**	**0.00**	Speed	**0.00**	**0.00**
Radius	0.00	0.94	Radius	0.00	0.46
lnAADT	0.33	0.21	lnAADT	**0.92**	**0.00**
Ramp_Length	0.00	0.82			

Statistically significant values of the previous analysis are used to construct a grid for the warrant of lighting. First, the coefficients' values are expressed in absolute value, and a relative weight is estimated by dividing each coefficient by the summation of the coefficients (Table 5.7). The relative weights provide the basis for a calibrated value of the score. The classification points are preserved and their values are not modified in any sense. The new grid (G1) is constructed for highway segments and ramps. The new grid is a reduced version of the old one, containing only those significant factors previously selected. The only remaining challenge is the fact that the grid scores should add to one hundred.

Table 5.7 Calibration of the Coefficients for Lighting Warrant: Obtaining Relative Weights

Calibration of Lighting Warrant for G1 based on collision Frequency									
RAMPS	**Coef.**	**ABS**	**Weight**	**Score**	**SEGMENTS**	**Coef.**	**ABS**	**Weight**	**Proposed Score**
Lanes					Lanes	-0.54	0.54	10%	1.96
Intersection	2.13	2.13	53%	10.57	Intersection	3.46	3.46	63%	12.65
Shoulder					Shoulder	-0.43	0.43	8%	1.57
ND_ratio	0.65	0.65	16%	3.23	ND_ratio	0.60	0.60	11%	2.18
Speed	0.00	0.00	0%	0.01	Speed	0.00	0.00	0%	0.01
Radius					Radius	0.00	0.00	0%	0.00
lnAADT	1.25	1.25	31%	6.20	lnAADT	0.45	0.45	8%	1.63
Ramp_Length									
SUMMATION		4.03	100%				5.47	100%	
Calibration of Lighting Warrant for G1 based on collision Severity									
RAMPS	**Coef.**	**ABS**	**Weight**	**Score**	**SEGMENTS**	**Coef.**	**ABS**	**Weight**	**Proposed Score**
Lanes				0.00	Lanes	-0.84	0.84	19%	3.72
Intersection				0.00	Intersection	1.87	1.87	42%	8.32
Shoulder	-0.66	0.66	53%	10.70	Shoulder	-0.56	0.56	12%	2.49
ND_ratio	0.23	0.23	19%	3.82	ND_ratio	0.31	0.31	7%	1.37
Speed	0.00	0.00	0%	0.05	Speed	0.00	0.00	0%	0.01
Radius				0.00	Radius				
lnAADT	0.33	0.33	27%	5.43	lnAADT	0.92	0.92	20%	4.09
Ramp_Length									
SUMMATION		1.23	100%				4.49	100%	

At this stage, the theoretical maximum value of points could reach up to 500%, because the grid could see a multiplication of its factors of up to five times. This issue is solved by dividing the new scores (Table 5.7) by 5 and multiplying by one hundred (or simply by multiplying by 20). The scores shown on Table 5.8 are based on this approach. An alternate solution would be to reduce the weight of the classification points into a zero-to-one scale and use the relative weights of Table 5.8 without re-scaling. The decision should be based on the consideration of what is more important, the levels of the factor or its value. The calibration opens a new possibility to the decision maker; it can be based on either frequency or severity, and either grid could justify the provision of lighting. As seen, the new grid is not only locally calibrated using the region's crash history, but is also a reduction of the previous system because it enables agencies to utilize existing data to justify their lighting decisions.

Table 5.8 Grid Assessment System for Road Segments – Frequency

Evaluation Grid (G1)									
Evaluated Element									
Length of Segment					Level (1, 2 or 3)			PD	
Description of Analyzed Criteria		Real Value	Classification Points (PT)					Old Score	New Score
			1	2	3	4	5		
Geometry									
1	Total number of lanes		≤4	5	6	7	≥8	0.15	1.96
4	Shoulder width		>3.0	2.5 to 3.0	1.8 to 2.5	1.2 to 1.8	<1.2	0.30	1.57
8	Frequent interchange distance		>6.5	5.0 to 6.5	3.5 to 5.0	1.5 to 3.5	<1.5	1.85	12.65
Operational									
9	Level of Service (Night-time) – ln AADT used as surrogate		A	B	C	D	≥E	3.05	1.63
Security (Accidents)									
12	Night-to-day accident ratio		<1.0	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	>2.0	4.90	2.18

An updated version of the new grid (G1) for road segments and highway ramps is presented on Table 5.8. As seen, not all factors from the old grid are included. This is due to several reasons.

One is that not all factors were available (as was the case of % of development, distance to development, slope and vertical gradient). Another reason is that some of factors were correlated, while others were not significant.

5.4.2 New Roads

The use of night-to-day accident ratio is not possible in the case of the design of new roads. For this reason, it is believed that the analysis could be based on a local calibration without the use of the night-to-day ratio (ND_ratio). Four new analyses were prepared for road segments and ramps from a frequency (Table 5.9) and severity (Table 5.10) perspective, this time without utilizing the night-to-day accident ratio (ND_ratio). Some researchers could argue that the use of such a ratio is not recommended in a statistical analysis given that it is constructed from the response itself. However, it should be noted that the ratio has no dimensions, its units cancel, therefore it represents only an estimate of deficiency from a crash perspective. Those practitioners and researchers not sharing such perspective can simply ignore the use of such a ratio and proceed without it, in the way illustrated below for new roads.

Table 5.9 Coefficients for the Calibration of Ramps and Segments – New Roads

RAMPS	Coef.	P-Value	SEGMENTS	Coef.	P-Value
Lanes	-0.24	0.56	Lanes	**-0.85**	**0.01**
Intersection	**1.29**	**0.04**	Intersection	**2.98**	**0.00**
Shoulder	-0.09	0.44	Shoulder	**-0.40**	**0.00**
ND_Ratio			ND_ratio		
Speed	**0.00**	**0.00**	Speed	**0.00**	**0.10**
Radius	0.00	0.68	Radius	**0.30**	**0.00**
lnAADT	**0.69**	**0.00**	lnAADT	**2.11**	**0.08**
Ramp_Length	0.00	0.65			

Table 5.10 Coefficients Calibration of Ramps & Segments – Severity Analysis – New Roads

RAMPS	Coef.	P-Value	SEGMENTS	Coef.	P-Value
Lanes	0.40	0.43	Lanes	**-1.00**	**0.02**
Intersection	-0.06	0.94	Intersection	**1.67**	**0.01**
Shoulder	**-0.69**	**0.00**	Shoulder	**-0.61**	**0.00**
ND_Ratio			ND_ratio		
Speed	**0.00**	**0.00**	Speed	**0.00**	**0.00**
Radius	0.00	0.52	Radius	0.00	0.43
lnAADT	0.20	0.44	lnAADT	**0.79**	**0.00**
Ramp_Length	0.00	0.94			

The results (Table 5.9 and Table 5.10) show that warrants for lighting of new highways should be based on the number of lanes, the presence of an intersection, the width of the shoulder, and expected traffic volume. The design speed can be ignored. This recommendation applies for both collision frequency and severity.

For ramps, the recommendation is a little more difficult given the limited amount of variables that resulted significant. Warrants for a ramp should be based on the proximity of an intersection and traffic volume from a frequency perspective, and on the width of the shoulder from a severity point of view. However, this poses an issue of over simplification. At this point the modeller is faced with the need to collect more data in order to include more variables into the analysis. Calibrated values of the scores for grid G1for new roads were obtained in the same way as explained in the previous section for existing roads. The only difference being the absence of night-to-day accident ratios.

Grids similar to those produced on Appendix A could be prepared for the case of new roads and based on the proposed scores found on Table 5.11.

Table 5.11 Calibrating the Coefficients for the Warrant of Lighting: New Roads

Calibration of Lighting Warrant for G1 based on collision Frequency-new roads									
RAMPS	Coef.	ABS	Weight	Score	SEGMENTS	Coef.	ABS	Weight	Proposed Score
Lanes				0.00	Lanes	-0.85	0.85	13%	2.57
Intersection	1.29	1.29	62%	12.44	Intersection	2.98	2.98	45%	8.97
Shoulder	-0.09	0.09	4%	0.83	Shoulder	-0.40	0.4	6%	1.22
ND_Ratio					ND_ratio				
Speed	0.00	0	0%	0.02	Speed	0.00	0	0%	0.00
Radius				0.00	Radius	0.30	0.3	5%	0.90
lnAADT	0.69	0.69	34%	6.71	lnAADT	2.11	2.11	32%	6.34
Ramp_Length									
SUMMATION		2.07	100%				6.65	100%	
Calibration of Lighting Warrant for G1 based on collision Severity- new roads									
RAMPS	Coef.	ABS	Weight	Score	SEGMENTS	Coef.	ABS	Weight	Score
Lanes				0.00	Lanes	-1.00	1.00	25%	4.92
Intersection				0.00	Intersection	1.67	1.67	41%	8.19
Shoulder	-0.69	0.69	100%	4.98	Shoulder	-0.61	0.61	15%	2.99
ND_ratio				0.00	ND_ratio				
Speed	0.00	0.00	0%	0.02	Speed	0.00	0.00	0%	0.01
Radius				0.00	Radius				
lnAADT				0.00	lnAADT	0.79	0.79	19%	3.89
Ramp_Length				0.00					
SUMMATION		0.69	100%				4.07	100%	

5.5 Conclusions

A new method to locally calibrate the warrant of lighting was presented in this chapter. The method is capable of using the crash-history to identify significant factors involved in the warrant of road lighting. Values of the scores corresponded to the relative importance of statistical factors in explaining nighttime crashes. The new grid system has two options and either frequency or severity could justify lighting. A case study based on hundreds of highway segments in the province of Quebec is used to illustrate the application of the method. It was revealed that for existing road segments, the number of lanes and width of the shoulder had a positive effect on collision frequency and severity. Also it was found that the frequency of intersections, traffic volume and night-to-day ratio had a negative impact on accident frequency and severity. Hence, frequency and severity formed the basis of two possible mechanisms to justify lighting. A similar analysis was prepared for ramps, however, the significant factors did not match; the density of intersections, traffic volume, and night-to-day accident ratios explained more frequent collisions, while from a severity perspective wider shoulders explained less severe accidents and traffic volume and night-to-day accident ratios explained more severe accidents. All these factors formed the basis of two similar mechanisms for ramps.

The use of night-to-day accident ratios was dropped for new roads, new statistical analyses were prepared, and it was found that, for road segments, having more lanes and wider shoulders resulted in less frequent and severe collisions (just as explained before for existing roads). The presence of intersections and traffic volume (AADT) resulted in more frequent and severe accidents. All these factors formed the basis for the new grid and their relative value of contribution in explaining the response was normalized and rescaled to produce the score on a locally calibrated grid G1. A similar analysis was conducted for ramps, resulting in only the width of a shoulder as being significant for severity and traffic volume and density of intersections as being significant for frequency.

CHAPTER 6 - IDENTIFYING RECOMMENDED LIGHTING LEVELS

6.1 Introduction

This chapter presents a method to identify recommended lighting levels for all forms of lighting characteristics currently used by practitioners as recommended by the industry standard (IESNA 2005). The identification of lighting levels is supported by statistical evidence of improvement of either accident frequency or severity as explained in each specific case. Hence, the main prerogative is that minimum required levels of luminance and illuminance, as well as maximum permissible variation of them, should be based on evidence that demonstrates reductions on the number of accidents (frequency) or their effects (severity). To understand the results found, it is important to have a clear understanding of the role of luminance and illuminance, as well as that of uniformity variation (from both of them). This chapter is divided in three main sections: the first one provides the reader with such understanding; the second one presents the methodology; the last one is divided into two case studies that illustrate the application of the method.

6.1.1 The role of luminance in night time collisions

In simple terms, luminance can be defined as the amount of light perceived by the human eye in a given context. Some studies have tested for the role of higher levels of average luminance with a driver's ability to detect and recognize signals, objects, and pedestrians (Easa *et al.* 2010). Such studies have found that higher levels of luminance do result in improvements of the perceived environment allowing the driver to make fewer errors and therefore resulting in lower levels of nighttime collisions. Most of these studies have used simulators or have manually collected luminance data at a controlled environment.

In general, researchers have looked into the role of luminance as a factor in nighttime collisions.

Worldwide practices in lighting design give preference to luminance as a design criterion for highways instead of illuminance. The Japanese guidelines (JSA 1988), the European code (CEN 2004) and the Austroads manual (AS/NZS 2010) all recommend the use of luminance from the perspective of the driver. Whenever the design involves high speeds or deals with the driver's ability to perceive objects and dangerous circumstances, luminance seems more adequate.

6.1.2 The role of illuminance in night time collisions

Illuminance (lux) is the amount of light arriving at the surface of the pavement, in contrast to luminance (candela/m2 or simply cd/m2), which is the amount of light being reflected towards the driver, as perceived by the driver.

According to Rea *et al.* (2009) for roads that are mainly used by non-motorized road users, illuminance can be used as a lighting criterion.

CIE (1992) found a large number of studies before 1992 revealing that night time accidents result in more severe collisions and that lighting did help reduce their frequency. Similar numbers have been found by TAC (2004) for intersections.

Several studies have been conducted to examine the relationship between roadway lighting levels and safety. Zhou and Hsu (2009) investigated how maintained illuminance levels impact the safety of pedestrians, and they found a higher frequency of pedestrian crashes at sites with low level of lighting, and similar findings were obtained by Isebrands *et al.* (2010) for Minnesota.

Neither transversal nor longitudinal uniformity has been identified to be significant (OPUS 2012) predictors of collision rates reductions.

6.2 Methodology

This section describes the method used to estimate recommended levels of lighting according to the ability of lighting characteristics (and their specific levels) to act as countermeasures. That is, it is expected that values of lighting above certain minimum average levels (or contained within a maximum variation) will contribute to reduce nighttime collisions. As suggested, the method utilizes a statistical approach to test various levels of lighting parameters in order to identify the breakpoint at which such parameters become incapable of explaining a beneficial effect through a reduction in accident rates.

Recommended values will correspond to specific types of roads according to their functional classification. A set of recommended values will be determined. Current values as recommended by IESNA (2005) will be used as an initial point. Figure 6.1 illustrates the method; the approach is repeated for average values of illuminance, luminance, and uniformities. The first step consists of selecting a trial level for each lighting explanatory variable, and a dummy variable is used to categorize segments above or below this level. The explanatory capability of the factor is learned from the statistical analysis. If decreasing the lighting variable helps to explain a lower number of collisions, then the procedure is repeated by setting up a new trial level. If the variable does not help explain a reduction in the frequency/severity of collisions, then the procedure is terminated and the previous significant lighting level that explains less collisions is used as recommended minimum value (Figure 6.1). The method must go in this fashion and not follow a continuous variable approach, because of the need to identify the minimum or maximum levels for each lighting parameters according to their capability to explain less lighting.

The dummy variable divides the data into two groups by assigning a value of one for those observations with values above the proposed lighting level, and zero for those below it. The statistical analyses will investigate if the first group explain more or less collisions (frequency or severity) as compared to the other group.

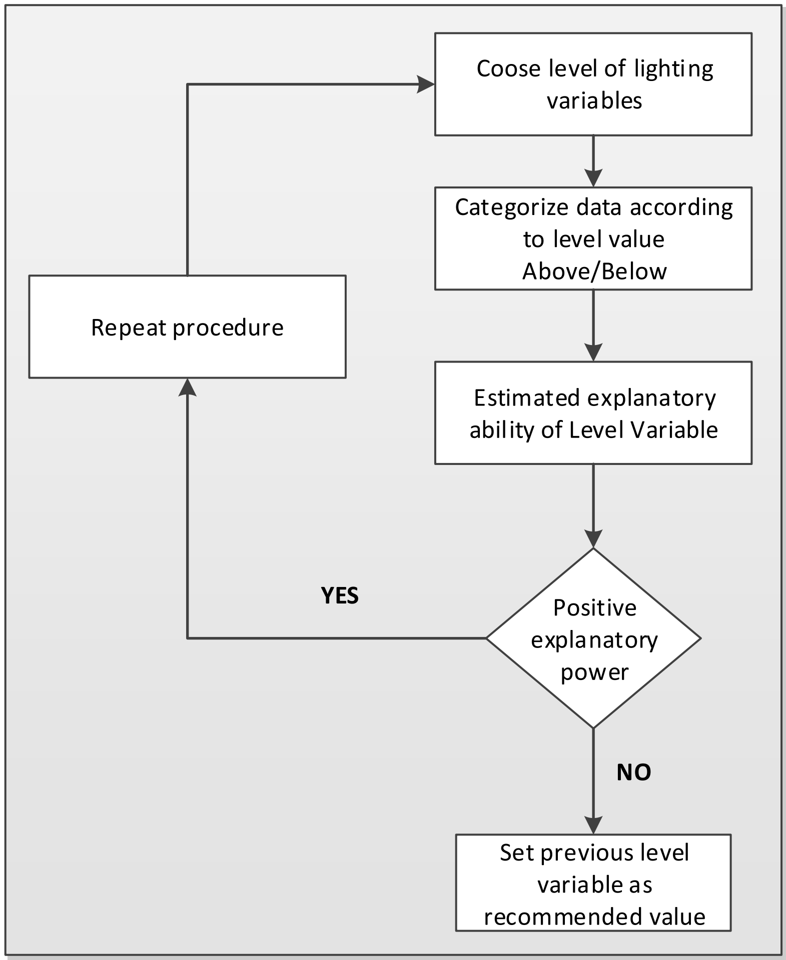

Figure 6.1 Method for the Estimation of Recommended Level

6.3 Case Study of the Arthabaska Region

6.3.1 Establishment of possible levels

The first step for the identification of recommended levels of lighting characteristics is to establish possible levels for the dummy variable. Levels of illuminance and luminance, along with their corresponding uniformity variation ratios, must be given possible values from which the analysis will determine the minimum maintained or maximum permissible variation, depending on the nature of the indicator at hand. Values of luminance and illuminance must be specified in terms of minimum maintained levels. Uniformity recommended values were given in terms of maximum permissible variation and they came from either an illuminance or a luminance perspective. Illuminance-based uniformity is computed as average over minimum, while luminance-based uniformity could be computed as average over minimum (uniformity 1) or as maximum over minimum (uniformity 2). The values of all such lighting indicators could be determined from either expert criteria or by testing which consists of checking whether a given level of lighting does explain less severe or frequent collisions. In this case study, several analyses were conducted and used to identify the ideal levels of lighting as those capable of effectively explaining fewer and less severe collisions. For each analysis, a dummy variable was codified on the database reflecting whether or not (1 or 0) the corresponding lighting level was satisfied at each road segment. Statistical analyses were run for each level of the corresponding lighting indicator. These values of possible lighting levels are shown in Table 6.1 below and were established from those given by IESNA (2005) which were called "low" for average illuminance and luminance and "high" for uniformity. The values were modified in the desired direction until the dummy variable took on a negative and significant value, which was interpreted as observing improvement from a safety perspective (frequency or severity). In the case study of Arthabaska, the dummy variable had specific values for each of the observed classes of roads (functional classification).

Table 6.1 Values for the Analysis (Arthabaska Region)

Road Type	Illuminance							Luminance								
	Average				Uniformity			Average			Uniformity 1			Uniformity2		
	Low[a]	Medium	High	**Very High***	High[a]	Medium	**Low***	Low[a]	Medium	**High***	High[a]	**Medium***	Low	High[a]	**Medium***	Low
Highway	6	9	12	**15**	3	2	**1**	0.4	0.6	**0.8**	3.5	**2**	0.5	6	**4**	2
Arterial	9	13	17	**21**	3	2	**1**	0.6	0.9	**1.2**	3.5	**2**	0.5	5	**3**	1
Collector	6	10	14	**18**	4	3	**2**	0.4	0.6	**0.8**	4	**2.5**	1	8	**6**	4
Local	4	8	12	**16**	4	3	**2**	0.3	0.5	**0.7**	6	**4**	2	10	**8**	s
No. of Observations	160	160	110	77	874	854	829	245	67	59	899	897	718	96	90	0
Percentage of Observ.	17%	17%	12%	8%	94%	92%	89%	26%	7%	6%	97%	96%	77%	10%	10%	0%

Note: * denotes recommended levels. [a] denotes IESNA reference level

6.3.2 Identification of recommended values

One analysis per possible level is prepared, while the remaining lighting variables are left outside the analysis and a dummy variable for the lighting indicator and its corresponding level is used to estimate if such form of lighting, explains less accidents. For this, the dummy variable (0 or 1) must obtain a negative coefficient and be significant. Another important detail is that the specification of the dummy variable follows a *bigger than* criteria for those indicators that require minimum maintained level, that is, for each value of the potential level, those observations with values above the given level are assigned a value of one (they fulfil or exceed the required level). For the uniformity ratios, one must use the *smaller than* criteria, as those values below the reference level represent better conditions in terms of lighting variations.

Results from the analysis are shown on Table 6.2. As seen, levels of illuminance, luminance, and uniformity which corresponded to significant reductions in accident rates were identified and highlighted back in Table 6.2.

The table shows that illuminance should be increased to a very high level in order to observe significant reductions on accident frequency. Variation of uniformity from illuminance should be reduced to low levels to show a reduction in accident rates of -0.574. Luminance should be increased to the range deemed high in order to observe a strong explanatory power on accident frequency (-1.078). Similarly, uniformity 2 values (from luminance) must be moved to those deemed medium in order to observe a reduction in accident frequency (-1.934) as seen in Table 6.2.

Table 6.2 Ability of Recommended Levels to Explain Less Frequent Accidents

	Level of Lighting Indicator	Coefficient	P-Value
Illuminance	Low	Insignificant	0.859
	Medium	Insignificant	0.859
	High	Insignificant	0.375
	Very High*	-0.588	0.037
Uniformity illuminance	High	Insignificant	0.13
	Medium*	-0.456	0.089
	Low	-0.574	0.016
Luminance	Low	Insignificant	0.822
	Medium	Insignificant	0.303
	High*	-1.078	0.022
Uniformity 1 from Luminance	High	Insignificant	0.343
	Medium*	-4.258	0.076
	Low	Insignificant	0.8
Uniformity 2 from Luminance	High	-1.859	0.001
	Medium*	-1.934	0.001
	Low	Insignificant	Insignificant

Note: * denotes recommended levels

6.4 Case Study of the Province of Quebec

6.4.1 Establishment of possible levels

As explained before in the case of Arthabaska, the first step consists of establishing possible levels of minimum maintained illuminance and luminance and of maximum permissible uniformity variation, depending on the nature of the indicator at hand. For this case study, the departure values were obtained from IESNA (2005) and modified accordingly until the desired effect was observed, that is, a negative and significant value of the coefficient for the observed dummy variable. This was interpreted as the ability of the lighting indicator to explain improvements from a road safety historical perspective (less frequent or severe).

A summary of each statistical analysis, containing observed effects and significance, as well as, observed coefficients for other variables are presented in the following section.

6.4.2 Identification of recommended values

The initial values of possible levels of lighting indicators are set following those provided by IESNA (2005) in the RP-80 report. For instance, lower levels of luminance and illuminance are preferable from energy-saving and cost perspectives. However, from a safety perspective, there is a minimum level that effectively reports less frequent and/or severe collisions. Hence, the analysis followed a trade-off between cost and safety.

Table 6.3 presents the results of the analyses for luminance. The dummy variable represented whether or not (1 or 0) each road segment satisfied at least the required level of luminance. A positive value of the dummy represented having more frequent and severe collisions at those segments where the dummy took a value of 1. A negative value signified having less frequent and severe collisions at those segments above the required level of luminance.

As seen in Table 6.3, a level of luminance of 0.6cd/m2 did not result in reductions in a collision's severity or frequency. A value of 1.5 (and above) resulted in statistically significant reductions of severity and frequency of nighttime motorized collisions, hence such a value (1.5 cd/m2) clearly becomes the recommended one for the province of Quebec.

Table 6.3 Identification of Recommended Levels for Luminance

Luminance-Levels Analysis of Severity								
	Level of Lighting Indicator on Dummy Variable							
	0.6 cd/m2		**1.5 cd/m2 ***		**1.7 cd/m2**		**1.9 cd/m2**	
Variable	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.29	0.00	0.25	0.00	0.27	0.00	0.27	0.00
Number_Lanes	-0.52	0.11	-0.26	0.43	-0.32	0.34	-0.36	0.27
Intersections	1.12	0.03	1.74	0.00	1.63	0.00	1.57	0.00
Shoulder_Width	-0.55	0.00	-0.61	0.00	-0.59	0.00	-0.59	0.00
Lnaadt_Night	0.78	0.00	0.70	0.00	0.75	0.00	0.76	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.24	0.00	0.33	0.00	0.28	0.00	0.27
DUMMY	0.40	0.05	**-3.39**	**0.01**	-4.74	0.18	-15.02	0.98
Effect	*negative*	*significant*	*positive*	*significant*	*positive*	*80% CI*	*positive*	*insignificant*
No.Obs.above	450		121		74		67	
Luminance-levels analysis of frequency								
	Level of Lighting Indicator on Dummy Variable							
	0.6 cd/m2		**1.5 cd/m2 ***		**1.7 cd/m2**		**1.9 cd/m2**	
Variable	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.67	0.00	0.48	0.00	0.49	0.00	0.48	0.00
Number_Lanes	-0.33	0.10	-0.09	0.63	-0.01	0.96	-0.18	0.35
Intersections	1.65	0.00	2.69	0.00	2.90	0.00	2.57	0.00
Shoulder_Width	-0.21	0.00	-0.29	0.00	-0.28	0.00	-0.28	0.00
Lnaadt_Night	0.50	0.00	0.48	0.00	0.52	0.00	0.49	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.00	0.00	0.05	0.00	0.04	0.00	0.02
DUMMY	1.14	0.00	**-2.08**	**0.00**	-3.85	0.00	-699.79	Not converge
Effect	*negative*	*significant*	*positive*	*significant*	*positive*	*80% CI*	*positive*	*insignificant*
No.Obs.above	450		121		74		67	

Note: * denotes recommended values

A similar analysis resulted from illuminance (Table 6.4). However, it was impossible to observe the desired effect under any tested level. This confirms that illuminance is incapable of explaining safety improvements (frequency or severity) on segments.

Table 6.4 Identifying Recommended Levels for Illuminance.

Illuminance-Levels Analysis-Severity								
Dummy level	**4 lux**		**6 lux**		**8 lux**		**15 lux**	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.29	0.00	0.30	0.00	0.30	0.00	0.29	0.00
Number_Lanes	-0.49	0.13	-0.54	0.10	-0.52	0.12	-0.38	0.24
Intersections	1.29	0.01	1.22	0.01	1.35	0.00	1.48	0.00
Shoulder_Width	-0.50	0.00	-0.45	0.00	-0.44	0.00	-0.55	0.00
Lnaadt_Night	0.60	0.00	0.51	0.00	0.46	0.00	0.72	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.39	0.00	0.43	0.00	0.55	0.00	0.21
Dummy	0.70	0.01	1.14	0.00	1.43	0.00	1.34	0.01
Effect	*negative*	*significant*	*negative*	*significant*	*negative*	*significant*	*negative*	*significant*
No.Obs.Above	164		113		80		19	
Illuminance-Levels Analysis-Frequency								
Dummy level	**4 lux**		**6 lux**		**8 lux**		**15 lux**	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.70	0.00	0.74	0.00	0.76	0.00	0.64	0.00
Number_Lanes	-0.40	0.10	-0.49	0.06	-0.44	0.08	0.14	0.50
Intersections	2.36	0.00	2.43	0.00	2.69	0.00	2.59	0.00
Shoulder_Width	-0.11	0.13	-0.12	0.10	-0.13	0.08	-0.23	0.00
Lnaadt_Night	0.28	0.00	0.29	0.00	0.28	0.00	0.46	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.06	0.00	0.08	0.00	0.17	0.00	0.00
Dummy	1.91	0.00	2.22	0.00	2.50	0.00	2.77	0.00
Effect	*negative*	*significant*	*negative*	*significant*	*negative*	*Significant*	*negative*	*significant*
No.Obs.Above	164		113		80		19	

Table 6.5 contains the results for uniformity based on illuminance. The dummy variable for uniformity captures observations having the given level or better (lower) uniformity variation, hence it is only at a value of uniformity of 1.5 that the dummy variable explains less severe accidents.

Table 6.5 Identifying Recommended Levels for Illuminance Variation.

Uniformity Illuminance Levels Analysis-Severity								
Dummy level	**4 times**		**3 times**		**2 times**		**1.5 time ***	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.29	0.00	0.29	0.00	0.28	0.00	0.26	0.00
Number_Lanes	-0.43	0.19	-0.42	0.20	-0.47	0.16	-0.45	0.16
Intersections	1.55	0.00	1.54	0.00	1.48	0.00	1.02	0.04
Shoulder_Width	-0.60	0.00	-0.59	0.00	-0.58	0.00	-0.56	0.00
Lnaadt_Night	0.83	0.00	0.83	0.00	0.81	0.00	0.76	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.28	0.00	0.27	0.00	0.26	0.00	0.32
DUMMMY	0.14	0.54	0.08	0.72	-0.07	0.73	**-0.60**	**0.00**
Effect	*negative*	*insignificant*	*negative*	*Insignificant*	*negative*	*insignificant*	*Positive*	*significant*
No.Obs.Below	1133		1101		1040		632	
Uniformity_Illuminance Levels Analysis-Frequency								
Dummy level	**4 times***		**3 times***		**2 times***		**1.5 time***	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.55	0.00	0.55	0.00	0.56	0.00	0.64	0.00
Number_Lanes	-0.26	0.18	-0.31	0.11	-0.51	0.01	-0.20	0.32
Intersections	2.37	0.00	2.36	0.00	2.33	0.00	1.57	0.00
Shoulder_Width	-0.24	0.00	-0.23	0.00	-0.24	0.00	-0.27	0.00
Lnaadt_Night	0.58	0.00	0.57	0.00	0.53	0.00	0.50	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.07
DUMMMY	-0.46	0.00	-0.49	0.00	-0.78	0.00	**-1.47**	**0.00**
Effect	*positive*	*significant*	*Positive*	*Significant*	*Positive*	*Significant*	*Positive*	*significant*
No.Obs.Below	1133		1101		1040		632	

Note: * denotes recommended values

It is important to note that from the perspective of uniformity variation, as measured by average over minimum illuminance, ratios of uniformity variation of 1.5 are required to explain less severe accidents. From a frequency perspective, any of the ratios explained a lower number of collisions, therefore from this angle any uniformity up to 4 could be recommended. However, the final selection of uniformity values should be based on the more critical of the two approaches (frequency and severity). Values for uniformity of luminance (maximum over minimum) are shown on Table 6.6. One can see that uniformity variation for maximum over minimum luminance can vary anywhere from 1 to 8 without affecting the safety of drivers from frequency or severity of observed accidents. After this value, one finds a dummy variable explaining more severe and frequent accidents, possibly from glare from large contrast between the brightest and darkest spots for the driver's.

Table 6.6 Identification of Permissible Levels of Luminance Variation U_2

Uniformity Luminance (Max/Min) Levels Analysis-Severity								
Dummy level	**1.1 times**		**6 times**		**8 times***		**12 times**	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.29	0.00	0.29	0.00	0.29	0.00	0.29	0.00
Number_Lanes	-0.52	0.11	-0.52	0.11	-0.52	0.11	-0.43	0.18
Intersections	1.12	0.03	1.11	0.03	1.11	0.03	1.52	0.00
Shoulder_Width	-0.55	0.00	-0.55	0.00	-0.55	0.00	-0.59	0.00
Lnaadt_Night	0.78	0.00	0.78	0.00	0.78	0.00	0.82	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.24	0.00	0.24	0.00	0.24	0.00	0.27
DUMMMY	-0.40	0.05	-0.41	0.04	**-0.41**	**0.04**	12.70	0.99
Effect	*negative*	*significant*	*Negative*	*significant*	*negative*	*significant*	*positive*	*insignificant*
No.Obs.Below	947		948		950		1394	
Uniformity Luminance (Max/Min) Levels Analysis-Frequency								
Dummy level	**1.1 times**		**6 times**		**8 times***		**12 times**	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.67	0.00	0.67	0.00	0.67	0.00	0.53	0.00
Number_Lanes	-0.33	0.10	-0.33	0.10	-0.32	0.10	-0.25	0.20
Intersections	1.65	0.00	1.65	0.00	1.64	0.00	2.50	0.00
Shoulder_Width	-0.21	0.00	-0.21	0.00	-0.21	0.00	-0.25	0.00
Lnaadt_Night	0.50	0.00	0.50	0.00	0.50	0.00	0.57	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
DUMMMY	-1.14	0.00	-1.14	0.00	**-1.14**	**0.00**	118.89	0.30
Effect	*positive*	*significant*	*Positive*	*significant*	*positive*	*Significant*	*positive*	*significant*
No.Obs.Below	947		948		950		1394	

Note: * denotes recommended values

Values of luminance uniformity 1 (Table 6.7) corresponding to average over minimum luminance resulted as insignificant and no conclusion could be withdrawn from them. The problem came from the data; 95% of the data ranged from 1 to 1.05 and 99% of the values of uniformity 1 had values that ranged between 1 and 1.2.

Table 6.7 Identification of Recommended Levels for Luminance Variation U_1

Uniformity_Luminance (Avg/Min) Levels Analysis-Severity								
Dummy level	**1.05 times**		**1.1 times**		**1.15 times**		**1.2 times**	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.28	0.00	0.28	0.00	0.29	0.00	0.29	0.00
Number_Lanes	-0.36	0.27	-0.39	0.23	-0.40	0.22	-0.38	0.26
Intersections	1.59	0.00	1.63	0.00	1.60	0.00	1.57	0.00
Shoulder_Width	-0.61	0.00	-0.60	0.00	-0.59	0.00	-0.59	0.00
Lnaadt_Night	0.84	0.00	0.81	0.00	0.82	0.00	0.82	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.32	0.00	0.30	0.00	0.28	0.00	0.28
DUMMMY	0.65	0.17	1.15	0.24	0.92	0.42	1.56	0.39
Effect	*negative*	*Insignif.*	*negative*	*Insignif.*	*negative*	*Insignif.*	*negative*	*Insignif.*
No.Obs.Below	1337		1379		1388		1390	
Uniformity_Luminance (Avg/Min) Levels Analysis-Frequency								
Dummy level	**1.05 times**		**1.1 times**		**1.15 times**		**1.2 times**	
	Coeff	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**	**Coeff**	**P-Value**
ND_Ratio _One	0.52	0.00	0.53	0.00	0.53	0.00	0.53	0.00
Number_Lanes	-0.24	0.22	-0.25	0.20	-0.26	0.20	-0.26	0.19
Intersections	2.50	0.00	2.50	0.00	2.50	0.00	2.49	0.00
Shoulder_Width	-0.26	0.00	-0.25	0.00	-0.25	0.00	-0.25	0.00
Lnaadt_Night	0.57	0.00	0.56	0.00	0.56	0.00	0.56	0.00
Speed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radius	0.00	0.03	0.00	0.02	0.00	0.02	0.00	0.02
DUMMMY	0.21	0.52	0.23	0.68	0.22	0.79	0.15	0.87
Effect	*negative*	*Insignif.*	*negative*	*Insignif.*	*negative*	*Insignif.*	*negative*	*Insignif.*
No.Obs.Below	1337		1379		1388		1390	

6.5 Conclusions

Lighting parameters were estimated for the recommended minimum levels of illuminance and luminance (IESNA 2005) and for the maximum variation of uniformity ratios. For the case study of the Arthabaska region, calibrated levels of illuminance suggested an increase in average values, as well as in average maintained luminance along with more strict (reduced) variation on uniformity. All these to obtain truly significant reductions in accident rates. The specific values depended on the functional classification of the roads.

Levels of luminance for highways in Quebec should increase to at least 1.5 cd/m2, instead of the currently used level of 0.6 cd/m2; both frequency and severity of road collisions diminish at those sites with values above 1.5 cd/m2. Variation of illuminance (average to minimum) should be based on a value of 1.5. From the perspective of uniformity of luminance, the design can tolerate up to 8 times between the brightest and darkest spots of the driver's visual range. Variations larger than 8 times should be avoided as they will likely result in negative effects from a safety perspective and could represent the fact that the driver is now under the presence of some degree of glare. From the perspective of this analysis, levels of luminance-based uniformity, given by average to minimum (uniformity 1), cannot be used to conclude in regards to recommended levels. The fact that average and minimum luminance values were so close suggests that we are already in the presence of a very consistent lighting environment in the form of luminance.

CHAPTER 7 - CONCLUSIONS AND FUTURE RESEARCH

7.1 Conclusions

7.1.1 From the literature review

A comprehensive literature review of the role of lighting on night time collisions found that illuminance should be used in the presence of pedestrians and low speed vehicles, and that luminance is preferred for highway segments. The literature identified that both frequency and severity should be used, as they serve different purposes.

It was concluded based on the literature that there is a need to count with a calibration method for the warrant of lighting and that such a method should be based on crash history. It was also concluded that current lighting warrants must go beyond the current criteria and integrate levels of lighting into it to ensure the reduction in collision frequency and severity.

7.1.2 From the pilot study

Co-linearity analysis must precede any statistical analysis aimed to calibrate or identify recommended roadway lighting. Co-linear elements, even if present on the grid, must be dropped off the analysis and subsequently off the calibrated warrants (*i.e.* number of lanes and width of the road).

Severity of collisions must be used in combination with frequency. It was also concluded that luminance is better for the statistical analysis of the role of lighting. Even though illuminance is incapable of explaining nighttime collisions, it was not concluded that its use should be dropped, but rather explored on each analysis as it may be useful for certain types of sites such as intersections or junctions.

7.1.3 From the calibration of the warrant system of lighting

It was recommended the use of a new method to locally calibrate the warrant of lighting. The method is capable of using the crash-history to identify significant factors involved in the warrant of road lighting and properly justify the warrant from a scientific perspective. The new grid system provides the decision maker with two options to justify lighting: frequency or severity.

A case study based on hundreds of highway segments in the province of Quebec allowed the following conclusions: for existing road-segments, the number of lanes and width of the shoulder must be used in the grid in addition to the frequency of intersections, traffic volume and night-to-day ratios. It was concluded that two possible mechanisms must be used for the grid, depending on the explanatory power of the aforementioned elements on frequency or severity.

Similarly, for a grid to warrant lighting on ramps, one should consider the presence of an intersection, traffic volume, and night-to-day accident ratios from a frequency perspective, while from a severity perspective wider shoulders, traffic volume, and night-to-day accident ratios should be considered.

The use of night-to-day accident ratios must be dropped for new roads. In this case, the grid system should consider the number of lanes, the width of the shoulder, the presence of intersections, and traffic volume (AADT).

For ramps, the new grid for new highways must consider the width of the shoulder for severity and traffic volume and presence of intersections for frequency.

7.1.4 From the identification of recommended lighting levels

IESNA recommended values are minimums (as well established by this organization) and practitioners must follow the mechanism herein presented to find recommended levels for their designs.

For the case study of the Arthabaska region, calibrated levels of illuminance, as well as average maintained luminance, must be increased along with more strict (reduced) variations on uniformity in order to obtain truly significant reductions in accident rates.

Levels of luminance for lighting on highways in Quebec must be increased to at least 1.5cd/m2 instead of the currently used level of 0.6cd/m2; both frequency and severity of road collisions diminish at those sites at such values. Variation of illuminance (average to minimum) must be reduced to 1.5 times. If the decision of lighting is done, then luminance-based uniformity of average over minimum for Quebec highways must observed a very uniform consistent design.

Non-illuminated roads are preferable to those with significant variations of the amount of light landing on the surface of the road (illuminance-based uniformity variation). From the perspective of uniformity of luminance, the design can tolerate up to 8 times for severity and frequency between the brightest and darkest spots. Variations larger than 8 times should be avoided, as they will likely result in negative effects of more severe or frequent collisions. It was concluded that this observation is likely linkable to the fact that one is now under the presence of some degree of disability glare.

Luminance-based uniformity variation given by average to minimum (uniformity 1) cannot be used to conclude in regards to recommended levels.

7.1.5 Novelty of this doctoral thesis

This research proposes a method for the calibration of the warrant of roadway lighting. The method integrates AASHTO 2005 and IESNA 2005 methods. It provides an evidence-based mechanism to connect statistical analyses of night time collisions with lighting warrants and levels. A new method over the basis of such a mechanism is proposed and used to calibrate lighting warrants to local circumstances and to find effective levels of lighting that will reduce the number of roadway collisions and their degree of severity. In this sense, the methods expand current industry standards and reformulate them from the perspective of frequency and severity criteria. These methods provide the decision maker with a justifiable way to support his/her recommendations and place him/her in a stronger position from a liability perspective, given that his/her decisions are supported over statistical analysis that link lighting decisions with expected reductions on night time collisions frequency and severity.

The methods proposed herein can be used by any transportation agency in the world, not necessarily just those in North America, as they are generic and easy to follow. For researchers, the evidence-based methods create a new mechanism that could be used in similar problems and applications, such as the design of civil engineering facilities and infrastructure and to support decision making from a policy perspective. Also researchers will have access to a large database applicable to future analysis involving lighting and road safety.

7.2 Future Research Work

This research explores the identification of minimum recommended levels from an evidence-based approach. Future research could explore the optimization of such levels which itself could justify another PhD dissertation.

Future research (possibly at a master's thesis level) can contrast the selection of lighting from both the traditional system and the one herein proposed in order to investigate the practical implications on resources and the degree of agreement from a spatial perspective (geographical location of lighting).

Other elements left for future research work are:

1. Attempt to adapt the method herein presented to those circumstances when no crash data is available, perhaps through the use of indicators of risk or some other approach.

2. Adapt the method herein presented to those circumstances in which non-standard levels of illumination are currently being provided.
3. Explore the use of levels of risk and latent class models in the methods herein proposed.
4. Explore the role of light color as an additional variable to the method.
5. Explore the use of glare and other visibility indicators in addition to the lighting measurements of luminance and illuminance conducted herein.

REFERENCES

AASHTO. 2005. Roadway lighting design guide. American Association of State and Highway Transportation officials. Washington.

American Association of State Highway Transportation Officials. Highway Safety Manual. 2010. Washington DC USA: AASHTO.

Abdel-Aty, M., Keller, J., and Brady, P.A. 2005.Analysis of Types of Crashes at Signalized Intersections by Using Complete Crash Data and Tree-Based Regression. Transportation Research Record: Journal of the Transportation Research Board; 1908: pp. 37-45.

Amador, L. and Willis, C. 2013. Demonstrating a Correlation between the Maturity of Road Safety Practices and Road Safety Incidents. In Press, Traffic Injury Prevention.

Amador, L. and Mrawira, D., 2011. Bayesian Regression in Pavement Deterioration Modeling: Revisiting the AASHO Road Test Rut Depth Model. Proceedings of the 90th Annual Congress of the Transportation Research Board. Washington DC, USA.

Armas, J. and Laugis, J. 2007. Road safety improved road lighting: Road Lighting Measurements and Analysis. Doctoral School of Energy and Geo-Technology. Kuressaare, Estonia.

AS/NZS. 2010. Council of Standards of Australia and New Zealand. Lighting for roads and public spaces. AS/NZS 1158.1.2. Australian/New Zealand Standard

Baek, J. and Hummer, J.E. 2008. Collision Models for Multilane Highway Segments to Examine Safety of Curbs. Transportation Research Record: Journal of the Transportation Research Board; 2083: 48-56.

Baglivo, J. A., 2004. Mathematica laboratories for mathematical statistics. Society for Industrial & Applied Mathematics. Philadelphia, USA.

Barua, U., Azad, A.K., and Tay, R. 2010. Fatality Risk of Intersection Crashes on Rural Undivided Highways in Alberta, Canada. Transportation Research Record: Journal of the Transportation Research Board; 2148: pp. 107-115.

Bedford, T., Cooke, R., 2001. Probabilistic risk analysis. Cambridge University Press, Cambridge, UK.

Bishop, R. 2007. Camera-Controlled LED Arrays Pinpoint Danger. European Automotive Design (1 May 2007).

Box, P.C. 1989. Major Road Accident Reduction by Illumination. Transportation Research Record 1247, TRB, National Research Council, Washington, D.C., pp. 32-38.

Box, P.C. 1970. Relationship between illumination and freeway accident. Transportation Research Record, Transportation Research Board of the National Academies. No. 416. pp. 10-20

Bruneau, J.F. and Morin, D. 2005. Standard and Nonstandard roadway lighting compared with darkness at rural intersections. Transportation Research Record: Journal of the transportation research board of the national academies. Washington, DC., 2005, pp.116-122.

Bullas, J.C. 2004.Tyres. Road Surfaces and Reducing Accidents: A Review: A report on Research Carried Out for the AA Foundation for Road Safety Research and the County Surveyors' Society. Available at: http://www.roadsafetyfoundation.org/media/11323/aa_foundation_fdn34.pdf, accessed on August 05, 2013.

Bullough, J., Donnell, E.T. and Rea, M. 2012. To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. Accident Analysis and Prevention Vol.53. pp. 65-77

Bullough, J.D., Rea, M.S. and Zhou, Y. 2009. Analysis of visual performance benefits from roadway lighting. New York.

Cai, H. and Li, L. 2014. Measuring Light and geometry data of roadway environments with a camera. Journal of Transportation Technologies. pp. 44-62

CEN. 2004. European Committee for Standardization. Road lighting. CEN/TR 13201.

CIE. 2007. Road Transport lighting for developing countries. CIE 180-2007. International Commission on illumination. Austria.

CIE. 1992. International Commission on Illumination. Road Lighting as an Accident Countermeasure. 1992. Austria: CIE Publications; 1992. Research Report CIE093-1992.

CIE. 1976. Glare and Uniformity in Road Lighting Installations. CIE 031-1976. International Commission on illumination. Austria

City of Edmonton. 2014. Street Lighting. Available online at http://www.edmonton.ca/transportation/on_your_streets/street-lighting.aspx [May 23 2014]

Cobb, J., Hargroves, R.A., Marsden, A.M., and Scott, P.P. 1979. Road Lighting and Accidents. Proceedings of Meeting of the International Commission on Illumination (CIE) pp-79-63, Kyoto, Japan.

COMT. 2013. Canada's National Highway System Annual Report 2012. Manitoba. pg. 17.

Congdon, P.D. 2010. Applied Bayesian Hierarchical Methods. Chapman & Hall/CRC. Taylor & Francis Group. Boca Raton, Florida.

Cornwell, P.R. and Mackay, G.M. 1972. Public Lighting and Road Accidents. Traffic Engineering and Control, pp. 142-144

CTC and Associates LLC. 2013. Highway Lighting Practices and Policies. Caltrans Division of Research and Innovation. Preliminary Investigation. Available online at: http://www.dot.ca.gov/research/researchreports/preliminary_investigations/docs/highway_lighting_practices_and_policies_preliminary_investigation.pdf [February 26, 2015]

Dailymail, 2010. New dark age on our streets: Up to 75% of councils are dimming the lights to save money. Available online http://www.dailymail.co.uk/news/article-1328243/Up-75-cent-councils-dimming-street-lights-save-money.html

De Leur, P., Thue. L. and Ladd, B. 2010. Collision Cost Study. Final Report prepared for Capital Region Intersection Safety Partnership (CRISP), Edmonton, Alberta, pp. 76-77.

Desktopwallpapers.me. 2015. Available online at http://www.desktopwallpapers4.me/world/street-lamp-17581/ Accessed on June 5 2015

DMD & Associates Ltd. 2009. Energy efficient street lighting strategies for Nova Scotia Municipalities. Report. Union of Nova Scotia Municipalities. UNSM. British Columbia, Canada.

Easa, S., Reed, M., Russo, F., Dabbour, E., Mehmood, E., and Curtis, K. 2010. Effect of increasing road light luminance on night driving performance of older adults. Intern. J.App. Sci., Eng. and Techn., 6(1), pp. 41-48.

Eassa, S. M. and You, Q. C. 2009. Collision Prediction Models For Three-Dimensional Two-Lane Highways: Horizontal Curves. Transportation Research Record: Journal of the Transportation Research Board; 2092, pp. 128-136.

El-Basyouny, K. and Sayed, T. 2010. Full Bayes Approach to Before-and-After Safety Evaluation with Matched Comparisons: Case Study of Stop-Sign In-Fill Program. Transportation Research Record: Journal of the Transportation Research Board, 2148, pp. 1-8.

E-streetlight. 2014. The E-streetlighting project. Available online at http://www.e-streetlight.com/. Accessed online [June 14 2014]

Elvik, R. 1995. Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure. Transportation Research Record No.1485, Transportation Research Board of the National Academies, National Research Council, D.C., pp. 112-123.

Feldman, M., Manzi, J.G. and Mitman, M.F. 2010. An Empirical Bayesian Evaluation of the Safety Effects of High-Visibility School (Yellow) Crosswalks in San Francisco. Transportation Research Record: Journal of the Transportation Research Board.

Gamerman, D., Lopes, H.F. 2006. Markov Chain Monte Carlo stochastic simulation for Bayesian inference, 2nd ed. Chapman & Hall/CRC. London, UK.

Gelman, A., Hill, J., 2008. Data analysis using regression and multilevel/hierarchical models. Cambridge University Press. Cambridge, UK.

Gilfillan, G. 2000. Road Safety Benefits of Liquid Anti-Icing Strategies and Agents: Kamloops, British Columbia, Canada. Transportation Research Record: Journal of the Transportation Research Board.; 1700, pp. 24-31.

Government of Canada. Canadian Motor Vehicle Traffic Collision Statistics: 2012. Transport Canada. [Online] October 24, 2012. [Cited: April 16, 2013.] http://www.tc.gc.ca/eng/roadsafety/tp-1317.htm.

Greene, W.H. 2003. "Econometric Analysis. Pearson Education". Prentice Hall, New Jersey. pp. 750.

Griffith, M.S. 1994. Comparison of the Safety of Lighting Options on Urban Freeways. Public Roads, Vol. 58, No. 2, pp.8-15.

Hadayeghi, A., Malone, B., and De Gannes, R. 2006. Development of New Crash Experience Warrants for Traffic Signals in Ontario, Canada. Transportation Research Record: Journal of the Transportation Research Board; 1953, pp. 120-127.

Haque, M.M. and Chin, H.C. 2010. A Mixed Logit Analysis on the Right-Angle Crash Vulnerability of Motorcycles at Signalized Intersections. Transportation Research Record: Journal of the Transportation Research Board.

Hauer, E. 1997. "Observational Before-After Studies in Safety". Pergamon, Washington, D.C.

Hargroves, R.A., and Scott, P.P. 1979. Measurements of Road Lighting and Accident Results. Public Lighting, 44, pp. 213-221.

Heydari, S., Miranda-Moreno, L.F. and Amador, L. 2013."Full Bayes Methods for Road Safety Studies: Does Prior Specification Matter?", Journal of Transportation Research Record, in press.

Hiscocks, P.D. 2011. Measuring Luminance with a Digital Camera [online]. Available at www.ee.ryerson.ca/~phiscock/astronomy/light.../luminance-notes.pdf. Retieved August 31 2013.

Hummer J.E., Rasdor, W. and Findley, D.J. 2010. Curve Collisions: Road and Collision Characteristics and Countermeasures. Journal of Transportation Safety & Security; 2(3), pp. 203-220.

IESNA. 2008. lluminating Engineering Society of North America. Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products. LM-79-08. New York: IESNA.

IESNA. 2006. lluminating Engineering Society of North America. Technical Memorandum TM-12-06 Spectral Effects of Lighting on Visual Performance at Mesopic Light Levels, New York: IESNA.

IESNA. 2005. Illuminating Engineering Society of North America. Roadway Lighting: American Standard Practice for Roadway Lighting. 2005. New York: IESNA Publication; Report RP-08-00.

IESNA. 1989. Illuminating Engineering Society of North America. Value of Public Roadway lighting. IE SCP-31-1989. Illuminating Engineering Society of North America. New York

Isebrands, H.N., Hallmark, S.L., Li, W., McDonald, T., Storm, R. and Preston, H. 2010. Roadway Lighting shows safety benefits at rural intersections. Journal of Transportation Engineering. Vol 36, No. 11. pp. 949 – 955

Jackett, M. and Firth, W. 2013. Quantifying the impact of road lighting on road safety - A New Zealand Study. International Association of Traffic and Safety Sciences. IATSS Research, Vol 36, pp. 139-145

JAGS 2014, Just another Gibbs Sampler. Available online [February 14, 2014.] http://mcmc-jags.sourceforge.net/

JSA. 1988. Japanese Standard Association: Japanese Industrial Standard of Lighting for Roads JIS Z 911.

Jonsson, T., Ivan, J.N., and Zhang, C. 2007.Crash Prediction Models for Intersections on Rural Multilane Highways: Differences by Collision Type. Transportation Research Record: Journal of the Transportation Research Board.

Karlaftis, M.G. 2002. Effects of Road Geometry and Traffic Volumes on Rural Roadway Accident Rates. Journal of Accident Analysis & Prevention.; 34(3), pp. 357-365.

Lamm, R., Kloeckner, J.H., and Choueiri, E.M. 1985. Freeway Lighting and Traffic Safety: A Long Term Investigation. Transportation Research Record. No. 1027, Transportation Research Board of the National Academies, National Research Council, Washington, D.C., pp. 57-63.

Lennie, P., Pokorny, J. and Smith, V.C. 1993. J. Opt. Soc. Am. No. 10, pp. 1283-1293.

Lord, D. and Persuad, B. N. 2000. Accident Prediction Models With And Without Trend: Application Of The Generalized Estimating Equations Procedure. Transportation Research Record: Journal of the Transportation Research Board; 1717, pp.102-108.

Lord, D. and Miranda-Moreno, L.F. 2008. Effects of the low sample mean values and the small sample size on the estimation of the fixed dispersion parameter of Poisson-gamma models: A Bayesian Perspective. Safety Science. 46, pp. 751-770.

Lovegrove, G. and Sayed, T. 2006. Using Macro-Level Collision Prediction Models in Road Safety Planning Applications. Transportation Research Record: Journal of the Transportation Research Board; 1950, pp.73–82.

Lunn. D., Thomas, A., Best, N.G.,Gilks, W. and Spiegelhalter D.J. 2000. WINBUGS – A Bayesian modeling framework: Concepts, structure and extensibility. Statistics and Computing. Volume 10, pp. 325 – 337.

Lyon, C., and Persuade B. 2002. Pedestrian Collision Prediction Models for Urban Intersections. Transportation Research Record: Journal of the Transportation Research Board; 1818, pp.102-107.

Malyshkina, N. and Mannering, F., 2010. Empirical assessment of the impact of highway design exceptions on the frequency and severity of vehicle accidents. Accident Analysis and Prevention 42(1), pp. 131-139.

Malyshkina, N., Mannering, F. and Tarko, A., 2009. Markov switching negative binomial models: An application to vehicle accident frequencies. Accident Analysis and Prevention 41(2), pp. 217-226.

Mei-ling, S., Hu, T.W., Keeler, T.E., Ong, M., and Sung, Y. 2004. The Effect of a Major Cigarette Price Change on Smoking Behavior in California: A Zero-Inflated Negative Binomial Model. Health Economics; 13(8), pp.781-791.

Mitra, S. and Washington, S., 2006. On the nature of over-dispersion in motor vehicle crash prediction models. Accident Analysis and Prevention. 39, pp. 459–468.

Monsere, C., and Fischer, E. 2008. Safety Effects of Reducing Freeway Illumination for Energy Conservation. Accident Analysis and Prevention, 40(5), pp. 1773-1780.

Mullahy, J. 1986. Specification and testing of some modified count data models. Journal of Econometrics, 33, pp. 341-365.

OpenBUGS (2014). Open Source Software for Bayesian using GIBBS Sampler. Available online [February 05, 2014.] http://mathstat.helsinki.fi/openbugs/

OPUS. 2012. How does the level of road lighting affect crashes in New Zealand - A pilot study. Opus International Consultants Central Laboratories. New Zealand.

Oya, H., Ando, K., and Kanoshima, H. 2002. A Research on Interrelation Between Illuminance at Intersections and Reduction in Traffic Accidents. J. Light & Vis. Env., 26(1), pp. 29-34.

Peng, Y., and D. Lord. 2011. Applying the latent class growth model into a longitudinal analysis of traffic crashes. Transportation Research Record2236, pp. 102-109.

Persaud, B., Lan, B., Lyon, C. and Bhim, R. 2009. Comparison of empirical Bayes and full Bayes approaches for before–after road safety evaluations. Accident Analysis and Prevention. Volume 42, Issue 1, pp. 38-43.

Photolux, 2012. Photolux 3.2 User's Guide [online]. Softenergy consultants. Available at http://www.photolux-luminance.com/images/stories/photolux/download/Photolux_public_lighting_3_2_Users_guide_

Eng. pdf [December 27 2013]

Preston, H. and Schoenecker, T. 1999. Safety Impacts of Street Lighting at isolated rural intersections. Final report. Minnesota Department of Transportation.

Rea, M.S., Bullough, J.D. and Zhou, Y. 2009. A method for assessing the visibility benefits of roadway lighting. Lighting Research Technology. No. 42. pp. 215-241

Rea, M.S., Bullough, C.R.F., Brons, J.A. and Van Derlofske, J. 2009. Review of the safety benefits and other effects of roadway lighting.

Sabey, B.E., and Johnson, H.D. 1973. Road Lighting and Accidents: Before and After Studies on Trunk Road Sites. Transport and Road Research Laboratory, Report LR 586, Crowthorne, Berkshire, UK.

Santiago-Chaparro, K. R., Qin, X., and Noyce, D.A. 2010. Proposed Safety Index Based on Risk-Taking Behavior of Drivers. Transportation Research Record: Journal of the Transportation Research Board; 2147, pp.51-57.

Scott, P.P. 1980. The Relationship between Road Lighting Quality and Accident Frequency. TRRL Report No. 929. Transport and Road Research Laboratory.

Sharma, A.K., Landge, V.S. 2013. Zero Inflated Negative Binomial For Modeling Heavy Vehicle Crash Rate On Indian Rural Highway. International Journal of Advances in Engineering & Technology.

SAAQ. 2012. *Societe de l'Assurance Automobile du Quebec*. *Bilan Routier* 2012. C-5195.

Sullivan. 2009. Relationships between Lighting and Animal-Vehicle Collisions. Report No. UMTRI-2009-35. Michigan, US.

The National UAE. 2014. Dubai's RTA to dim street lights in areas with low traffic. Available at http://www.thenational.ae/uae/environment/dubais-rta-to-dim-street-lights-in-areas-with-low-traffic [August 29 2014]

TAC. 2004. The Canadian Guide to In service Road Safety Reviews. Transportation Association of Canada. Ottawa.

TAC. 1999. Geometric Design Guide for Canadian Roads. Transportation Association of Canada. Ottawa.

Transportation Association of Canada. Guide for the Design of Roadway Lighting. 2006. Ottawa Canada: TAC Publications.

Transportation Association of Canada. 2004. The Canadian Guide to In-Service Road Safety Reviews. Ottawa Canada: TAC Publications;

Transports Quebec. 2012. *Norm éclairage routier*. *Manuel de conception d'un système d'éclairage routier*. Quebec Minister of Transportation. 2012.

Walton, N.E. Warrants for highway lighting. National Cooperative Highway research program, National Research Council. Report NCHRP-152, 1974.

Wanvik, P.O. 2009. Effects of Road Lighting: An Analysis Based on Dutch Accident Statistics, 1987-2006. Accident Analysis and Prevention, 41(1), pp. 123-128.

Wilde, G. 1994. Target risk: Dealing with the Danger of Death, Disease and Damage in Everyday Decisions. PDE Publications, Toronto.

WinBUGS 2014. Windows Bayesian using GIBBS Sampler. Available online [March 10, 2014.] http://www.mrc-bsu.cam.ac.uk/software/bugs/the-bugs-project-winbugs/

World Bank. 2004. World report on road traffic injury prevention. World Health Organization. Geneva

WHO. 2013. World Health Organization. Global Status Report on Road Safety 2013. 2013. Available at: http://www.who.int/violence_injury_prevention/road_safety_status/2013/en/index.html, accessed on January 13, 2013.

Yanmaz-Tuzel, O. and Ozbay, K. 2010. A comparative Full Bayesian before and after analysis and application to urban road safety countermeasures in New Jersey. Accident Analysis and Prevention. Volume 42, Number 6, pp. 099-107

Yannis, G. Kondyli, A. and Mitzalis, N. 2013. Proceedings of the Institution of Civil engineers, Transport 166, Issue TR5. pp 271-281.

Zein, S.R., Geddes, E., Hemsing, S., and Johnson, M. 1997. Safety Benefits of Traffic Calming. Transportation Research Record: Journal of the Transportation Research Board; 1578, pp. 3-10.

Zhou, H. and Hsu, P. 2009. Effects of roadway lighting level on the Pedestrian Safety. On Critical Issues in Transportation Systems Planning and Management, ASCE.

APPENDIX A

Grid Assessment System for Existing Road Segments - Frequency

Evaluation Grid (G1)									
Evaluated Element									
Length of Segment					Level (1, 2 or 3)				
Description of Analyzed Criteria		Real Value	Classification Points (PT)					Score (PD)	Proposed Score
			1	2	3	4	5		
Geometry									
1	Total number of lanes		≤4	5	6	7	≥8	0.15	1.96
4	Shoulder width		>3.0	2.5 to 3.0	1.8 to 2.5	1.2 to 1.8	<1.2	0.30	1.57
8	Frequent interchange distance		>6.5	5.0 to 6.5	3.5 to 5.0	1.5 to 3.5	<1.5	1.85	12.65
Subtotal									
Operational									
9	Level of Service (Night-time) *ln* (AADT) as surrogate		A	B	C	D	≥E	3.05	1.63
Subtotal									
Security (Accidents)									
12	Night-to-day accident ratio		<1.0	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	>2.0 (see Note 1)	4.90	2.18
Subtotal									
								Grand Total	
								Required Scoring to provide lighting	60

Notes:
1.Provision of lighting
2. Current speed: 80kph (95% of night-time operational speed if available, otherwise use the posted speed)
3. Development is defined based on the presence of commercial, industrial, or residential buildings.
4. Use the most deficient geometrical characteristics for road segments.

Grid Assessment System for Existing Road Segments - Severity

Evaluation Grid (G1)									
Evaluated Element									
Length of Segment					Level (1, 2 or 3)				
Description of Analyzed Criteria		Real Value	Classification Points (PT)					Score (PD)	Proposed Score
			1	2	3	4	5		
Geometry									
1	Total number of lanes		≥ 8	7	6	5	≤4	0.15	3.72
4	Shoulder width		>3.0	2.5 to 3.0	1.8 to 2.5	1.2 to 1.8	<1.2	0.30	2.49
8	Frequent interchange distance		>6.5	5.0 to 6.5	3.5 to 5.0	1.5 to 3.5	<1.5	1.85	8.32
Subtotal									
Operational									
9	Level of Service (Night-time) *ln* (AADT)		A	B	C	D	≥E	3.05	4.09
Subtotal									
	Speed		0	0 to 24	25 to 50	50 to 75	>75	1.85	0.01
Security (Accidents)									
12	Night-to-day accident ratio		<1.0	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	>2.0 (see Note 1)	4.90	1.37
Subtotal									
Notes: 1.Provision of lighting 2. Current speed: 80kph (95% of night-time operational speed if available, otherwise use the posted speed) 3. Development is defined based on the presence of commercial, industrial, or residential buildings. 4. Use the most deficient geometrical characteristics for road segments.								Grand Total	
								Required Scoring to provide lighting	60

Grid Assessment System for Existing Ramps - Frequency

Evaluation Grid (G1)									
Evaluated Element									
Length of Segment					Level (1, 2 or 3)				
Description of Analyzed Criteria		Real Value	Classification Points (PT)					Score (PD)	Proposed Score
			1	2	3	4	5		
Geometry									
8	Frequent interchange distance		>6.5	5.0 to 6.5	3.5 to 5.0	1.5 to 3.5	<1.5	1.85	10.57
Subtotal									
Operational									
9	Level of Service (Night-time) *ln* (AADT) as surrogate		A	B	C	D	≥E	3.05	6.20
Subtotal									
Environment									
10	Speed		0	0 to 24	25 to 50	50 to 75	>75	1.85	0.01
Subtotal									
Security (Accidents)									
12	Night-to-day accident ratio		<1.0	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	>2.0 (see Note 1)	4.90	3.23
Subtotal									
Notes: 1.Provision of lighting 2. Current speed: 80kph (95% of night-time operational speed if available, otherwise use the posted speed) 3. Development is defined based on the presence of commercial, industrial, or residential buildings. 4. Use the most deficient geometrical characteristics for road segments.								Grand Total	
								Required Scoring to provide lighting	60

Grid Assessment System for Existing Ramps - Severity

Evaluation Grid (G1)									
Evaluated Element									
Length of Segment					Level (1, 2 or 3)				
Description of Analyzed Criteria		Real Value	Classification Points (PT)					Score (PD)	Proposed Score
			1	2	3	4	5		
Geometry									
4	Shoulder width		>3.0	2.5 to 3.0	1.8 to 2.5	1.2 to 1.8	<1.2	0.30	10.70
Subtotal									
Operational									
9	Level of Service (Night-time) *Use AADT as surrogate*		A	B	C	D	≥E	3.05	5.43
Subtotal									
Environment									
10	Speed		0	0 to 24	25 to 50	50 to 75	>75	1.85	0.00
Subtotal									
Security (Accidents)									
12	Night-to-day accident ratio		<1.0	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	>2.0 (see Note 1)	4.90	3.82
Subtotal									
Notes: 1.Provision of lighting 2. Current speed: 80kph (95% of night-time operational speed if available, otherwise use the posted speed) 3. Development is defined based on the presence of commercial, industrial, or residential buildings. 4. Use the most deficient geometrical characteristics for road segments.								Grand Total	
								Required Scoring to provide lighting	60