KARLA CRISTINA RODRIGUES SILVA

Avaliação da transferabilidade de modelos de previsão de acidentes em rodovias de pista simples do Brasil

Tese apresentada à Escola de Engenharia de São Carlos da Universidade de São Paulo, como parte dos requisitos para obtenção do grau de Doutor em Ciências, Programa de Pós-Graduação em Engenharia de Transportes.

Área de Concentração: Planejamento e Operação de Sistemas de Transportes

Orientador: Prof. Antonio Clóvis Pinto Ferraz

São Carlos
Setembro
2017

Silva, Karla Cristina Rodrigues.

S586a Avaliação da transferabilidade do modelo de previsão de acidentes do HSM em rodovias de pista simples do Brasil / Karla Cristina Rodrigues Silva; orientador Antonio Clóvis Pinto Ferraz. São Carlos, 2017.

Tese (Doutorado) - Programa de Pós-Graduação em Engenharia Transportes e Área de Concentração em Planejamento e Operação de Sistemas de Transportes-- Escola de Engenharia de São Carlos da Universidade de São Paulo, 2017.

1. Segurança viária. 2. Método de previsão de acidentes. 3. Rodovia de pista simples. 4. HSM. 5. Transferabilidade 6. Brasil 7. Florida. I. Título.

KARLA CRISTINA RODRIGUES SILVA

Assessing the transferability of crash prediction models for two lane highways in Brazil

A Dissertation presented to the graduate school of engineering of the University of São Paulo in fulfillment of the requirement for the degree of Doctor in Sciences.

Advisor: Prof. Antonio Clóvis Pinto Ferraz

São Carlos
September
2017

Silva, Karla Cristina Rodrigues.

S586a Assessing the transferability of crash prediction models for two lane highways in Brazil / Karla Cristina Rodrigues Silva; orientador Antonio Clóvis Pinto Ferraz. São Carlos,2017.

Tese (Doutorado) - Programa de Pós-Graduação em Engenharia Transportes e Área de Concentração em Planejamento e Operação de Sistemas de Transportes-- Escola de Engenharia de São Carlos da Universidade de São Paulo, 2017.

1. Safety Analysis. 2. Crash Prediction Model. 3. Two Lane Highway. 4. HSM. 5. Transferability 6. Brazil 7. Florida. I. Título.

FOLHA DE JULGAMENTO

Candidata: **KARLA CRISTINA RODRIGUES SILVA**

Título da tese: "Avaliação da transferabilidade de modelos de previsão de acidentes em rodovias de pista simples do Brasil"

Data da defesa: 04.09.2017

Comissão Julgadora:	Resultado:
Prof. Titular **Antonio Clovis Pinto Ferraz (Orientador)** (Escola de Engenharia de São Carlos/EESC)	APROVADA
Prof. Dr. **Sivaramakrishnan Srinivasan** (University of Florida/UF – EUA)	APROVADA
Profª. Drª. **Bárbara Stolte Bezerra** (Universidade Estadual Paulista "Júlio de Mesquita Filho"/Unesp – Bauru)	APROVADA
Profª. Associada **Cira Souza Pitombo** (Escola de Engenharia de São Carlos/EESC)	Aprovada
Profª. Drª. **Michelle Andrade** (Universidade de Brasília/UnB)	Aprovada

Coordenadora do Programa de Pós-Graduação em Engenharia de Transportes:
Profª. Associada **Ana Paula Camargo Larocca**

Presidente da Comissão de Pós-Graduação:
Prof. Associado **Luis Fernando Costa Alberto**

DEDICATION

For my loved ones, who have faced this challenge with me
believing in a safer tomorrow

ACKNOWLEDGMENTS

I would like to acknowledge many people that helped me to keep going and end this dissertation along these years.

First, my distinct thanks to my advisor, Dr. Coca Ferraz and my host at University Florida, Dr. Siva Srinivasan for the guidance and for creating an environment that made this research possible.

Second, my extensive gratitude to all the professors and staff of Department of Transportation of University of São Paulo, especially Dr. Antonio Nelson, Dr. André Cunha, Dr. Cira Pitombo, Dr. Ana Paula Larocca, Dr. José Reinaldo Setti for sharing with me their knowledge. Also, Heloisa Belo and Beth Ortega who were so helpful and supportive in this stage.

My further appreciation goes to Dr. Magaly Romão, and Dr. Bárbara Bezerra, for the wise advices and for encouraging me. Inasmuch as the guidance was fundamental for this work, I would thank also Dr. Erza Hauer for introducing me the art of regression modeling in road safety.

My acknowledgement to CEFET – MG that supported me to get finally this degree and all my co-works, specially Dr. Matheus Justino, for the trustworthy; Dr. Sergio Saraiva, for the technical guidance, Prof. Agmar Bento, for the unconditional help. Also, the staff Amanda Fernandes, Miriam Greiner and Natalia Oliveira for making my work easier.

I would like to thank TECTRAN Group and my colleagues for the first contact with transportation engineering and the opportunity to learn always more in the many years of work. Also, I thank Raissa for always questioning and for being so attentive to learn more about road safety engineering.

I thank my colleagues at USP and UF, for their nice company and friendship, especially those who were more closely involved in helping me and supporting me emotionally: Mariana Tebit, Fernando Hirose, Tiago Bastos, Andressa NG, Renata Sasahara, Fabio Sasahara, Gaurav Sultania, Kiarash Fariborzi, Aschkan Omidvar and Marilo Gasulla.

I am so thankful to Autovias, Rodonorte highway administration and Minas Gerais government for providing data to this work. Moreover, I thank Philip Haas that kindly allow me work with Florida database from his dissertation.

Last but not least, my profound gratitude to my understanding husband, Gustavo; my wonderful son, Rafael; my parents, my brother and my sister as well as my family, whose always support me in my decisions and for being source of infinite love.

RESUMO

SILVA, K. C. R. **Avaliação da transferabilidade de modelos de previsão de acidentes em rodovias de pista simples do Brasil**. 98 p. Tese (Doutorado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos. 2017.

O foco desta pesquisa foi avaliar a aplicação de alguns modelos de previsão de acidentes em rodovias de pista simples de três estados brasileiros. Ainda, a transferabilidade destes modelos foi abordada, especificamente por meio de uma comparação entre características do Brasil, Florida e aquelas recomendadas pelo *Highway Safety Manua*l. O uso dos distintos modelos se mostrou promissor para situações nas quais as características da via se mantiveram semelhantes às condições para as quais os modelos foram desenvolvidos. A avaliação foi empreendida para todos os segmentos homogêneos, separados posteriormente segundo a existência de curvas horizontais. Adicionalmente, dois novos modelos foram equacionados para a amostra brasileira. O modelo de previsão de acidentes desenvolvido apresentou melhores medidas de desempenho para segmentos sem curvas horizontais, sendo recomendável para previsão de acidentes em análises preliminares. Por fim, foi constatado que outros fatores não comtemplados pelos modelos podem ter impactado as condições de segurança dos locais estudados. Ainda assim, essa pesquisa representa no contexto do Brasil um ponto de partida em análises relacionadas à segurança de rodovias de pista simples.

Palavras-chave: Segurança viária, Método de previsão de acidentes, Rodovia de pista simples, HSM, Transferabilidade, Brasil, Florida.

ABSTRACT

SILVA, K. C. R. **Assessing the transferability of crash prediction models for two lane highways in Brazil**. 98 p. Tese (Doutorado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos. 2017.

The present study focused on evaluating some crash prediction models for two lane highways on Brazilian conditions. Also, the transferability of models was considered, specifically by means of a comparison between Brazil, HSM and Florida. The analysis of two lane highways crash prediction models was promising when the road characteristics were well known and there was not much difference from base conditions. This conclusion was attained regarding the comparison of results for all segments, non-curved segments and curved segments, confirming that a transferred model can be used with caution. In addition, two novel models for Brazilian two-lane highways segments were estimated. The model developed showed better results for non-curved segments in the calibration/validation sample. Thus, for a general analysis purpose of non-curved segments this model is recommended. Finally, there are many factors that could not be measured by these models and reflects road safety various condition. Even so, the study of crash predict models in Brazilian context could provide a better start point in safety road analysis.

Keywords: Safety Analysis, Crash Prediction Model, Two Lane Highway, HSM, Transferability, Florida, Brazil.

ABBREVIATIONS

AADT - Annual Average Daily Traffic

AASHTO - Association of State Highway and Transportation Officials

ADT - Average Daily Traffic

AVG - Average

BR - Brazil

CARS - Crash Analysis Reporting System

CMF - Crash Modification Factors

CPM - Crash Prediction Models

CURE - Cumulative Residual

DD - Driveway Density

DNIT – Departamento Nacional de Infraestrutura de Transporte

EB – Empirical Bayes

FDOT - Florida Department of Transportation.

FHWA - Federal Highway Administration

FI – Fatal and Injury

FL – Florida State

GLM - Generalized Linear Model

GOF - Goodness-of-fit

GPS – Global Positioning System

HSM - Highway Safety Manual

IHSDM - Interactive Highway Safety Design Module

LW – Lane width

MAD - Mean Absolute Deviation

MAPE - Mean Absolute Percentage Error

MG – Minas Gerais State

MPB - Mean Prediction Bias

MSE - Mean Square Error

NB – Negative Binomial

NHTSA - National Highway Traffic Safety Administration

PDO – Property Damage Only

PR – Paraná State

RCI - Roadway Characteristics Inventory

RHR - Roadside Hazard Rating (RHR)

RQ – Research Question

SP – São Paulo State

SPF – Safety Performance Function

SW – Shoulder width

TIA - Traffic influence area

TLH – Two Lane Highway

TLHS - Two Lane Highway Segments

TWLTL - Two Way Left Turn Lanes

WHO - World Health Organization

TABLE LIST

Figure List

TABLE OF CONTENTS

1 INTRODUCTION

Understanding traffic accidents' nature is a challenge, and is a continued a subject of scientific research. In this chapter, the status of transportation safety engineering is addressed, and the main objectives and motivation of this study are presented. The chapter ends by outlining the structure of the rest of this manuscript.

1.1 SAFETY OVERVIEW

Traffic accidents result in more than 1.2 million deaths each year, making road traffic injuries a leading cause of mortality globally; furthermore, over 20 million people suffer non-fatal injuries, which lead to severe consequences that prevent a normal life (WHO, 2015). To extenuate an increasing problem, in 2010 the United Nations General Assembly established an agreement with its member states to enroll in the Decade of Action for Road Safety (2011–2020). The target was halving the number of deaths and injuries from road traffic crashes by 2020 in the world.

The situation of traffic safety in Brazil is also of concern. According to statistics for 2015, about 40 thousand people died due to traffic accidents (DATASUS, 2015). Only in Brazilian federal highways, representing 4% of the entire roadway network, about 180 thousand crashes occurred resulting in seven thousands deaths in 2010 (DNIT, 2015). Even though some measures were taken since the agreement has been signed, the number of traffic fatalities presented a timid reduction and the situation could deteriorate if adequate effective measures are not implemented.

Likewise, the United States lost 35,092 people in crashes in roadways during 2015 (NHTSA, 2016). Almost half of this number could be attributed to rural highways. Thus, based on the premise that even one traffic related fatality is unacceptable, the Federal Highway Administration (FHWA) developed a program entitled Toward Zero Deaths: A Decade of Action for Road Safety. The goal was to decrease considerably traffic fatalities and serious injuries on public roads (FHWA, 2012).

To improve transportation safety involvement from multiple sectors is needed. Possible interventions include designing safer infrastructure, integrating road safety features into land-use and transport planning, enhancing safety features of vehicles, improving post-crash care for victims of road crashes and road user behavior, and improving law enforcement related to the key risk factors.

Assessment of the measure of effectiveness of road safety intervention is still one of the most critical aspects the management of highway safety. Over the past few decades there has been several studies that have developed methods for evaluating the safety conditions of an existing or planned roadway (Harwood, Council, Hauer, Hughes, & Vogt, 2000; Hauer, 2010; Solomon, 1964; Venkataraman, Ulfarsson, & Shankar, 2014; Zegeer, Hummer, Reinfurt, Herf & Hunter, 1987). In order to summarize these efforts realized over decades, the American Association of State Highway and Transportation Officials (AASHTO) published in 2010 the first edition of the Highway Safety Manual (HSM).

The HSM was issued as an analytical tool based on scientific knowledge supported by a software of FHWA called Interactive Highway Safety Design Module (IHSDM). It is divided in four parts, of which the third one (Part C) addresses crash prediction models. Although the HSM equations provide a good baseline for safety evaluation, it is highly recommended that the equations be calibrated to account for local peculiarities. As the search for improving roadway safety in the world has been increasing, it is desirable to discuss the important questions regarding the transferability of crash prediction models and how to assess the performance and accuracy of these models.

1.2 Aim and Motivation

The aim of this research was to improve the quality of accident prediction for two lane highways segments using data from the states of São Paulo, Paraná and Minas Gerais. As the data from Brazil are limited, the study examines whether equations from the HSM (developed in the United Stated) can be transferred to Brazil. Further, the study examines whether HSM equations that have been calibrated to specific locations in the United States (in this case to Florida) are more transferable to Brazil instead of the equations directly out of the manual.

The following are the key research questions:

RQ1: How to evaluate two lane highways safety in Brazil using HSM Crash Prediction Models?

RQ2: What will be the sample of highways used in that research?

RQ3: Which are the main characteristics of the sample of two lane highways in Brazil?

RQ4: How can the data be obtained to apply HSM Crash Prediction model?

RQ5: What type of characteristics can really affect two lane highway safety in Brazil?

RQ6: Which characteristics are considered to develop Crash Prediction Models for two lane highways?

RQ7: How a Crash Prediction Model can be transferable?

RQ8: How to evaluate transferability of Models using data from some places in Brazil and Florida?

Crash prediction models for Brazilian highways are still incipient due to the difficulty of obtaining reliable data. There is a gap in the knowledge related to CPM models for Brazilian conditions (Cunto, Sobreira, & Ferreira, 2013; Silva, 2012; Waihrich, 2015) and modeling crashes phenomena is an important step to avoid future accidents and consequently unnecessary deaths. Moreover, an evaluation of the transferability of models is always desirable to improve safety analysis and take advantage of the most recent models. For that, a great deal of effort to assemble all relevant information and building a consistent safety diagnosis is required.

The following structure is adopted to accomplish the research goals: (1) development of a literature review on accident prediction techniques and related performance measures; (2) collection of data as detailed as possible on infrastructure and associated accident occurrence; (3) identification of possible relationships between operational characteristics and safety conditions; (4) investigation of ways to improve safety analysis built on crash prediction models appropriate to Brazil. Besides that, the motivation that constitute this study was based on the search for an answer the presented research questions.

Throughout this manuscript, the structure to response these questions is shown in the next section.

1.3 DISSERTATION STRUCTURE

This dissertation addressed some ways to enhance safety analysis, concerning crash prediction models appropriate to Brazil. This introductory chapter closes with a brief presentation of the outlined structure to achieve the goal of this research, as displayed in Figure 1.1.

Figure 1.1 – Dissertation structure

Chapter 1 Introdution	• Contextualization and Motivation • Dissertation Structure
Chapter 2 Crash Prediction Model	• Literature Review • Highway Safety Manual model and its applications in two lane highways.
Chapter 3 Segment Data	• Data obtaining and treatment • Main charachteristics for Brazil and Florida
Chapter 4 Safety Data Analysis	• Crash analysis • Comparison of Brazilian and Florida database
Chapter 5 Transferability of HSM Crash Prediction Model	• Application in Brazil and Florida • Assessment of transferability
Chapter 6 Transferability of Florida Crash Prediction Model	• Presentation and application of Florida equations • Assessment of Transferability
Chapter 7 Building a Brazilian Crash Prediction Model	• Estimatition of a local model and its evaluation
Chapter 8 Conclusions and recommendations	• Last result analysis • Future research

2 CRASH PREDICTION MODELS

This chapter contains topics related to Crash Prediction Models (CPM) for rural two-lane highways segments, including the methods presented in the HSM. In addition, the spatial transferability of CPMs using methods such as calibration and localized model estimation are discussed.

2.1 CRASH PREDICTION ANALYSIS

The evaluation of safety conditions of an existent or planned road can be based on one of four approaches: averages from historical accident data, predictions from statistical models based on regression analysis (CPMs) , results of before-after studies, and expert judgments (Harwood et al., 2000).

Generally, CPM's are developed using statistical methods applied on historical crash data from similar infrastructure but varying levels of annual average daily traffic – AADT. A safety performance function (SPF) is a CPM that uses only AADT as the independent variable to estimate crashes (Haas, 2015; Lord & Mannering, 2010). The Poisson, negative binomial, and generalized regression models are the three most common statistical approaches used in SPF estimations. Additionally, Bayesian inference has been studied together with these approaches.

The Poisson distribution has been used in accident modeling since the work of L. von Bortkiewitcz who, in 1989, undertook analyses of the number of deaths by horse-kicks over a period of 20 years (Hauer, 2015). Because of its practicality, research has commonly used this distribution to estimate the SPF (Bezerra, Silva, Bastos, & Ferraz, 2011; Caliendo, Guida, & Parisi, 2007; Jovanis & Chang, 1986; Miao, 1993). The Poisson distribution assumes that the variance is equal to the mean; hence, the size of random variance in the count of accidents equals the expected number of accidents. Then, the number of accidents (K) in time the period (T) during which the mean number of accidents per unit of time (λ) prevails (k), is given by the Poisson probability (P):

$$P(K = k|\mu) = \frac{e^{-\mu}\mu^k}{k!} \qquad 2.1$$

where μ is the number of accidents expected to be reported during T, given alternatively by the product of (λ) and (T).

Although it represents a good starting point to fit safety models, the simple application of the Poisson distribution has had some inconveniencies on real transportation systems due to the nature of the crash generation process (Hauer, 2015; Lord & Mannering, 2010). The Negative Binomial regression is largely used (Ackaah & Salifu, 2011; Cafiso, Di Graziano, Di Silvestro, La Cava, & Persaud, 2010; Harwood et al., 2000; Lord & Persaud, 2000; McCullagh & Nelder, 1989; Srinivasan & Bauer, 2013) because of the possibility of accounting for the overdispersion of crash frequency. Negative Binomial regression is also preferred to a Poisson regression (AASHTO, 2010). These models can take different empirical forms, including just length and AADT, as well as and multiplicative coefficients to account for different roadway characteristics, as seen in Equation (2.2) (Haas, 2016).

$$N = \exp(b_o + b_1 \ln AADT + b_2 \ln L + b_3 X_3 + \cdots + b_n X_n) \qquad 2.2$$

where N is predicted crash frequency per year for a specified segment; *AADT* is annual average daily traffic volume (veh/hr) for the segment; *L* is length of the segment; $b_0, \ldots, b_n$ are regression coefficients and $X_1, \ldots X_n$ are segment characteristics.

The generalized regression-based estimating equations have been applied to model crash data over the years (Caliendo et al., 2007; Dinu & Veeraragavan, 2011; Lord & Persaud, 2000). This approach can assume several forms. The base model, called Generalized Linear Model (GLM), has a random and a systematic component, as well as a link function. The popularity of this method comes from the simplification in the algorithm of estimation and interpretation of parameters.

In addition to the application of the SPFs, the Empirical Bayes methods can be used for correcting the regression-to-mean bias (Elvik, 2008; Hauer, Harwood, Council, & Griffith, 2002; Miaou & Lord, 2003). The Empirical Bayes Method consists of weighting the crash estimate from a statistical model with the historical crashes form that location. In safety analysis, the best approach is obtained by the combination of two sources: accident history and a safety prediction modeling.

The choice of the statistical model depends on the study objective. Per AASHTO, 2010 the Binomial Negative Regressions are more appropriated to modeling the high variability of crash data and consequently develop Safety Performance Functions (SPF). SPF's are statistical based models used in the HSM to estimate the average crash frequency for a facility type with base conditions. In the next section, the main structure employed in HSM and its related procedures can be found.

2.2 HIGHWAY SAFETY MANUAL

The Highway Safety Manual was published in 2010 to help the decision-making process in safety analyses using analytical methods. The main goal of HSM was to compile and systematize existing consistent research to provide quantitative information as well as to introduce new methods and techniques to transportation professionals. Since it addressed several aspects of safety analysis, it is recommended to evaluate its applicability case by case.

The procedures for crash prediction estimation were presented in part C and D of the HSM. In Part C, a base model and SPF for crash prediction are provided for different facility types: (1) rural two-lane highways; (2) rural multilane highways; (3) urban and suburban arterials (AASHTO, 2010). In Part D, information regarding the effects of safety treatments quantified as Crash Modification Factors (CMF) are introduced. For each facility type, there are corresponding assumptions and models to estimate crashes.

For all facility types, the base model consists of a multiplication of many elements, such as SPF for a facility type; calibration factor for a specific location; and CMF's for various characteristics of each facility type. As a result of this model, the dependent variable represents the total expected accident frequency on the roadway segment during a specified time, and the independent variables reflect some operational and geometric features (AASHTO, 2010).

2.2.1 BASE MODEL

The base model to predict crash numbers, including the severity of related to accidents, depends on the local infrastructure as well as operational characteristics. For each facility type a SPF is expected along with the CMFs related to this facility. An additional Calibration factor, C_x, can be used to adjust the model for a condition other than the one for which that it was developed. The base model to determine the predicted average crash frequency, $N_{predicted}$, was presented in

HSM, as shown in Equation 2.3 (AASHTO, 2010).

$$N_{predicted} = N_{SPFx} \times C_x \times (CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx}) \qquad 2.3$$

where N_{SPFx} is the predicted average number of crashes for base conditions of the SPF developed for a facility type x. C_x is the calibration factor to adjust SPF for a specific local condition and CMF_{ix} is crash modification factors specific to road characteristic type x.

It is recommended to apply to a base model the Empirical Bayes (EB) Method for existent location in order to improve the estimation. This method can be seen on the next sub section.

2.2.2 EMPIRICAL BAYES METHOD

The Empirical Bayes (EB) method consists of weighting the predicted crash frequency by the observed crashes. The EB method improves the statistic reliability of crash prediction method because it can compensate the potential bias associated to regression-to-the mean. The weighted adjustment model depends on the SPF overdispersion parameter to combine the two estimates in a weighted average as seen in the Equation 2.4 (AASHTO, 2010). The weight factor is inversely proportional to the overdispersion parameter as presented in the Equation 2.5.

$$N_{expected} = w \times N_{predicted} + (1{,}00 - w) \times N_{observed} \qquad 2.4$$

$$w = \frac{1}{1 + k \times \sum N_{predicted}} \qquad 2.5$$

where $N_{expected}$ is the expected crash number for a specific period. $N_{predicted}$ is the predicted average crash frequency and $N_{observed}$ is the observed average crash number of previous time. w is weight factor related to the SPF and k is the overdispersion parameter associated to the SPF. In HSM, the EB Method can be applied to a project in which geometric conditions are constant over time or changes are so small to not affecting the prediction model.

2.2.3 SAFETY PERFORMANCE FUNCTION TO TWO LANE HIGHWAYS

For rural two-lane highways segments, the SPF development was based on regression modeling. This model, like all regression models, predicts the value of a dependent variable as a function of a set of independent variables. The base model for rural two-lane roadway segments is presented in Equation 2.6 (AASHTO, 2010, adapted).

$$N_{SPF\ rs} = AADT \times \frac{L}{1.609} \times 365 \times 10^{\alpha} \times e^{\beta} \qquad 2.6$$

where N_{SPFrs} is the predicted total crash frequency for roadway segment base condition; *AADT* is the annual average daily traffic volume (vehicles per day); *L/1.609* is the segment length in meters; α is assumed -6 and β, -0.312 as obtained from HSM data. The overdispersion parameter associated with this SPF is given by Equation 2.7.

$$k = \frac{0.236 \times 1.609}{L} \qquad 2.7$$

where L is segment length of highway converted to kilometers.

According to AASHTO, 2010, the base geometric characteristics surveyed to develop this SPF were lane width (LW) equal to 12 feet (~ 3.60 meters), paved shoulder equivalent to 6 feet (~ 1.80 meters), roadside hazard rating (RHR) of 3, driveway density (DD) like 5 driveways per mile (around 8 per kilometer) and level terrain. In addition, the segment had to be devoid of horizontal and vertical curvature, centerline rumble strips, passing lanes, two-way left turn lanes (TWLTL). Characteristics other than those cited are adjusted by CMF's.

2.2.4 CRASH MODIFICATION FACTORS

The crash modification factors (CMF's) are presented in Part D of HSM. They are used to consider the characteristics that differ from the base conditions and the peculiarities of specific segments (AASHTO, 2010). The adjustment of the SPF model is done by multiplication, as shown in Equation 2.3. When any condition of the segment does not differ from the base conditions, the CMF is equal to 1.0. If the condition studied is more conservative (from the safety point of view) than the base condition the CMF will be less than 1.0. Otherwise, the CMF value will be greater than 1.0, depicting less efficient safety conditions.

For two lane highway segments, twelve modification factors are considered in HSM. These twelve factors do not, of course, depict all the possible conditions, either because some situations are not fully known because some aspects are not statistically relevant or even quantifiable. In AASHTO (2010) the related conditions are shown as following with HSM respective reference in parenthesis:

- CMF_1: Lane Width (HSM Table 10-8, Figure 10-7, Equation 10-11)
- CMF_2: Shoulder Width and Type (HSM Tables 10-9 and 10-10, Figure 10-8, Equation 10- 12)
- CMF_3: Horizontal Curves: Length, Radius, Transition (HSM Equation 10-7)
- CMF_4: Horizontal Curves: Superelevation (HSM Equations 10-14, 10-15, 10-16)
- CMF_5: Grades (HSM Table 10-11)
- CMF_6: Driveway Density (HSM Equation 10-17)
- CMF_7: Centerline Rumble Strips (HSM Page 10-29)
- CMF_8: Passing Lanes (HSM Page 10-29)
- CMF_9: Two-Way Left-Turn Lanes (HSM Equation 10-18, 10-19)
- CMF_{10}: Roadside Design (HSM Equation 10-20)
- CMF_{11}: Lighting (HSM Equation 10-21, Table 10-12)
- CMF_{12}: Automated Speed Enforcement (HSM Page 10-31)

The basic idea of CMF was previously addressed to guarantee that the predicted accident frequency could reflect geometric design condition and traffic control features, while the base models would represent the magnitude of the predicted accident frequency appropriately (Harwood et al., 2000). Besides the original CMF development, researchers have been exploring new relationships between crashes and roadway characteristics and most of them can be found on the website CMF Clearinghouse (FHWA, 2017).

2.2.5 Calibration

In order to develop a safety model and consequently a SPF, a large sample of similar sites, an analyst with statistical expertise and a reliable technique of data collection are necessary (AASHTO, 2010; Srinivasan, Colety, Bahar, Crowther, & Farmen, 2016). These three combined factors can make a project unfeasible and for this reason, calibrating a model is suitable. Thus, to take advantage of the most recent models, many agencies and researches start safety evaluation by improving HSM crash predicting model.

The method for calculating calibration factors, C_r, for highway segments was addressed in HSM

Part C, Appendix A (AASHTO, 2010). The C_r default value is assumed 1.0, but might be different when roadways experience more or fewer crashes than SPF developing conditions. The calibration factor can be obtained from the Equation 2.8.

$$C_r = \frac{\sum_{All\ sites} observed\ crashes}{\sum_{All\ sites} predicted\ crashes} \quad 2.8$$

The minimum sample size required for calibrating a SPF varies between 30 and 50 sites, obtained either by selecting sites randomly or using the entire sample (AASHTO, 2010). The objective of calculating calibration factor is to take in account specific variations from selected sites, as well as fluctuations inherent to accidentality. For this reason, it is recommended to obtain calibration factor for different locals. The steps involved in the calibration method are: (1) Facility identification (2) Site selection for CPM calibration (3) Data obtaining for the chosen facility; (4) Application of HSM predict model using calibration factor (C_r) as equal to one. (5) Calculating calibration factor (C_r) (AASHTO, 2010).

Before the HSM was published, its applicability was evaluated using Louisiana data, regarding the practicality for potential users (Sun, Li, Magri, & Shirazi, 2006). This research was related to two lane highways and attained reasonable results, however the authors recognized the risks associated with considerations of discrepancy due to the stochastic nature of accidents. All calculated calibration factors were over 1.0, with maximum of 2.30. The limitation of that study lies in the fact that some parameters, such as road side hazard rating, driveway density, and horizontal and vertical curvatures were assumed equal to the base case.

Shortly after HSM publication, its calibration method was implemented for Oregon State Highways, using a wide variety of data sources, obtained in field and digitally available (Xie, Gladhill, Dixon, & Monsere, 2011). Most of their found values for calibration factor were under 1.0, suggesting that driving in Oregon roads is safer than doing so in the average American states. As explained in the report from this work, some complications were met in the collection of pedestrian volumes and minor road signal phasing, as well as the minor road AADT values (Dixon, Monsere, Xie, & Gladhill, 2012).

Many other researchers in the USA developed calibration factors for different states. In Washington State, a comparison between a newly developed model and a calibration of CPM as described in HSM indicated that the performance of the calibrated HSM model could achieve results as good as the new one (Banihashemi, 2011). For Kansas highways, HSM calibration procedure was tested and an alternative procedure was recommended (Lubliner, 2011). In Utah, after calibrating HSM model and analyzing new models, the results led to similar conclusion found by Banihashemi (2011) (Saito, Brimley, & Schultz, 2011; Saito, Knecht S, Schultz G, & Cook A, 2015).

Similarly, this HSM procedure was recommended to specifics highway segments in Illinois (Williamson & Zhou, 2012). The calibration results in Missouri showed that the HSM can be used, with few sites exceptions (Sun, Brown, Edara, Claros, & Nam, 2013). In Alabama, the calibration factors derived from HSM method were greater than one and the relationship between accidents and road features was different from what the HSM base SPF describes (Metha & Lou, 2013). Florida studies evaluated besides the calibration, HSM transferability (Haas, 2015; Srinivasan et al., 2011).

Corroborating calibration efforts in the United States, some similar studies have been developed in Brazil. The calibration of HSM for two lane highways of São Paulo state and the method of Bayes, showed satisfactory results in a preliminary analysis (Silva, 2012). For multilane highways of the states of Minas Gerais, Goiás and Distrito Federal due to the small size of the sample used, the calibration of HSM model showed better results for Minas Gerais than for the combination of Goiás and Distrito Federal (Waihrich, 2015). For urban intersections in the city of Fortaleza, the HSM was used for estimating the expected average crash frequency, regarding its transferability, and the study suggested that the HSM should be used with caution (Cunto et al., 2013).

In addition, other countries have studied the HSM calibration performance. One of the effort to calibrating the HSM model in Canada was launched by The *Ministère des transports du Québec* (MTQ). In general, the calibration factors obtained were around one, as observed in the United States (Barber, 2014). The calibration to New Zealand has showed to be promising for safety and operational assessment of highway alignments (Koorey, 2010). Also, the calibration procedure was evaluated in Italy. It has been applied to highways in Arezzo and some potential problems related to transferability of this methodology were outlined (Martinelli, La Torre, & Vadi, 2009). For Catania, Italy, two approaches to estimate crashes were investigated, focusing on a comparison in terms of model transferability. The results from calibration were considerate satisfactory (D'Agostino, 2014). After these studies, a calibration for the Motorway Network in Italy was developed, regarding HSM transferability (La Torre, Domenichini, Corsi, & Fanfani, 2014).

Although there were some differences in the various studies, most researches agreed that the calibrated HSM model can be used to estimated safety performance fittingly. However, the most demanding and challenging part of this effort has been linked to data collection, especially in intersections, due to its complexity. Another point to be highlighted is the fact that several studies began investigating two lane highways, because their importance in rural areas (Banihashemi, 2011; Barber, 2014; Koorey, 2010; Lubliner, 2011; Martinelli et al., 2009; Metha & Lou, 2013; Saito et al., 2011; Silva, 2012; Srinivasan et al., 2011; Sun et al., 2006; Williamson & Zhou, 2012; Xie et al., 2011). A synthesis of the current situation in two lane highways segments is shown in the Table 2.1.

A calibration procedure is often followed by a validation using an independent set of data. Though, in HSM is not provided guidelines for validation procedures. Most of the calibration effort that followed the HSM instructions have not performed validation, which means that model accuracy was not properly measured. According to Lubliner (2011) selecting validation metrics is also challenging, and the results of the model comparison will reflect the metric selected.

Depending of the subject, a wide variety of metrics can be used to validate a model. For CPM, most commonly used measures are: Pearson Correlation Coefficient (r), Mean Absolute Deviation (MAD), Mean Prediction Bias (MPB), Mean Square Error (MSE), measures of statistical adherence, percent difference between observed and predicted crashes, average of the absolute percent differences between observed and predicted crashes, Cumulative Residual (CURE) plots and other visual methods (Haas, 2015). To perform validation, a random sample of the studied highways can be selected or another state can be evaluated as well as the same highway in a different period (Banihashemi, 2011; Harwood et al., 2000; Vogt & Bared, 1998).

Table 2.1 - Calibration factors for two lane highways segments (TLHS)

Publication Year	Autor	State-Country	*Cr* TLHS	Period
2006	Sun et al.	Louisiana -USA	1.630	1999-2001
2009	Martinelli et al.	Arezzo -Italy	0.369	2002-2004
2010	Koorey	New Zealand	0.884 0.851	1996-2000 2002-2006
2011	Xie et al.	Oregon -USA	0.740	2004-2006
2011	Banihashemi	Washington -USA	1.501	2002-2004
2011	Lubliner	Kansas – USA	1.480	2005-2007
2011	Saito, Brimley, & Schultz	Utah -USA	1.160	2005-2007
2011	Srinivasan et al.	Florida – USA	1.066 1.005	2005-2006 2007-2008
2012	Williamson & Zhou	Illinois -USA	1.400	2007-2009
2012	Silva	São Paulo – Brazil	3.730	2008-2010
2013	Sun et al.	Missouri - USA	0.820	1985-1989 1993-1995
2013	Metha & Lou	Alabama - USA	1.392	2006-2009
2014	Barber	Quebec – Canada	1.070	2006-2008

In addition, proper investigation using a model developed in one region to another could be done by checking its transferability. The interest in model transferability for safety purposes has been gaining relevance because the development of a new SPF involves many aspects, as can be seen on the next subsection. The ability to transfer models can reduce a cost of a project and save time specially for developing countries that cannot afford to finance data collection and model development procedures.

2.3 TRANSFERABILITY OF CRASH PREDICTION MODELS

Since a calibration factor can vary from one region to another and there is a gap between a models' representation of crash nature, it is expected to investigate if these models can be transferred, regarding practical purposes. The metrics to transfer a model are not clearly defined, which means it will reflect certain statistical and pragmatic criteria. The assessment of model performance will depend on the objective of the study and the quality of data.

Checking model transferability is highly used for predicting choice models (Koppelman & Wilmot, 1982; Zuo, 2016). Though, only few researches performed an examination of transferability for safety analysis. Previous studies found out four more significant metrics (Al Kaaf & Abdel-Aty, 2015; Cafiso, Di Silvestro, & Di Guardo, 2012; Cunto et al., 2013; D'Agostino, 2014; Haas, 2015; Sacchi, Persaud, & Bassani, 2012; Waihrich, 2015; Washington, Persaud, Lyon, & Oh, 2005): (1) R^2; (2) Mean Absolute Percentage Error (MAPE); (3) Mean Absolute Deviation (MAD); (4) Cumulative Residuals (CURE).

The R^2 can provide a measure of how well the observed crashes are likely to be predicted by the model. This metric was addressed in most studies due to its popularity and simplicity (Al Kaaf & Abdel-Aty, 2015; Cafiso et al., 2012; Cunto et al., 2013; D'Agostino, 2014; Silva, 2012; Waihrich, 2015). Depending on the analysis, Efron's, Macfadden's or Person's R^2 was used. For log-likelihood functions, a pseudo R^2 is a good approach to measure the fit of the model, as shown in Equation 2.9 (Efron's R^2).

$$R^2 = 1 - \frac{\sum_{i-1}^{n}(N_{Observed-i} - N_{predicted-i})^2}{\sum_{i-1}^{n}(N_{Observed-i} - \overline{N}_{observed})^2} \qquad 2.9$$

where N is the number of crashes (predicted or observed) in a segment i of n segments and $\overline{N}$ is the average number of crashes.

The mean absolute percentage error (MAPE) has been used for some researches to assess the predictive performance avoiding bias due to different segments with more accidents (Al Kaaf & Abdel-Aty, 2015; Cunto et al., 2013; Waihrich, 2015). Through Equation 2.10 MAPE can be obtained:

$$MAPE = \sum_{i=1}^{n} \frac{\left|\frac{N_{Observed-i} - N_{predicted-i}}{N_{Observed-i}}\right|}{n} \times 100 \qquad 2.10$$

Most studies used Mean Absolute Deviation (MAD) as Goodness-of-fit (GOF) measure (Al Kaaf & Abdel-Aty, 2015; Cunto et al., 2013; Persaud, Saleem, Faisal, & Lyon, 2012; Sacchi et al., 2012; Waihrich, 2015). It differs from MAPE because it can consider segments where no crashes happened, which means observed values were equal to zero. Other noticeable property is that positive and negative prediction errors will not cancel each other out, unlike MPB (Washington et al., 2005). MAD is the difference between the number of crash observed

($N_{observed}$) and predicted crash frequencies ($N_{predicted}$) as shown in Equation 2.11, where n is the data sample size:

$$MAD = \sum_{i=1}^{n} \frac{\left|N_{Observed-i} - N_{predicted-i}\right|}{n} \qquad 2.11$$

Other popular GOF is a graphic of Cumulative Residuals (CURE). The CURE method has the benefit of not being dependent on the number of observations, as are some of other kind of measures (D'Agostino, 2014). On the other hand, for similar segments condition dataset, it could not be appropriate, since it does require a range of values of the independent variable (Waihrich, 2015).

Table 2.2 was created to illustrate the use for each of these performance measure in the past. The intention was to compile all recent studies linked to HSM transferability. It is important to highlight that some metrics like Pearson χ^2 and MSE are widespread used, though it can be calculated along with or instead of R^2 and MAPE, respectively.

Table 2.2 - Goodness-of-fit linked to HSM transferability

Publication	R^2	MAPE	MAD	CURE	Others
Al-Kaaf and Abdel-Aty, 2015	X	X	X	X	Pearson χ2, MSE and and Bayesian information criterion (BIC)
Cafiso, Di Silvestro, & Di Guardo, 2012	X				Pearson χ2 and RMSE
Cunto et al., 2013		X	X	X	Pearson χ2 and z-score
D'Agostino, 2014	X			X	-
Haas, 2015					The mean square error (MSE)
Persuad et al., 2012			X	X	overdispersion parameter (k)
Sacchi, Persaud, & Bassani, 2012			X	X	-
Silva, 2012	X				χ2 and Kolmogorov-Smirnov
Waihrich, 2015	X	X	X		-
Washington et al., 2005			X	X	Pearson χ2 , MPB, MSE, MSPE

From the presented review it was possible to conclude that the assessment of the transferability of a model is not absolute, which means that further investigation on this issue is relevant for road safety analysis. In Brazilian context, only few researches carried out the transferability of HSM model as preliminary studies for different facility types (Cunto et al., 2013; Silva, 2012; Waihrich, 2015). There is still a gap in the knowledge of effective safety treatments and crash prediction models due to the difficulties associated to obtaining appropriate data source. The assemble of data is the focus of the next chapter.

In this research, the investigation of transferability of some current models should be beneficial to fill this lack of information. In addition, the examination of systematic procedures for assessing whether a model is transferable or not could be a starting point for future works in this field.

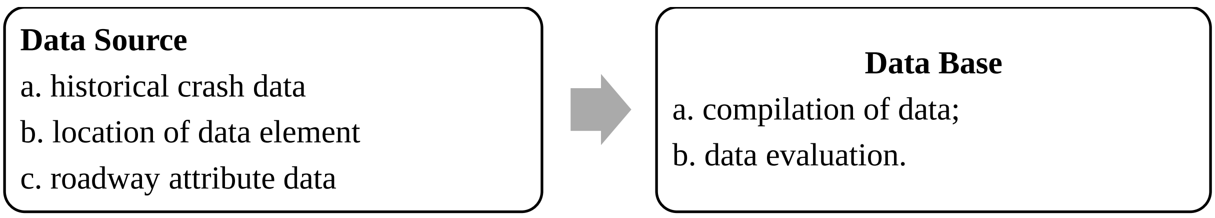
3 SEGMENT DATA

This chapter describes the data sources for two lane highways located in some regions from Brazil and the state Florida, USA. The background to prepare the data analysis and the selection of the facility type is also presented in this section. A brief consideration of samples and the main characteristics of road segments are discussed.

3.1 REQUIRED DATA

The procedure to assemble the calibration dataset involves accessing the historical crash data as well as to delimiting the scope of study. Also, the roadway attributes should be provided, comprising the characteristics of each segment. After identifying all valid data sources, a compilation of all data and its evaluation are intended. A simplified scheme of the database assembling process is shown in the Figure 3.1.

Figure 3.1 - Data base assembling



The historical crash data is normally given by roadway administration and some police agencies, responsible to collect information *in loco*. The location of each data element is defined previously due to convenience or to a special attention to a determined area. The roadway attribute is attained regarding HSM requisites (see Table 3.1).

After classifying all data required above, as defined by HSM (also cited on section 2.2.3), the segmentation procedure can be done. The establishment of homogeneous segment permits that operational conditions collected at a given point to be considered valid for their entire length of that segment (Andrade & Setti, 2011). A homogeneous segment starts either in a middle of an intersection or where there is a change of roadway characteristics that justifies the establishment of another homogeneous segment (AASHTO, 2010).

Table 3.1 - Data needs for calibration of TLHS of HSM predictive models (AASHTO, 2010)

Roadway Segments – Data Element	**Data Need**		***Default Assumption****
	Required	**Desirable**	
Historical crash data	X		Required
Segment length	X		Required
Average annual daily traffic (AADT)	X		Required
Lengths of horizontal curves and tangents	X		Required
Radii of horizontal curves	X		Required
Presence of spiral transition for horizontal curves		X	Design policy
Superelevation variation for horizontal curves		X	No variation
Percent grade		X	Base default[a]
Lane width	X		Required
Shoulder type	X		Required
Shoulder width	X		Required
Presence of light		X	No lighting
Driveway density		X	8 driveways/km
Presence of passing lane		X	Not Present
Presence of short four-lane section		X	Not Present
Presence of center two-way left-turn lane	X		Required
Presence of center line rumble strip		X	Not Present
Roadside hazard rating (*RHR*)		X	*RHR* = 3
Use of automated speed enforcement		X	Not Present

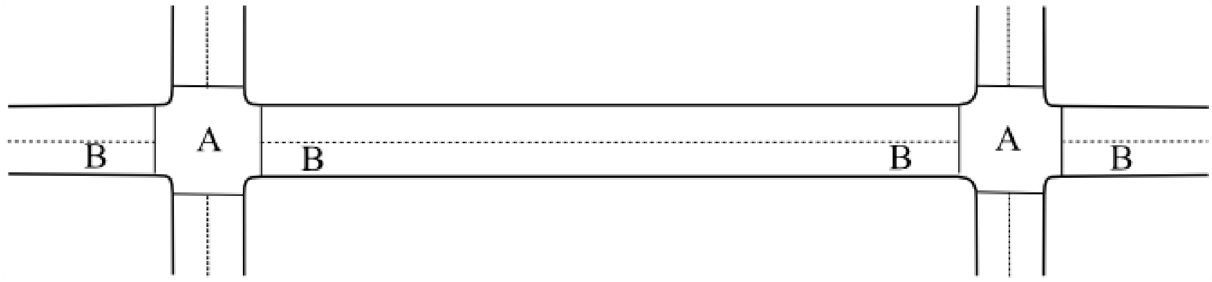
* Suggested for calibration purposes

[a] Suggested values for *CMF*: 1,00 for level terrain; 1,06 for rolling terrain, 1,14

It is hard to stipulate a correct characterization associated to complications in data collection. Although some variables have objective criteria, obtaining the accurate values is not simple. An example is the Radii of horizontal curves because most roads were built long time ago so that geometric design records are incomplete or missing at all. Another common problem is related to the lack of turning volumes at intersections, especially in rural areas or less developed regions or countries, where the resources are scarce.

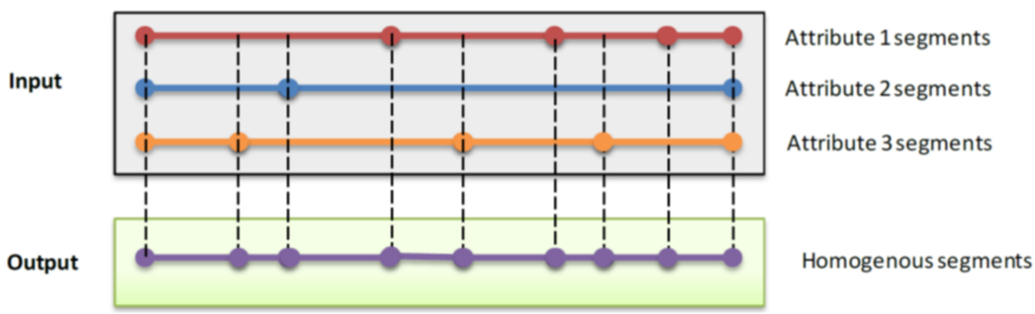
Furthermore, for applying the EB method, observed accidents should be attributed to individual segments or intersections. Accidents occurring between intersections are classified either as related to intersections or highway segment, depending on their proximity to the intersection (AASHTO, 2010). However, in the HSM methodology, to assign accidents to intersections there is no objective guidance on the area of influence of the intersections, within which accidents would be assigned to, only the followings recommendation for specialist judgment: (1) all crashes happened at the boundary of the intersection (region A of Figure 3.2) are linked to the intersection; (2) crashes occurrence outside the boundary of the intersection (region B of Figure 3.2) are attributed to the highway segment depending on the nature of the accident. Rear collisions should be included in this analysis, since they may be associated with queues from the approach (AASHTO, 2010).

Figure 3.2 - Boundary between intersections and segments for crash assignment (AASHTO, 2010)



Moreover, the segmentation procedure includes several consistency checks to be reliable. In the Figure 3.3 is shown a scheme of homogenous roadway segments procedure. Florida database of highway segments was obtained using Python scripts (Srinivasan et al., 2011), while the segments for Brazilian Highways was divided following semi-automatized algorithms written in VBA as exposed on the next sections.

Figure 3.3 – Homogeneous segment procedure (Srinivasan et al., 2011)



3.2 DATA SOURCES

The data source for regions from Brazil come from different sources. Roadway attribute were collected *in loco* using a GPS navigator and the operational characteristics were conceded by the administration of each highway, as well as the historical crash data.

Roadway attribute data from Florida were collected through the Florida Roadway Characteristics Inventory (RCI) and the historical crash data were extracted from Crash Analysis Reporting System (CARS). Data source is maintained by the Florida department of transportation.

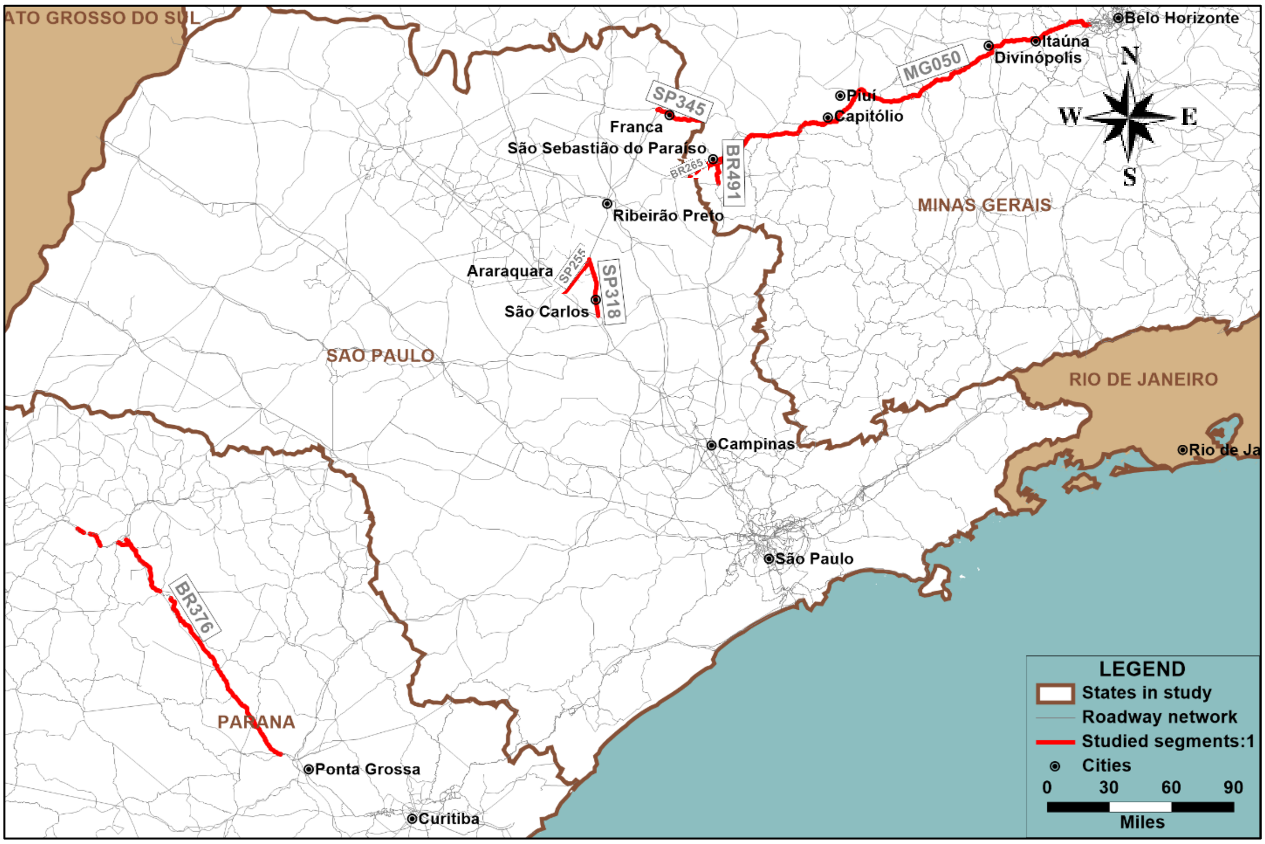
3.2.1 BRAZILIAN DATABASE

The database used for Brazilian context was composed only by toll highways due to the availability of crash records and traffic data for at least three years. Also, roadworks over the years were considered.

The database used in this study was aggregated from several data sources. The following list contains the main information used and their respective sources: (1) Historical crash data for three years or more given by highway administration; (2) Data collection using GPS navigator from field visits; (3) Photographic database provided by satellites from Google Earth software; (4) Digital terrain model from Shuttle Radar Topography Mission – SRTM (Farr & Kobrick, 2000); (5) Traffic characteristics for all highways provided by their administration, including volumes from toll plaza; volumes collected from sensors; volumes obtained from previous traffic studies.

The focus of this study was two lane highways segments. In this sense, a sample of segments from São Paulo (SP), Minas Gerais (MG) and Paraná (PR) states was analyzed, as can be seen in Figure 3.4. Sao Paulo state segments is composed by parts of SP-255, SP-318 and SP-345 highways. Minas Gerais segments contained MG-050, BR-491 and BR-265 highway, the part with two lane highway characteristics, likewise to BR-376 for Paraná. All major intersections were excluded from this study due to the difficulties to obtain accurate volume data. The accidents related to intersections were removed from database as well.

Figure 3.4 – Highways in study -BR



Historical crash database for cited location were attained for distinct range of years. For São Paulo state, the series obtained covers the period from 2008 to 2010. The records for highways segments of Paraná were assembled to the period between 2006 and 2012. For Minas Gerais state, the study was conducted for the period from 2011 to 2015. The database has the crash records classified by type, severity and time of incidence, as well as its location in highway. More details on this are given on the chapter 4.

Data collection using navigation GPS receiver was done in three distinct periods as close as possible of the historical crash availability (see Table 3.2). The GPS receiver collected data each second (or as configured by user) and the waypoints was assigned by user handed by a tablet with digital worksheet, as explained in previous research (Andrade & Setti, 2011).

Table 3.2 – Summary of data collection using GPS

Year	Highway	Total length (km)	Average Speed	Number of points
2011	SP-318	38.6	103.2	1220
2012	BR-376	238.5	69.6	12321
2014	MG-050	346.3	71.8	17330

Collecting data using GPS required onsite visits and it was done for most segments studied as far as possible. However, some segments were drawn using photographic database provided by satellites from Google Earth software. The main difference between them is the possibility of recording a path each second using GPS receptor while the data from Google Earth software depends on the quality of images and the drawn path. In addition, collecting data in field provided an opportunity for better understanding the road safety conditions in the site.

Although the exactness of handheld GPS receiver can be doubtable for building purpose or even for locate precisely crash data, it has been widely used in transportation planning analyses (Andrade & Setti, 2011; Lee, Sener, & Mullins III, 2016; Saito et al., 2015; Strauss, Miranda-Moreno, & Morency, 2016). The preliminary data treatment involved GPS data exportation and access of Shuttle Radar Topography Mission – SRTM digital terrain model to obtained grades for SP-318 and BR-376. For SP-255 and SP-345, information was accessed by satellites from Google Earth (Google, 2015). For MG-050, data was provided by the state administration.

Around 700 km of highways was considered for each studied year (Table 3.3). Nearly half of this located in Minas Gerais, more than 80 km in Sao Paulo State and the remining was in Paraná State. This location was selected in function of the possibility to obtain high quality of data from highway administration, especially linked to traffic and safety conditions.

Table 3.3 – Final sample of studied highways

State	Highway	Studied length (km)	Number of years
SP	SP-318	45.6	3
	SP-255	28.85	
	SP-345	8.7	
PR	BR-376	244.2	7
MG	MG-050	321.05	5
	BR-295	22.27	
	BR-491	2.12	

Annual Average Daily Traffic is used in many models that have traffic exposure as a dependent variable although its relationship with accident counts is not completely linear. In general, AADT is used as an independent variable for greater accuracy because it can interact with other controllable variables, and others measures the effect of traffic flow intensity.

Obtaining traffic volumes from several data source and doing their compatibilization were one of the critical part of this study. It demands several amounts of resources, time and technology. For contour this problem, some traffic influences areas (TIA's) were established in order to represent the entire segment. Also, for the points that was not found a regular series of traffic, seasonal expansion was performed. The compilation of traffic volumes considered is shown in Table 3.4.

Table 3.4 – Traffic volumes in highway segments

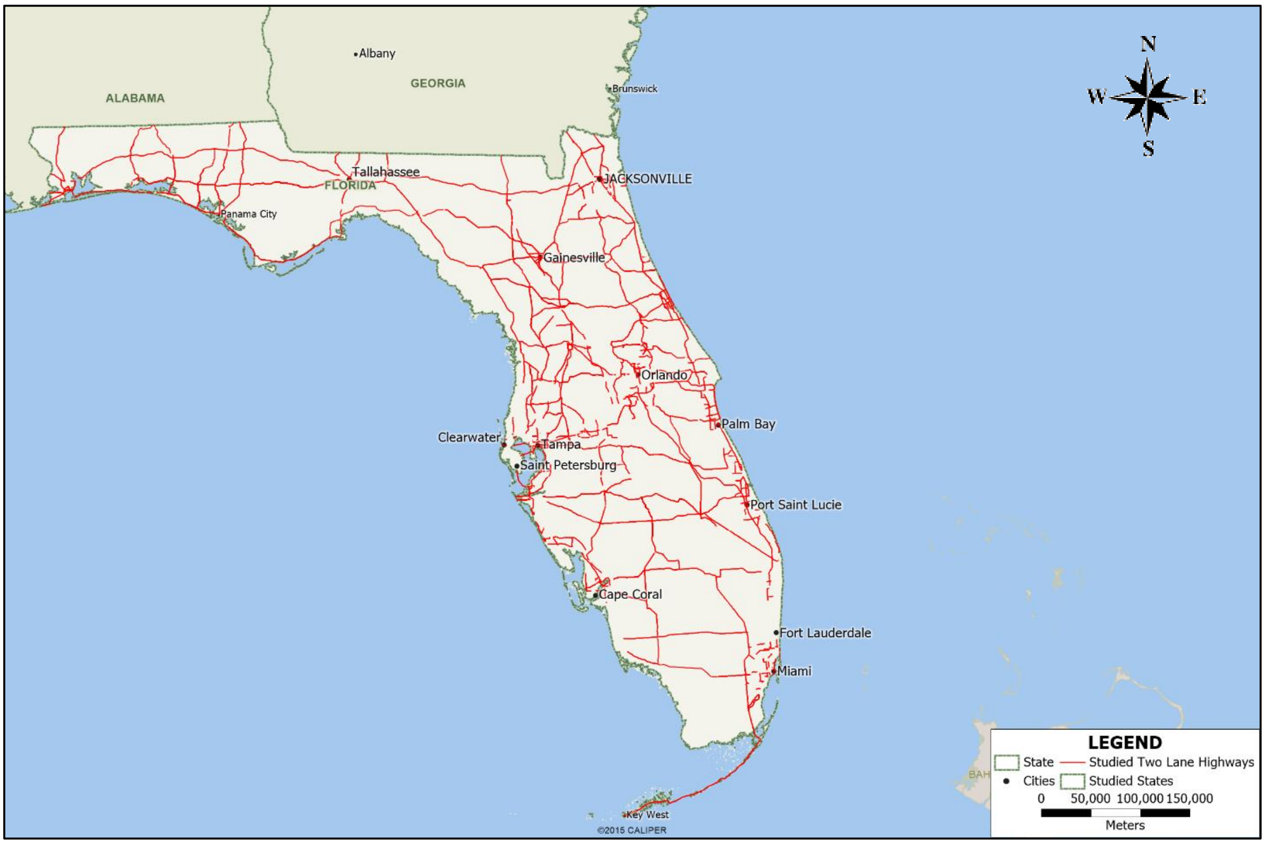
State	AADT (veh/day)			Number of TIA	Period
	Máx	Min	Average		
São Paulo	5856	3281	4498	3	2008-2010
Paraná	7910	2850	5339	16	2006-2012
Minas Gerais	18182	2650	6913	20	2011-2015

3.2.2 Florida Database

Roadway attribute data were composed by the Florida Roadway Characteristics Inventory (RCI), which contains an extensive diversity of roadway data for all roads that are maintained by Florida Department of Transportation (FDOT) (FGDL, 2017). The dataset represented the highway conditions for the years 2005 through 2010. The method for obtaining and the data treatment were explained in Haas (2015). In Figure 3.5, Florida two lane highways are highlighted.

Historical crash data for Florida were obtained for the same period from the Crash Analysis Reporting System (CARS), maintained by FDOT, which details are shown on chapter 4 . The crash related datasets extracted from CARS was related to homogeneous segments after several consistency checks (Haas, 2015). For the following analysis, only segments from two lane highways was taken into account to examine the spatial transferability of crash estimation models.

Figure 3.5 – Highways in study – FL (FGDL, 2017)



Florida database was attained from secondary data source and have not included intersections and curved segment. In addition, missing characteristics were filled by default values to estimate SPF. General conditions are exposed on Table 3.5.

Table 3.5 – Florida two lane highway overview (Haas, 2015)

Parameter	Value
AADT Maximum (veh/day)	32,500
AADT Minimum (veh/day)	350
AADT Average (veh/day)	5,060
Number of counties	64
Number of FL Highways	319
Length (km)	3,184
Period of analysis	2005 – 2010

3.3 Homogeneous Segments Characteristics

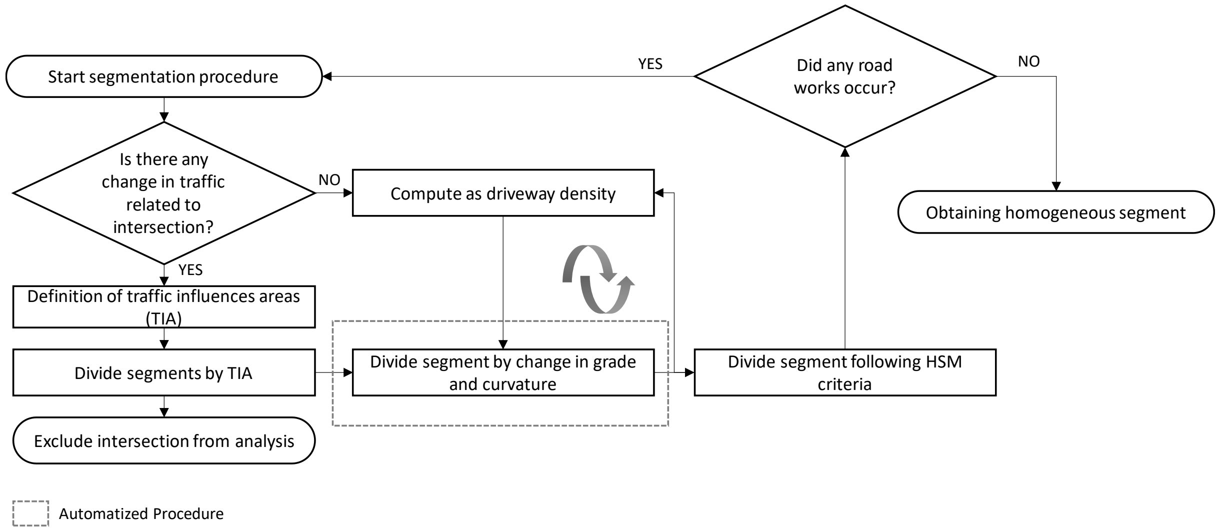
The segmentation procedure followed an iterative method along with several consistency checks. Only segments were included in the analysis, which means crashes related to intersections were removed. Before starting this process, an evaluation of data availability was performed. Some difference between Brazilian condition and Florida was found. For Brazilian sample, there was no center two-way left-turn lane in highways while for Florida, no automated speed enforcement was used during the study period. Also, due to the data collection in field for Brazil, it was possible estimated grades, preliminary curvature parameters and roadside characteristics (as RHR). However, the extension of sample as significantly inferior. A summary of data availability is presented in Table 3.6.

Table 3.6 – Data availability for Brazil and Florida

Roadway Segments – Data Element	**Data available**		**Additional comments**
	Brazil	**Florida**	
Historical crash data	✓	✓	Required
Segment length	✓	✓	Required
Average annual daily traffic (AADT)	✓	✓	Available
Lengths of horizontal curves and tangents	✓	-	Estimated for
Radii of horizontal curves	-	-	Brazilian condition
Presence of spiral transition for horizontal curves	-	-	Base default
Superelevation variation for horizontal curves	✓	✓	No variation
Percent grade	✓	✓	Calculated for Brazil
Lane width	✓	✓	Available
Shoulder type	✓	✓	Available
Shoulder width	✓	✓	Available
Presence of light	✓	✓	Identified
Driveway density	✓	✓	Estimated
Presence of passing lane	✓	✓	Located
Presence of short four-lane section	✓	✓	Located
Presence of center two-way left-turn lane	-	✓	Do not exist for Brazilian data
Presence of center line rumble strip	-	✓	Base default
Roadside hazard rating (RHR)	✓	✓	Obtained for Brazilian condition
Use of automated speed enforcement	✓	-	Located

As introduced previously on this chapter, homogeneous segments to Brazilian condition were obtained following semi-automatized algorithms. The criteria for a new homogeneous segment is illustrated in Figure 3.6. For Florida, an automatized procedure was developed according to Srinivasan et al. (2011) using Python scripts. The result of this process was a set of homogenous roadway segments with all the needed features required for calibration.

Figure 3.6 – Flowchart of segmentation procedure Brazilian condition



This procedure has not taken into account intersections. Curvature was considered with basic algorithms. The algorithm for the identification of grades, signalized as Automatized Procedure, was developed regarding the availability of smoothed elevation data (Andrade & Silva, 2018). Per the HSM, any grade steeper than 3% would result in a new segment and in a CMF_{5r} higher than unity. The algorithm calculates the difference in elevation (h) between each segment (Equation 3.1), identifying the locals where the sign and values of Δh changes.

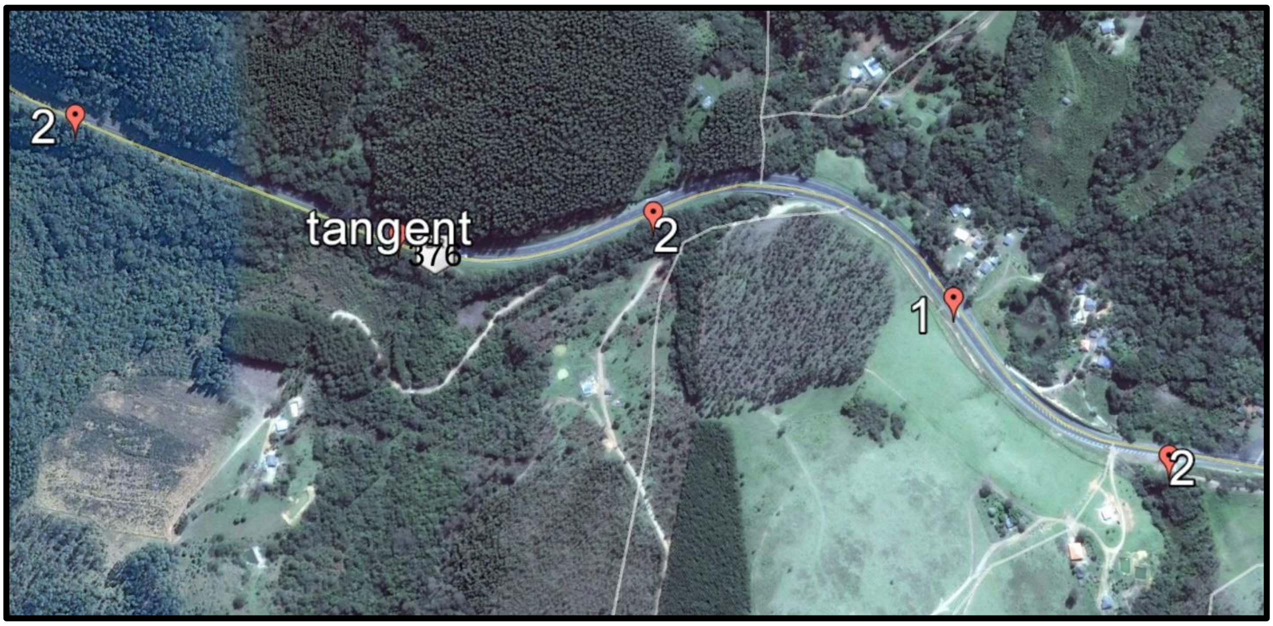
$$\Delta h_i = (h_i - h_{i-1}) \qquad 3.1$$

The method for identifying variation of horizontal curvature (Δc_i) worked analogously to the method for grades. The deflections of every segment i (c_i) are contrasted with a threshold $v1$, in degrees (Equation 3.2).

$$\Delta c_i = (c_i - c_{i-1}) \geq \nu_1 \qquad \forall i \in I \qquad 3.2$$

In a preliminary analysis, these factors were found only for the segments where there was missing information in Paraná related to vertical profile and horizontal alignment. The accuracy of these methods was not investigated. The purpose of developing the algorithm was to segment the highways as good as possible for crash prediction modelling, (see Andrade & Silva (in press)). An example of the application of the algorithm is exposed in Figure 3.7. For Minas Gerais and São Paulo, only grades were obtained using this method. Estimated horizontal alignment was provided by the highway administration.

Figure 3.7 – Example of the use of the algorithm to find curved segments



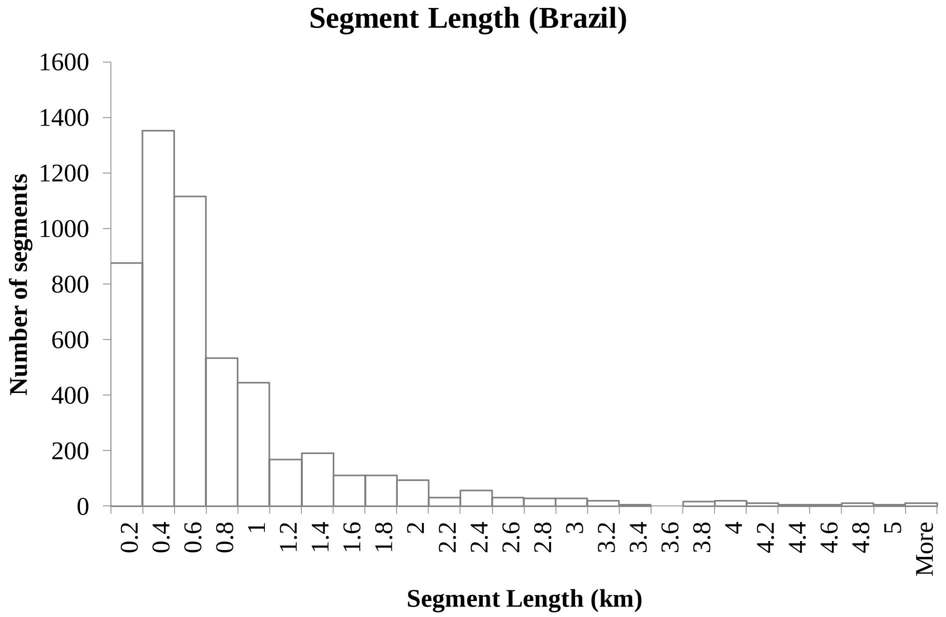
Segments that remained homogenous for all years were retained for analysis in order to ensure consistency of the comparisons. Few segments that changed over time have been joined in the analysis only if it has been possible to discern which kind of road work was done and when. Sites in the sample were classified as “rural” or “urban”, according to abutting land use.

3.3.1 Brazilian Database

To segment the highways for this study, only undivided two-lane highways were considered. Each segment was considered once per year since its characteristics may change over time. In the 5,263 resultants data points, lane width of TLH have not shown wide variations due to prevalent design practice. Typical lane width was 3.5 m for Minas Gerais and São Paulo State and 3.6 m in Paraná. Shoulder width varied between 0 and 2.6 m. The design practice in São Paulo State is 2.5 m while in Paraná is 2.6 m. In Minas Gerais, due to the rugged terrain, shoulder width ranged from 0 to 1.5 m. Average driveway density for the sample was found as 4.2 access per kilometer.

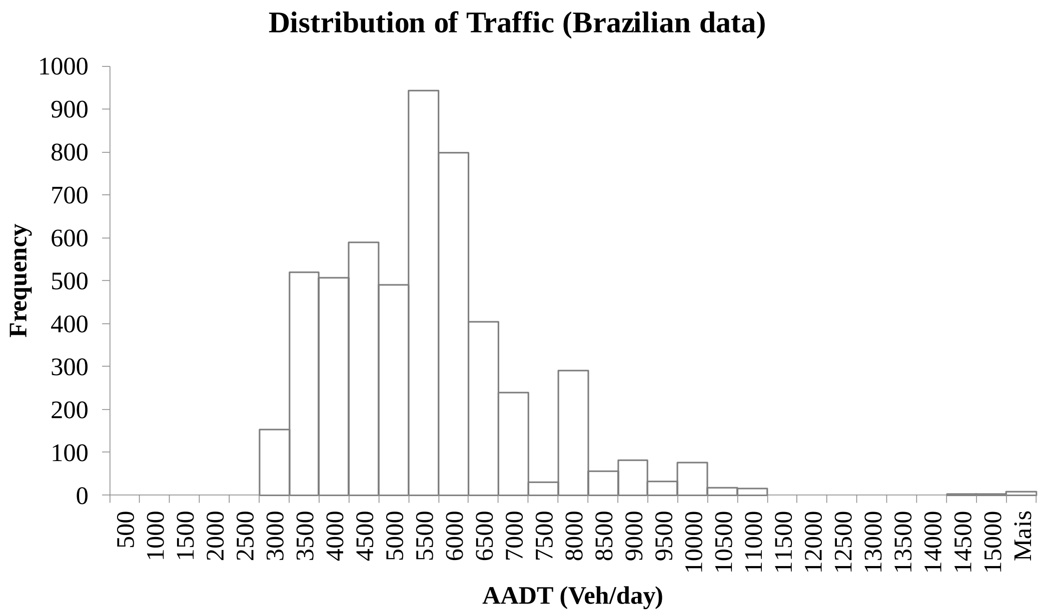
Segment length is a result from the segmentation procedure, which means that a single change in characteristics results in a new segment. The average length of segments was 0.70 km with maximum equal to 6.14 km and minimum 0.1 km. Even though an expected concentration can be seen around the average, the distribution is skewed to the left, as shown in Figure 3.8.

Figure 3.8 – Histogram of segment length - Brazil



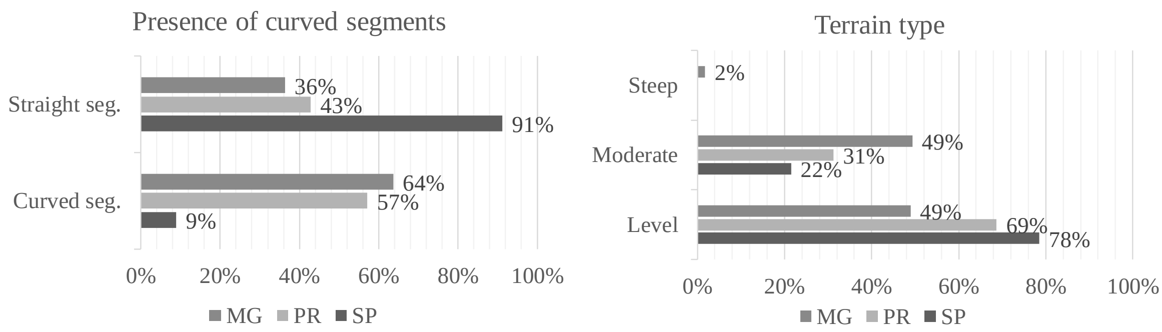
The distribution of the Annual Average Daily Traffic resultant of segment procedure is presented in Figure 3.9. The histogram is slightly asymmetric towards to right (skewed to the left). Most Brazilian studied segments can be considered low volume roads since 99% of them has traffic volume below 10,000 vehicles/day. No approach regarding heavy vehicle volumes was performed.

Figure 3.9 – Histogram of traffic in Brazilian highways



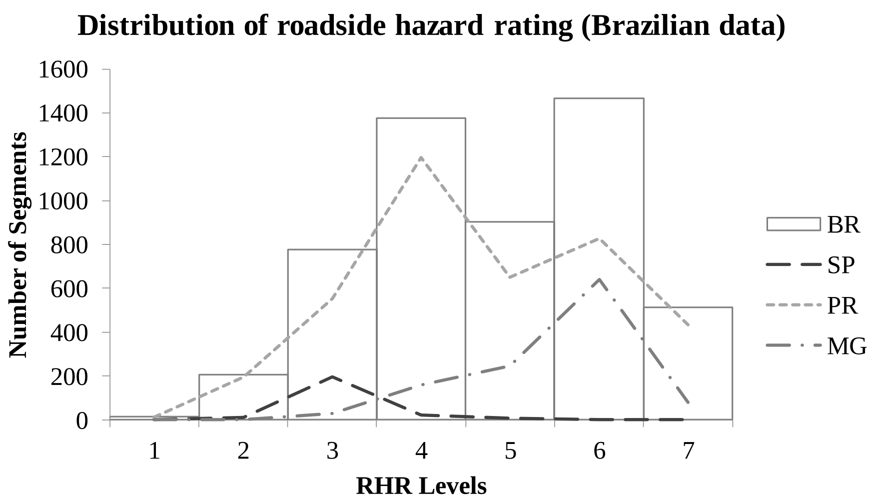
Regarding land use, 91.5% of sample was classified as rural highway segments. However, urban segments inside municipalities that have between 25,000 and 50,000 inhabitants in an area of dense occupation with a degree of urbanization of less than 25% were not excluded from the study. In addition, only 13% of segments were base segments as defined in HSM. Most segments are curved (56%), however to better understand this meaning, it was convenient to segregate data from different states (see Figure 3.10), as well as to compare terrain type according to HSM criteria.

Figure 3.10 – Concentration of curved segments and Terrain type



As expected, São Paulo State segments have more straight segments and level terrain than the other states. Minas Gerais presented 64% of curved segments from its total and it was the only state to have steep Terrain. Another related characteristic is the Roadside Hazard Rating (RHR) that varies from 1 to 7 as described in Appendix 13 A.3 of HSM (AASHTO, 2010). An analysis of the Figure 3.11 indicated that RHR tends to be higher when the highway is steeper.

Figure 3.11 – Roadside hazard rating related to segments



In HSM the default value for Roadside hazard rating is 3 in the RHR scale. RHR was detected by linking the roadworks related to guardrails to the location of segments, as shown in Figure 3.12. If the segment has a new guardrail implemented over time, this change in roadside was considered from that moment. For all segments, general characterization was performed by watching videos recorded during data collection and using Google Earth Pro Street View tool when available.

Additional characteristics regarding HSM premises can be found in Table 3.7. There is lighting just in a few segments as well as enforcement. It can be noticed that there is a high percent of segments with additional lanes, which can be passing or climbing lanes.

Figure 3.12 – RHR related to the segment of BR376 from km 254 to 253 (Google, 2015)

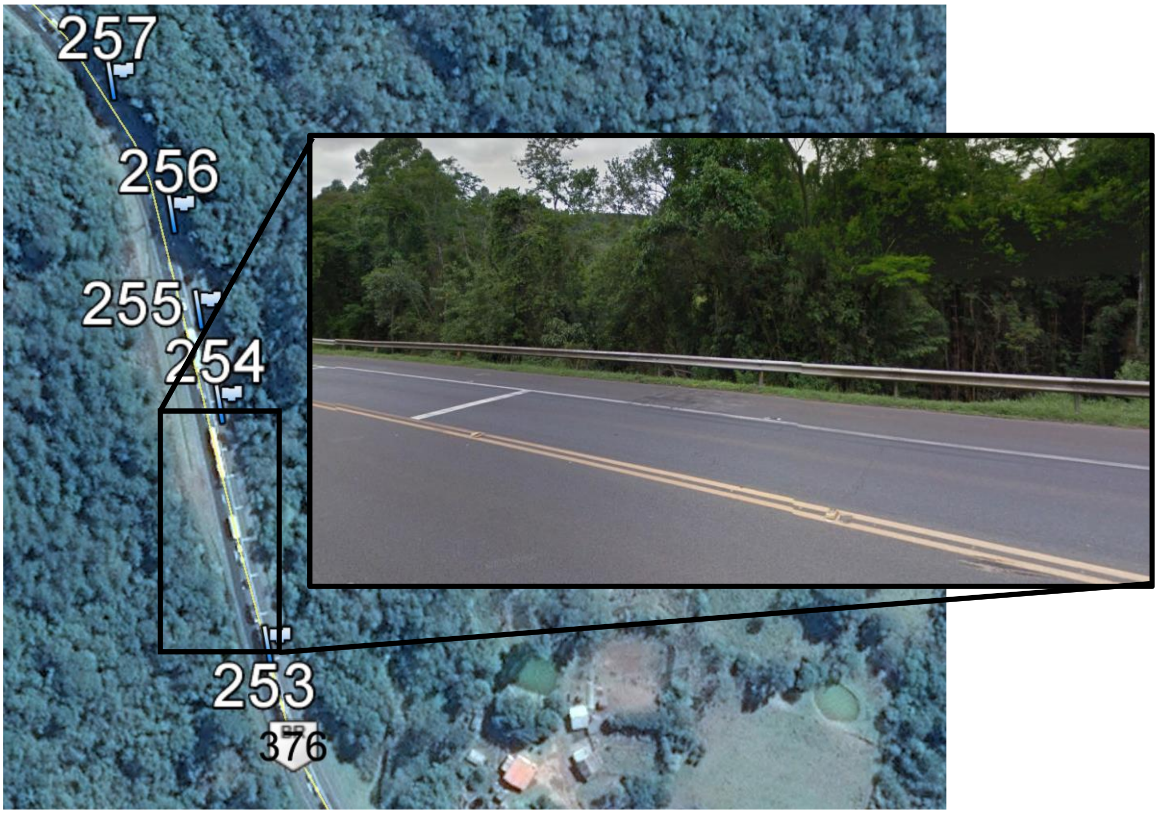


Table 3.7 – Additional segments characteristics

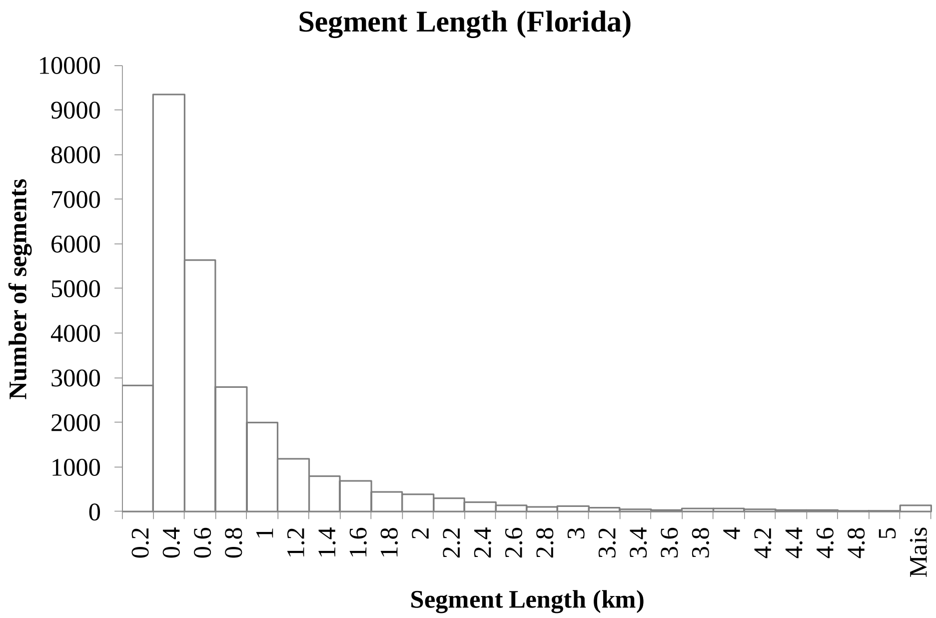
State/Characteristics	% of Number of segments			Number of segments/year	Studied Length km/year
	Additional lane	Illumination	Enforcement		
SP	59%	1%	8%	79	83.15
PR	41%	5%	15%	553	244.2
MG	31%	16%	11%	231	345.39

3.3.2 FLORIDA DATABASE

Florida database was obtained as described in Haas (2015). Intersections and curves were removed from the analysis. The segmentation procedure, regarding HSM criteria, used a Python script and segments that changed over time were excluded from the analysis, as detailed in Srinivasan et al., 2011. Comparing with Brazilian Database, Florida's is much larger, however many of the required characteristics was considered equal to the default recommended by HSM. The Florida data characteristics is addressed in the following paragraphs.

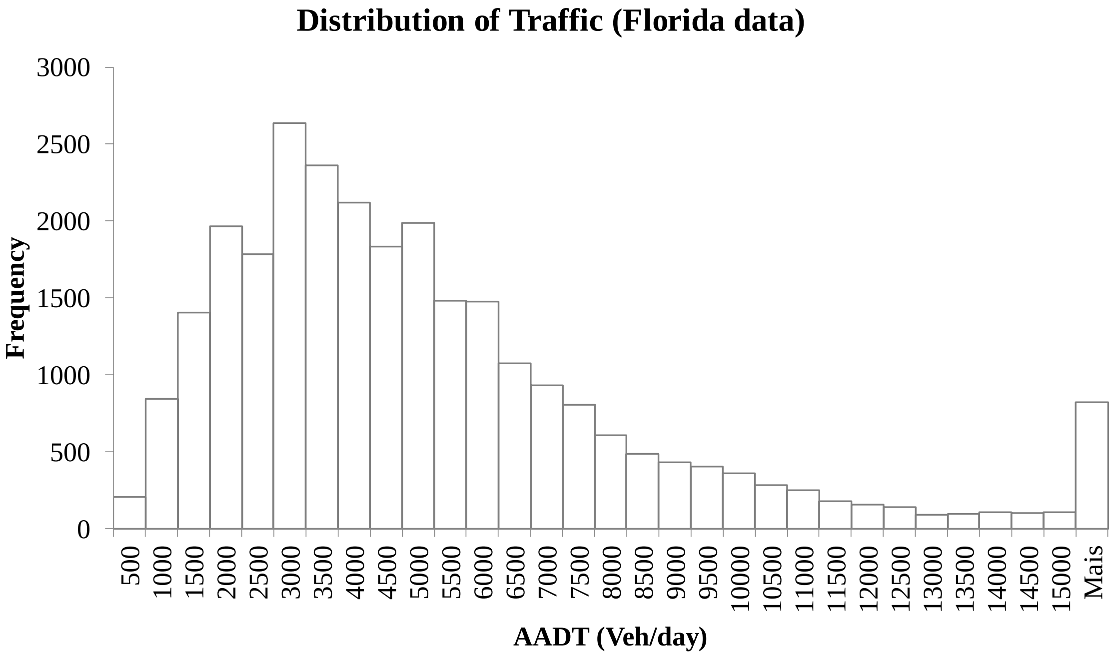
Distribution of segment lengths for Florida conditions is presented in Figure 3.13. The average segments length was 0.69 km with maximum equal to 10.09 km and minimum 0.16 km. The distribution of segment lengths is skewed to the left.

Figure 3.13 – Histogram of segment length - Florida



Regarding traffic volumes, Florida had a wide range of values in the studied years. The average obtained was 5,060 veh/day and the correspondent histogram is also skewed to the left. It was found some segments with high demand in which volumes overpassed 30,000 vehicle/day.

Figure 3.14 – Histogram of traffic in Florida highways



Additional characteristics of Florida highways are briefly shown in Table 3.8. Around 3,200 km of Florida highways were included. More details on database characteristics and data collection method were addressed in other studies (Haas, 2015; Srinivasan et al., 2011). In total, more than 4,500 segments were considered with same characteristics during the 2005-2010 period, resulting in a sample of 27,546 data points.

Table 3.8 – Florida segments characteristics

Characteristics	Values		
	Max.	Average	Min.
Lane Width (m.)	6.7	3.6	2.7
Shoulder Width (m.)	3.0	0.8	0.0
Driveway density (access/km)	12.4	2.3	0.0
Highway Classification	Rural (99.7%)	No classified (0.3%)	
Illumination (% of segments)	14%		

3.3.3 DATABASE CONSOLIDATION

Comparing models from highways of different countries with diverse characteristics is one way to investigated how far-reaching they can be. For the studied sample, some particularities were reflected in database consolidation and possibly in the final model. The method of data collection was responsible for some of them. Florida and Brazil presented similarities, nevertheless the range for Florida volumes is significantly wider while other Brazilian characteristics deviated more from base conditions as shown in Table 3.9.

Table 3.9 – Summary of database

Database	**Brazil**			**Florida**		
Roadway Segments – Data Element	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**
Segment length (m)	0.10	0.70	6.14	0.16	0.69	10.09
Average annual daily traffic (AADT)	2650	5294	18182	350	5060	32500
Lengths of horizontal curves and tangents (km)	0.10	0.72	6.14	-	-	-
Radii of horizontal curves	24.8	575.1	2342.3	-	-	-
Presence of spiral transition for horizontal curves	59% of existing curves			Removed		
Superelevation variation for horizontal curves	No variation			Removed		
Percent grade	0.0%	2.8%	6.4%	Default - Plane		
Lane width	3.3	3.6	3.6	1.7	3.6	6.7
Shoulder type	Paved and Lawn			Paved, Gravel and Lawn*		
Shoulder width	0.0	2.2	2.6	0.0	1.6	6.1
Presence of light	8% of segments			14% of segments		
Driveway density	44.2	4.2	0.0	12.4	2.3	0.0
Presence of passing lane	40% of segments			Default - not existent		
Presence of short four-lane section	4% of segments			Default - not existent		
Presence of center two-way left-turn lane	Not existent			0.5% of segments		
Presence of center line rumble strip	Default - not existent			Default - not existent		
Roadside hazard rating (RHR)	1 to 7			Default - RHR =3		
Use of automated speed enforcement	14% of segments			Not existent		

*(see S. Srinivasan et al. (2011))

The strength of the Brazilian database lies in the fact that most geometric details of the highway was included in the database thanks to the data collection method. As an example, it is possible to cite curves and roadside characteristics that are absent in Florida database. Roadside characteristics requires much more attention and normally is costly to obtain. On the other hand, Florida database has a larger sample of base condition segments that better supports a SPF development.

3.4 FINAL REMARKS

After obtaining information from highway segments, it was possible to answer some of the research question posed in chapter 1. Some points related to RQ2 to RQ5 can be highlighted.

First, the sample of Brazilian highways used in that research was composed of toll highways due to the availability of crash records and demand comprising a sample of 5,263 data points from 2008 to 2015. Brazilian database covered three different states. The database from Florida was obtained from previous study encompassing 27,546 from 2005 to 2010.

Brazilian two-lane highways sample was mostly composed by low volume roads that have a larger variety of roadway characteristics. Also, the fact that roadside had been rated following the HSM criteria led to a more diverse database. In contrast, Florida segments tend toward base conditions and the range of traffic volumes is wide. Both database could help to better understand safety performance and transferability of models.

Additionally, it can be noticed that a crash prediction method is highly dependent on traffic volumes and the feasibility of study is affected by how frequently it is collected. Consequently, for applying HSM Crash Prediction model all required data should be provided and additional information could help better understand the safety performance in each place.

Since the points of similarities and differences began to indicate a way to compare data from several conditions, some guidelines were defined. Initially, dedicating an entire stage of this work to address safety data and analysis. Following that, to investigate the accuracy of the method to estimate curve parameter, and finally, the possibility of not using all Brazilian sample to develop a model or to check transferability.

4 SAFETY DATA ANALYSIS

In this chapter, safety database from three Brazilian's states and the state Florida, USA are addressed for two lane highways segments. Also, the main aspects of crash type and severity used in HSM transferability are presented.

4.1 CRASH TYPE AND SEVERITY

In safety analysis studies, the evaluation of database is the first step to understand crash phenomenon. Crash record normally is separated by crash severity and crash type. In order to compare the various historical crash database, the same structure presented in Chapter 10 of HSM (AASHTO, 2010) was used.

Crashes severity was generally classified following the existence and level of injury according to KABCO scale (AASHTO, 2010). It is called (K) fatal injury, when at least one injury results in death; (A) incapacitating injury, when the disabilities caused by the accident prevent the injured person from living a normal live; (B) non-incapacitating injury, when there is any evident injury other than incapacitating or fatal; (C) possible injury, when none of the listed injury is evident but some minor problem can be felt by the involved person and (O) property damage only (PDO), when there is no injury.

Although the severity could be described easily, it is not simple to make this judgement on site. Moreover, it can change from one jurisdiction to another and the scale ABC for levels of injury of KABCO can have a widely variation. In some cases, this part can be reduced to injury crashes other than fatal.

Crashes at segments from undivided TLH are commonly categorized in crashes involving one vehicle and multiple vehicles. Single vehicle crashes are collisions with animal, pedestrian and bicycle, overturned and ran off road that is not the result of vehicle interaction. Multiple vehicle crashes are resultants of vehicle interaction, as rear end, head-on, angle and sideswipe.

According to AASHTO (2010), among the types of accidents that can impact crash prediction, there are some more likely to be affected by lane width, as single vehicle run off road, multiple vehicles head-on and sideswipe. The CMF_1 and CMF_2, associated to lane and shoulder width, uses a proportion of these related accidents (p_{ra}) to estimate this crash modification factor. The value of p_{ra} may be calculated from field data in the calibration process.

Another crash modification factor is affected by the proportion of nighttime crashes (CMF_{11}) on unlighted roadway segments. For CMF_{11}, it is encouraged by HSM to replace from field data the proportion of FI crashes that occurred during nighttime on unlighted segments (p_{inr}), the proportion of PDO crashes that occurred during nighttime on unlighted segments (p_{pnr}) and the proportion of total crashes for unlighted segments that occurred during night (p_{nr}) to calibrate HSM parameters (AASHTO, 2010).

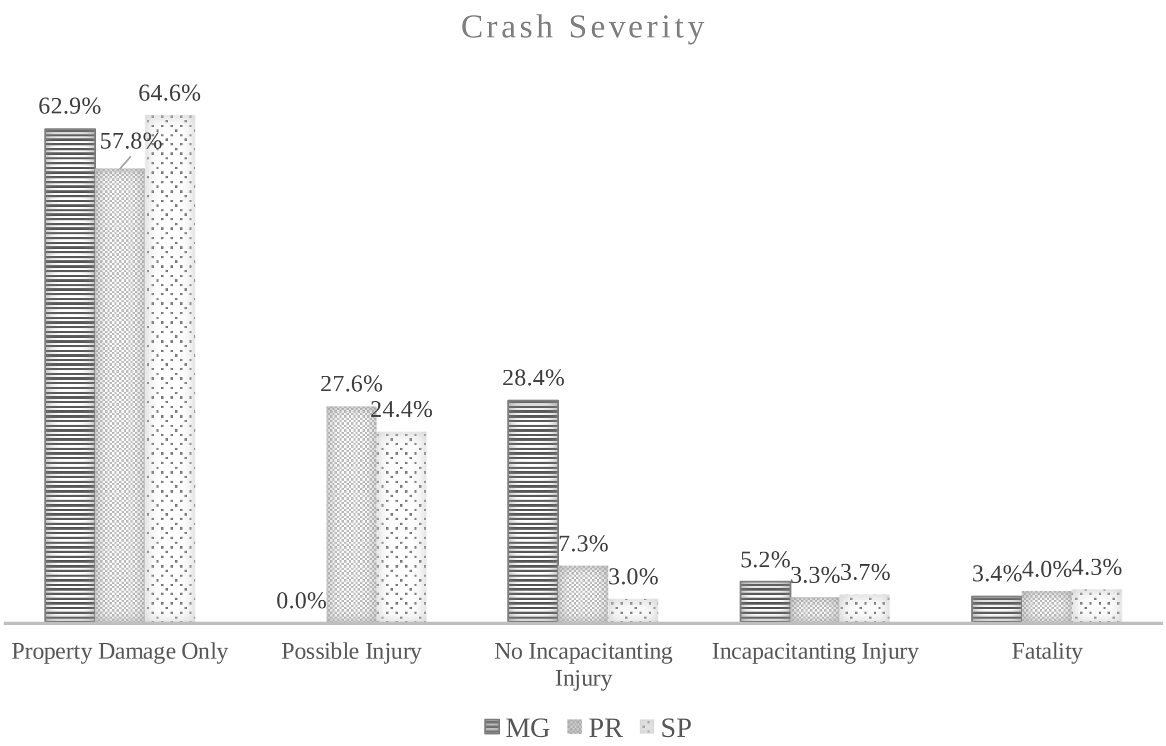
To further improve crash estimation methods, all the crash analyses were done to highways segments and the intersection related data were removed from the analysis. The values obtained were discussed on next subitems.

4.1.1 BRAZILIAN STATISTICS

As introduced in the previous chapter, historical crash database for Brazil (BR) were obtained for distinct range of years between 2006-2015 depending on the highway. The crash severity distribution for São Paulo, Paraná e Minas Gerais is shown in Figure 4.1.

Collision Type relative numbers is presented in Table 4.1. All injury accidents were added to Fatal, forming the category Fatal and Injury (FI), as per the HSM (AASHTO, 2010). Most FI’s crashes occurred with single vehicle, which indicates that run off road crashes play a significant role and deserves attention.

Figure 4.1 – Distribution of crash severity for Brazilian states



Also, it was found that there was a confusion in the classification of crashes named as "Other single", especially when the crash was originated by the loss of vehicle control. By reading the description of each register of the crash database, many of these accidents could be reclassified in this research as "run off road" crashes (Figure 4.2). The remaining crashes in that classification were normally related to fell off motorcycle.

Figure 4.2 – View of the reclassification of crash database**

fx (ROBERSON) O CLIENTE SEGUIA NO SENTIDO SUL, QUANDO PERDEU O CONTROLE SOBRE O VEÍCULO, SAINDO DA PISTA E CHOCANDO-SE CONTRA UMA PLACA DE SINALIZAÇÃO, RODANDO, FICANDO VIRADO PARA O SENTIDO NORTE.

DescricaoAcidente	TipoAcidente	Severidade	Intersecao	Reclassificac	Reclassificação Fir	Iluminaca
(ROBERSON) O CLIENTE SEGU	Outros	Danos materiais sem vítimas	FALSO	Choque	Choque	FALSO
(LUIZ CARLOS) CONDUTOR TR	Capotamento	Vítimas com ferimentos graves	FALSO		Capotamento	FALSO
VEÍCULOS SEGUIAM NO SENTI	Colisão - Traseira	Danos materiais sem vítimas	FALSO		Colisão - Traseira	FALSO
VEÍCULO GOL SEGUIA NO SEN	Colisão - Lateral	Vítimas com ferimentos leves	FALSO		Colisão - Lateral	FALSO
(LUIZ CARLOS) SEGUNDO REL	Outros	Danos materiais sem vítimas	FALSO	Choque	Choque	FALSO
(EVALDO) O VEÍCULO TRAFEG	Outros	Vítimas com ferimentos graves	FALSO	Outros	Outros	FALSO
(FÁBIO) CONDUTOR TRAFEGA	Tombamento	Danos materiais sem vítimas	FALSO		Tombamento	FALSO
CONDUTORA RELATOU QUE S	Outros	Vítimas com ferimentos leves	FALSO	Choque	Choque	FALSO
(PEDRO) OS VEÍCULOS TRAFE(	Colisão - Traseira	Vítimas com ferimentos leves	FALSO		Colisão - Traseira	FALSO
(EUDES) CONDUTORES TRAFE	Colisão - Traseira	Danos materiais sem vítimas	FALSO		Colisão - Traseira	FALSO
CONDUTOR INFORMOU QUE	Atropelamento de Animal	Danos materiais sem vítimas	FALSO		Atropelamento de Ai	FALSO

** Database in Portuguese. Transcription of highlighted cell: "(Roberson) The driver was going southbound when lost vehicle control, running off road and colliding with a vertical sign, turning northbound". Classified as "other single" and reclassified as "Impact" and after "run off road"

The proportion of fatal and injury (FI) related crashes was shown as the sum of values from Table 4.1 for each state separately and finally an average value of these three states. The night period considered to calculate the proportion of crashes for unlighted segments was between 6:30 pm and 6:00 am. The proportions of crashes for CMF calculation were mapped on Table 4.2 for each state separately and finally an average value of these three states.

Table 4.1 – Percentage of total roadway segments crashes by crash severity level

Collision Type	SP			PR			MG			BR Average		
	FI	PDO	Total	FI	PDO	Total	FI	PDO	Total	FI	PDO	Total
Animal	3.0	9.0	7.0	0.9	6.0	3.9	2.1	7.2	5.3	2.0	7.4	5.4
Pedestrian and Bicycle	3.7	0.0	1.3	5.0	0.0	2.1	6.3	0.1	2.4	5.0	0.0	1.9
Overturned	7.3	2.9	4.4	15.9	6.8	10.6	15.4	7.3	10.3	12.9	5.7	8.4
Run off road	37.2	42.6	40.7	30.8	49.9	41.9	21.0	27.8	25.3	29.7	40.1	36.0
Other Single	0.0	13.9	9.1	0.6	0.8	0.7	10.8	2.6	5.6	3.8	5.8	5.1
Total (single vehicle)	**51.2**	**68.4**	**62.4**	**53.2**	**63.6**	**59.2**	**55.5**	**45.0**	**48.9**	**53.3**	**59.0**	**56.8**
Angle	12.8	5.8	8.2	6.6	2.7	4.4	12.4	12.7	12.6	10.6	7.1	8.4
Head-on	9.8	0.3	3.6	8.4	0.7	4.0	7.4	1.0	3.4	8.5	0.7	3.6
Rear-end	17.7	11.6	13.7	10.2	16.5	13.8	12.1	31.2	24.1	13.3	19.7	17.2
Sideswipe	7.3	7.4	7.4	10.4	11.0	10.7	10.4	5.0	7.0	9.4	7.8	8.4
Other Multivehicle	1.2	6.5	4.6	11.1	5.6	7.9	2.2	5.2	4.1	4.8	5.7	5.5
Total (multivehicle)	**48.8**	**31.6**	**37.6**	**46.8**	**36.4**	**40.8**	**45.2**	**56.7**	**52.4**	**46.9**	**41.6**	**43.6**
Total crashes	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

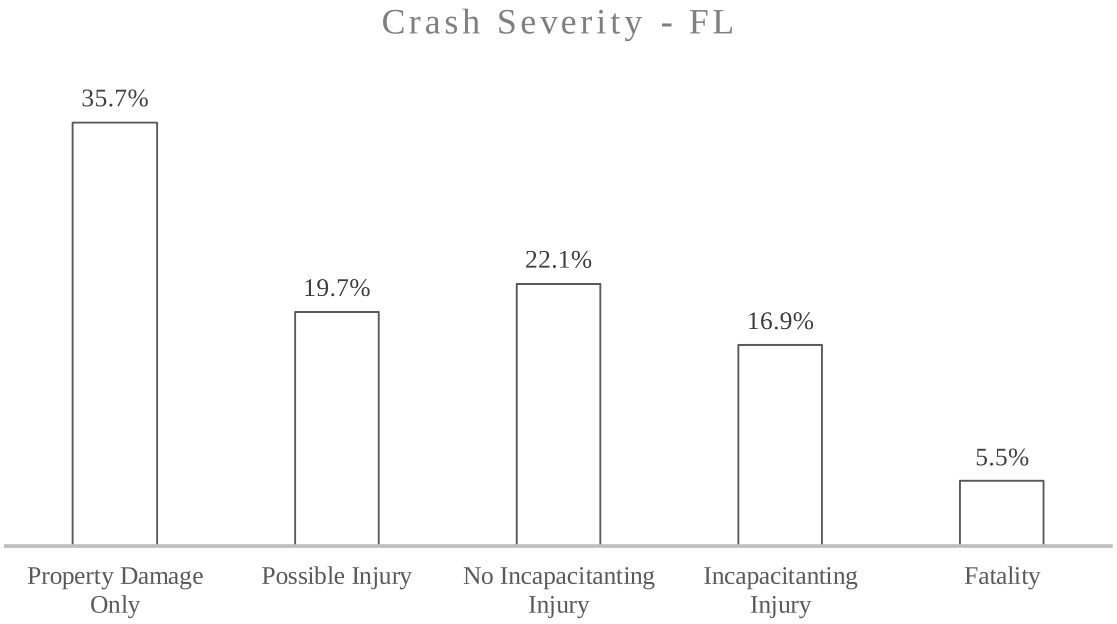
Table 4.2 –TLHS crash proportion used for CMF calculation

Proportion of FI related crashes (run-off-road, head-on, sideswipe) for CMF_1 and CMF_2				
State	SP	PR	MG	BR
Related crashes (p_{ra})	0.543	0.497	0.388	0.476
Proportion of crashes for unlighted segments that occurred during night (CMF_{11})				
State	SP	PR	MG	BR
FI crashes (p_{inr})	0.368	0.427	0.442	0.413
PDO crashes (p_{pnr})	0.632	0.573	0.558	0.587
Nighttime crashes (p_{nr})	0.482	0.372	0.279	0.377

4.1.2 FLORIDA STATISTICS

Florida historical crash database was assembled for six years (2005-2010) (Haas, 2015). The distribution of crash severity was plotted on Figure 4.3. It can be noticed that the proportion of fatal crashes was higher in Florida TLHS. Also, the classification of possible injury could be understood as PDO depending of the rigor of the register.

Figure 4.3 – Distribution of crash severity for Florida



Collision Type average distribution is shown in Table 4.3. Due to the poor data quality of PDO crashes, only the category Fatal and Injury (FI) was presented (Srinivasan et al., 2011). The estimated values were relative to the years of 2005-2008. The proportion of FI crashes for single vehicle was similar to multiple vehicle.

Based on these values, the proportion of FI related crashes for CMF_1 and CMF_2 (p_{ra}) was 0.422. The proportion of crashes for unlighted segments that occurred during night (p_{nr}) for CMF_{11} was 0.356 (Srinivasan et al., 2011). The division between PDO and FI for nighttime was not obtained due to the lack of information of PDO crashes, as aforementioned.

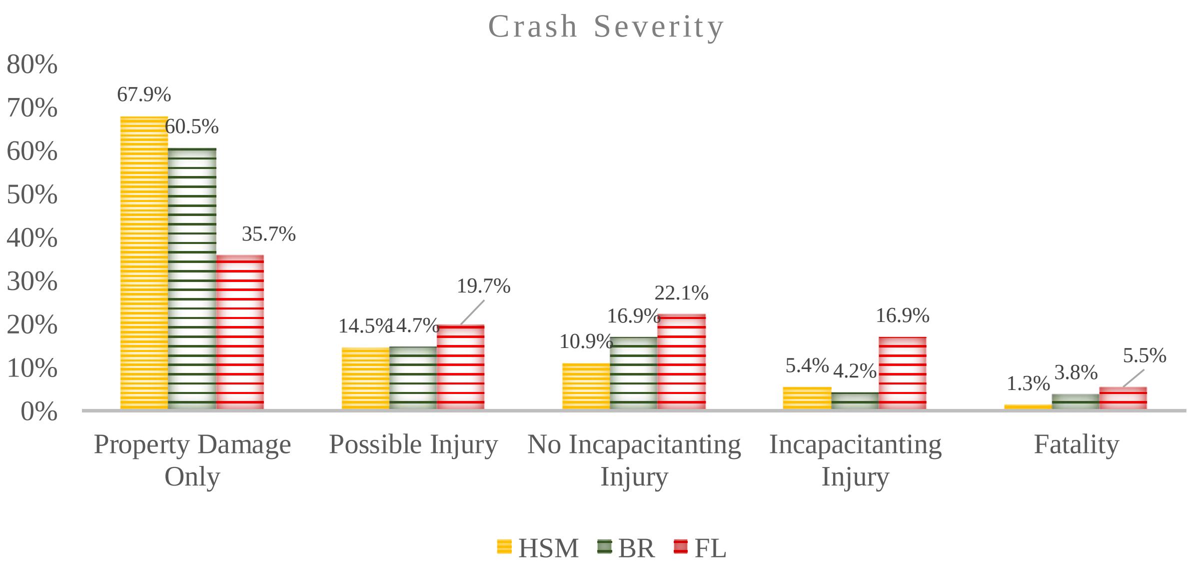
Table 4.3 – Rural TLHS crash proportion used for CMF (Srinivasan et al., 2011)

Collision Type	Florida FI
Animal	0.035
Pedestrian and Bicycle	0.013
Overturned	0.107
Run off road	0.324
Other Single	0.030
Total (single vehicle)	**0.509**
Angle	0.147
Head-on	0.050
Rear-end	0.187
Sideswipe	0.048
Other Multivehicle	0.059
Total (multivehicle)	**0.491**

4.2 COMPARISON OF BRAZIL AND FLORIDA RESULTS

The distribution of crash severity for Brazil (BR), Florida (FL) and HSM (Washington State - US) was plotted in Figure 4.4. The analysis of severity in Florida was affected by the missing of a large volume of PDO crashes leading to high relative proportion of incapacitating injury and fatalities. For Brazilian condition, the proportion of crashes by severity was similar to the one found in HSM except for the fatal injury.

Figure 4.4 – Distribution of crash severity for database and HSM



The summary of crash proportion by type is presented in Table 4.4. The accident type named run off road was the most remarkable in all cases, although HSM default values were higher than Brazil's and Florida's percentage. For FI, the distribution for Florida and Brazil was similar.

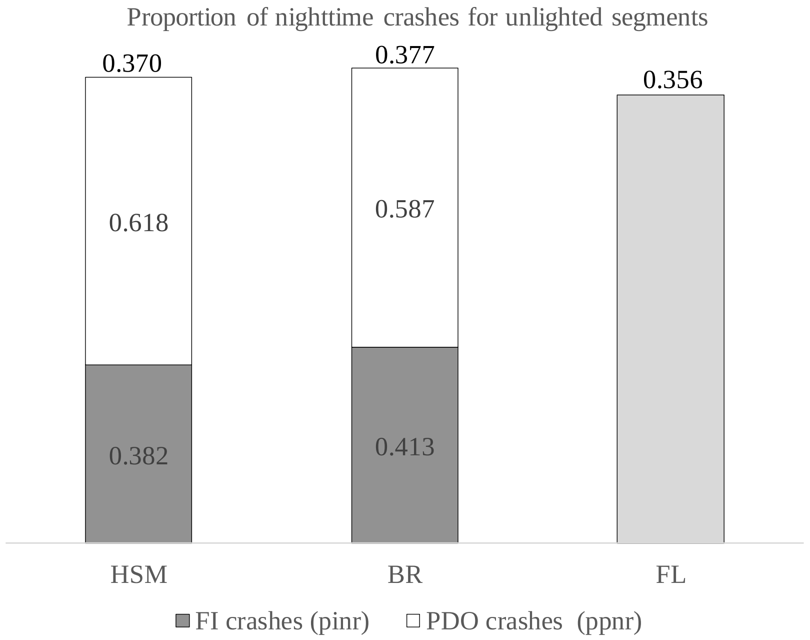
Table 4.4 –TLHS crash proportion for database and HSM

Collision Type	BR Average			FL Average	HSM		
	FI	PDO	Total	FI	FI	PDO	Total
Animal	2.00	7.39	5.36	3.48	3.80	18.40	12.10
Pedestrian and Bicycle	5.01	0.05	1.94	1.25	1.20	0.20	0.50
Overturned	12.85	5.66	8.44	10.73	3.70	1.50	2.50
Run off road	29.66	40.10	35.95	32.40	54.40	50.50	52.10
Other Single	3.78	5.77	5.14	3.03	0.70	2.90	2.10
Total (single vehicle)	**53.31**	**58.97**	**56.84**	**50.88**	**63.80**	**73.50**	**69.30**
Angle	10.62	7.06	8.39	14.73	10.00	7.20	8.50
Head-on	8.52	0.68	3.64	4.98	3.40	0.30	1.60
Rear-end	13.34	19.75	17.21	18.73	16.40	12.20	14.20
Sideswipe	9.38	7.81	8.39	4.78	3.80	3.80	3.70
Other Multivehicle	4.83	5.73	5.53	5.88	2.60	3.00	2.70
Total (multivehicle)	**46.69**	**41.03**	**43.16**	**49.08**	**36.20**	**26.50**	**30.70**

The contrast of proportion of crashes for unlighted segments at night for Brazil, Florida and HSM is presented in Figure 4.5. The maximum variation was 0.014, which indicates a pattern in this proportion. For Brazil, the percentage of FI crashes during night was little higher than

HSM values, more likely due to the larger number of injury crashes, as previously diagnosed. As abovementioned, the discrimination between PDO and FI was not calculated as a result of the lack of information.

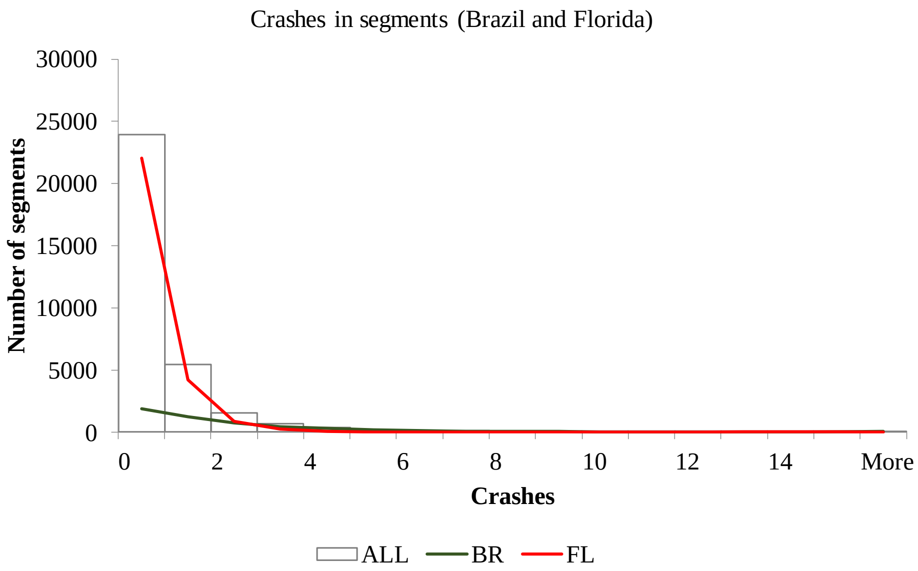
Figure 4.5 – Nighttime crashes for TLH unlighted segments



By locating crashes in each segment, the distribution of segments by number of crashes could be done in Figure 4.6 (more likely reflects the heterogeneity of Brazilian database, as discussed previously). As expected, most segments had zero to four crashes. However, for Brazil a smoother curve could be seen. These characteristics can indicate that crashes in Brazilian highways were more frequent than in Florida's.

Another investigation was done regarding the connection between crashes and exposure to the risk. From the road safety perspective, exposure expresses the amount of traveling in which there is the possibility of an accident to occur (Elvik, Hoye, Vaa, & Sorensen, 2009). Moreover, it is the fundamental element for traffic accidents existence, along with other aspects incorporated or inherent to this exposure (Bastos, 2014). Thus, its relationship with crashes could help to further understand crash phenomenon.

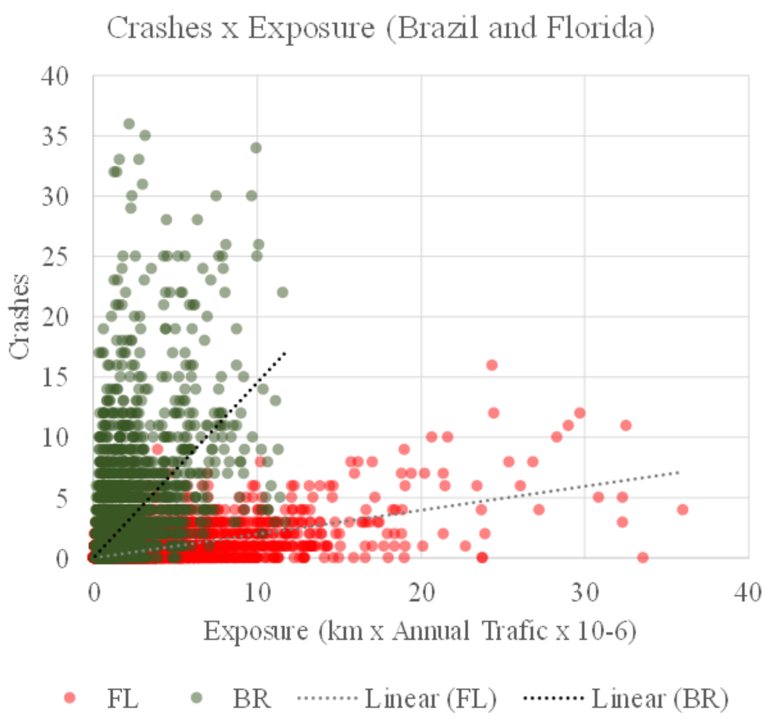
Figure 4.6 – Distribution of number of segments for crash occurrence



In that sense, the analysis of crashes and exposure indicates that, even for lower exposure, more crashes were observed in Brazil than in Florida. This relationship is illustrated in Figure 4.7. It should be noted that the trend line for Brazil had a greater angular coefficient than the trend line for Florida. Also, the dispersion of the data points more likely reflects the heterogeneity of Brazilian database, as discussed previously.

Some remarks could be made concerning crash statistics. First, the comparison between Brazil and Florida was limited to injuries or fatalities crashes, as the majority of the property damage only crashes were not readily available for this study in Florida. Second, it should be expected higher calibration factor (C_r) in Brazilian scenario due to its relationship with exposure to risk. Finally, the verification of transferability should distingue curved segments.

Figure 4.7 – Relationship between crashes and exposure



5 TRANSFERABILITY OF HSM CRASH PREDICTION MODEL

The analysis framework defined in this chapter addresses the spatial transferability of calibration factors of several different local categorizations that can be created within Brazilian condition. For Florida, a summary of the calibration values and peculiarities was presented, as calculated by Haas (2015) and Srinivasan et al. (2011).

5.1 APPLICATION OF HSM IN BRAZIL

The application of crash prediction model involved several steps as described in Part C - Chapter 10 of HSM (AASHTO, 2010). The estimated total number of crashes for roadway segments was given by the sum of the estimated number of crashes for each segment. Thus, after applying HSM prediction method, calibration was proceeded, as well as its validation. Despite the fact that calibration importance is clearly stated, the details related to obtaining data to local jurisdictions are not specified (Haas, 2015).

5.1.1 APPLICATION RESULTS

The HSM safety performance functions with CMF factors for the Brazilian sample from three states (São Paulo, Paraná and Minas Gerais) were applied individually to every segment using its specific AADT for each year of the study period. The predicted number of crashes for each segment was then summed up over the study period to obtain one composite entity as recommended by the HSM method.

The CMF related to curve characteristics was also included, using the values presented in the HSM, although the accuracy of values related to the curve design was not investigated. For estimating calibration factor (C_r), the sample was randomly divided into two groups to perform the calibration/validation. 70% of segments were used for calibration and the remaining 30% for validation procedure, as shown in Table 5.1. In addition, the investigation considers, separately, the straight and curved segment in order to enhance the analyses.

Table 5.1 –Proportion of segments for calibration/validation procedure

State	Number of segments /year			Studied length/year		
	Total	Validation	Calibration	Total	Validation	Calibration
SP	79	25	54	83.15	25.21	57.94
PR	553	169	384	244.2	74.03	170.17
MG	231	64	167	345.39	92.1	253.29
Total	863	258	605	672.74	191.34	481.4
Percentage	100%	30%	70%	100%	28%	72%

As a result of the application of HSM CPM, twelve calibration factors (C_r) for the Brazilian calibration sample was calculated, as can be seen in Table 5.2. The predicted crash number is the sum of all studied years, provided by HSM expression for each state. The calibration sample was split in non-curved segments and curved segments to investigate potential differences in results.

Table 5.2 – Calibration results for segment datasets using the HSM procedure

Calibration sample	States			
Description and results	SP	PR	MG	BR
Number of segments	54	384	167	605
Number of curved segments	5	220	106	331
Number of studied years	3	7	5	3-7
Total of observed crashes (all years)	339	3957	3931	8227
Total of observed crashes non-curved segments (all years)	303	1562	1117	2982
Total of predicted crashes (all years)	92	1050	1513	2655
Total of predicted crashes non-curved segments (all years)	81	502	452	1036
Calibration Factor (C_r)	3.67	3.77	2.60	3.10
Calibration Factor for non-curved segments (C_r - *NONCURVED*)	3.73	3.11	2.47	2.88
Calibration Factor for curved segments (C_r -*CURVED*)	3.24	4.38	2.65	3.24

The estimated C_r values obtained from curved segments were higher than the non-curved segment, except for São Paulo State that the sample of curves was too small for drawing any conclusions from it. This fact suggests that the CMF_3 of HSM could not reflect properly the additional number of crashes for Brazilian curves features. Other hypothesis is that the quality of curve data parameters may have compromised the results.

Additionally, it can be highlighted that the calibration procedure yielded C_r values greater than

2.0 for the studied sample. In most cases, *Cr* values were above 3.0, indicating that there are different scales in Brazilian crashes characteristics, corroborating others Brazilian calibration efforts (Cunto et al., 2013; Silva, 2012; Waihrich, 2015).

5.1.2 Assessing the transferability of HSM calibrated SPF

The performance of the calibrated HSM was assessed using the following goodness-of-fit measures: (1) the mean absolute deviance (MAD); (2) the mean average percentage error (MAPE); (3) coefficient of determination (R^2 Efron's) (4) Cumulative Residuals plots (CURE) and plots of the predicted-versus-observed crashes. The MAD, MAPE and R^2measures were exhibited in Table 5.3. The evaluation was conducted for the calibrated model, using each state calibration factor. Due to the various range of years for each state, the assessment of the transferability was done for average values of crashes in each segment.

The measures presented in Table 5.3 signalizes that the model provided a reasonable estimative for non-curved segments. The maximum MAD from non-curved segments was 2.75 crashes/year (there was an average of 3.7 accidents/year for non-curved segments in MG) for segment with MAPE equal a 47% for Minas Gerais. The lowest R^2 from non-curved segments was 0.47 for São Paulo State sample. For curved segments, more investigations should be done in order to better understand its impact on crashes estimations.

In addition, for the validation sample, the parameters were calculated as presented in Table 5.4. The model has not performed as well for the validation sample as it did for the calibration set. Also, the poor fit of the model calibrated for the whole sample suggests that this model could not reproduce crashes for the heterogeneous condition related to three different states.

It is important to note that the calibration and validation sample was evaluated for all segments, non-curved segments and curved segments, which means the equation of HSM was calibrated for each of these situations. Therefore, the GOF's presented on Table 5.3 is related to the calibration of each state (SP, PR, MG) using the corresponding calibration factor (3.67, 3.77, 2.60 for all segments; 3.73, 3.11, 2.47 for non-curved segments and 3.24, 4.38, 2.65 for curved segments respectively) and validated for the same state. In addition, a general model for Brazilian condition, without division for states, was assessed (line "BR" in the following tables).

Table 5.3 – Calibration goodness-of-fit for segment datasets using the HSM procedure

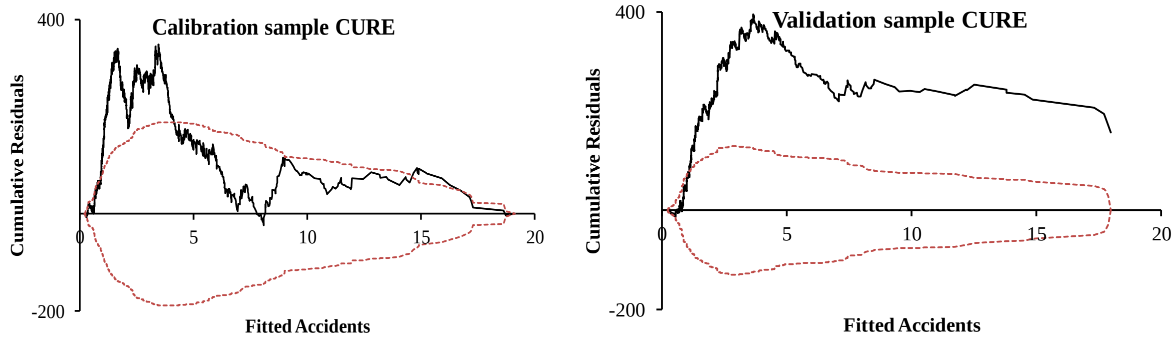
Calibration sample	Goodness-of-fit	States			
		SP	PR	MG	BR
All segments	Mean absolute deviance (MAD)	1.48	1.32	3.44	1.80
	Mean absolute percentage error (MAPE)	52%	58%	52%	56%
	R^2 Efron's	0.44	0.08	0.20	0.13
Non -curved segments	Mean absolute deviance (MAD)	1.48	1.12	2.75	1.46
	Mean absolute percentage error (MAPE)	43%	48%	47%	47%
	R^2 Efron's	0.47	0.73	0.82	0.78
Curved segments	Mean absolute deviance (MAD)	1.37	1.46	3.82	2.06
	Mean absolute percentage error (MAPE)	40%	47%	41%	46%
	R^2 Efron's	0.97	0.35	0.37	0.38

Table 5.4 – Validation sample results

Validation Sample	Description and results	States			
		SP	PR	MG	BR
All segments	Number of segments	25	169	64	258
	Mean absolute deviance (MAD)	1.38	1.32	3.87	1.84
	Mean absolute percentage error (MAPE)	58%	61%	53%	59%
	R2 Efron's	0.21	0.09	-0.02	0.13
Non-curved segments	Number of segments	23	74	24	120
	Mean absolute deviance (MAD)	1.26	1.12	2.89	1.43
	Mean absolute percentage error (MAPE)	49%	53%	44%	51%
	R2 Efron's	0.38	0.75	0.78	0.76
Curved segments	Number of segments	2	95	40	138
	Mean absolute deviance (MAD)	3.34	1.49	4.43	2.18
	Mean absolute percentage error (MAPE)	39%	48%	43%	47%
	R2 Efron's	0.73	0.33	0.17	0.24

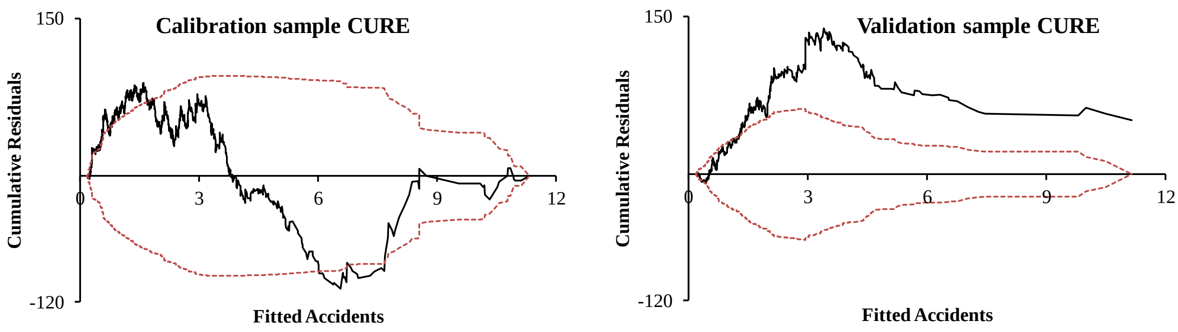
Also, the calibration/validation transferability was assessed using CURE plot. Due to the heterogeneity of segments over time, the CURE plot was developed comparing the estimated annual crash frequency of each segment to the observed annual crash frequency. The general model “BR” for all segments overestimated the number of crashes in segments that have less than three accidents in calibration sample (see Figure 5.1). For validation sample, an unsatisfactory performance was observed.

Figure 5.1 – CURE Plot for all segments – BR model



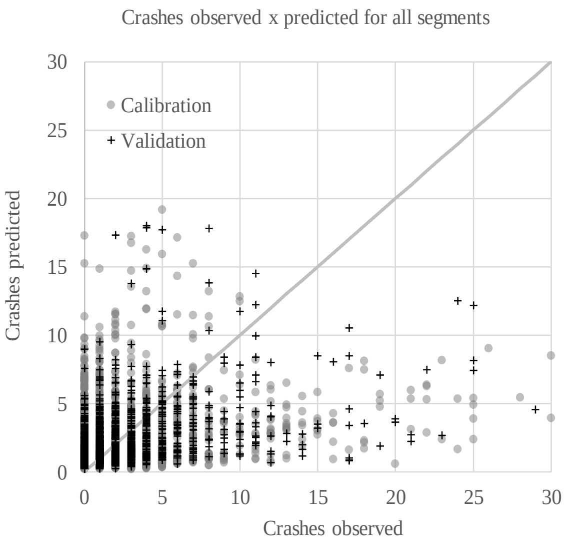
After removing curved segments, the model performance was better than observed for all segments, as exhibited in Figure 5.2. For validation sample, the model could not represent well the estimated values. Most of the calibration dataset do not stray outside of the two standard deviations boundaries, indicating that this bias may not be significant. However, validation sample presented a potential bias-in-fit.

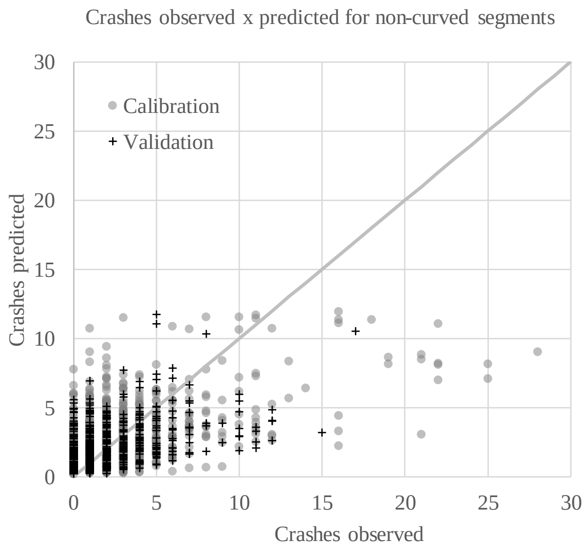
Figure 5.2 – CURE Plot for non-curved segments – BR model



The plots of the predicted-versus-observed crashes are shown in Figure 5.3. Even though some points are related to the same segment (varying AADT, crashes and road features over time), they were considered as an individual element in that analysis since it could bring additional information. The dispersion regarding all segments is more significant than in non-curved segments. Non-curved segment plot indicates a model underestimation trend for sites with more than 10 observed crashes.

Figure 5.3 – Predicted-versus-observed crashes





5.2 APPLICATION OF HSM IN FLORIDA

The application of HSM for Florida Two Lane Highways was performed by Srinivasan et al. (2011) and updated by Haas (2015). Calibration factors were developed and applied for two different periods, 2005 through 2007 and 2008 through 2010 to evaluated differences related to temporal transferability. The calculated calibration factors were developed and analyzed for their predictive accuracy.

For two lane highway facility type, statewide calibration evidenced substantially lower Mean Standard Error (MSE) values across all segments (Srinivasan et al., 2011; Haas, 2015). Also, the application of the uncalibrated HSM models showed more errors than seen with the calibration effort. The validation and comparison of the model accuracy was provided for rural two-lane roads set.

All calibration factors were around 1.0, which suggested that Florida TLHS were similar to the facilities used to develop the HSM equations (Srinivasan et al., 2011; Haas, 2015). A summary of Florida results for a subset comparable with Brazilian dataset, is presented in Table 5.5. Other investigations as spatial and temporal transferability were undertaken. The results for both analyses confirmed the transferability of statewide calibration.

Table 5.5 – Calibration effort in Florida (Haas, 2015)

Description and results	Period	
	2005-2007	2008-2010
Number of Segments	4591	
Extension (km)	3183.91	
Observed Crashes	2401	2288
Calibration Factor (*Cr*)	0.986	0.974
Mean Square Error (MSE)	0.108	0.074
Variance of SE	1.117	0.079

5.3 FINAL REMARKS

After obtaining information from crashes related to rural two-lane highway segments, some additional questions posed in chapter 1 could be addressed. Aspects related to RQ1, RQ6, RQ7 were discussed.

The evaluation of two lane highways safety in Brazil using HSM crash prediction model involved several steps to achieve the presented results. First, collecting data related to road features and crashes from different sources. Second, adjusting the variables to the same scale to allow for comparisons. Changes over time were considered as well as the distribution in space, since the model was calibrated for three different states.

For HSM calibration, the most time-consuming stage is usually to obtain and to prepare the dataset. The segmentation procedure was the base for this study, followed by assigning crashes to each segment. Some complications as the availability of road works records over time, the disparity of geometric design records and difficulty of getting series of AADT for several years and segments might have affected the crash prediction.

Therefore, the use of the HSM crash prediction model can be an alternative when the characteristics are well known and there is not much difference from base conditions. This conclusion was attained regarding the comparison of results for all segments, non-curved segments and curved segments, confirming that the calibration of HSM baseline SPFs can be used with caution.

Even so, the development of a novel crash prediction model for Brazilian conditions can be considered. For building a new model, it is important to evaluate the database in order to choose the parameters that would reflect safety conditions the most. However, it is worthwhile to consider the efforts involved to produce SPFs using local data.

Road safety data can be represented by a variety of functions and discovering a better fit to the data is challenging. Just little guidance for choosing a model exists (Hauer, 2015). As a start point, a widespread range of all selected parameters should be considered. Length and AADT are a popular choice since it can reflect the exposure to the risk and varies for each segment. Thus, due to the issues to assemble a bigger sample, the assessment of transferability of crash models to take advantage of existing models can represent a good alternative to save time and resources.

Another knowledge gap is establishing a benchmark of acceptable parameters for safety analysis in order to assess the transferability of models. The assessment of transferability is not absolute, which means there is significant research on the development of systematic procedures for assessing whether a model is transferable or not (Nowrouzian & Srinivasan, 2012).

In this section, the transferability was evaluated for some GOF applied in past researches related to safety analysis. Most metrics used measured the error between the observed number of crashes and the predicted ones. Assumptions on levels of acceptable errors should be investigated to assure whether the model is indeed transferable.

As shown in this chapter, the CURE plot exposed a good indication of model quality, combined with the other GOF. Since its drifts upwards or downwards signalizes a bias-in-fit, that can help the distinction of a better and worse fit.

In a nutshell, the answer for the application of foreigner models is not simple and its investigation can lead to better understanding the Brazilian needs. Likewise, the potential for further enhancements exist regarding not only the transferability of models but also the data collection and its assembly as well as the development of local crash models.

6 TRANSFERABILITY OF FLORIDA CRASH PREDICTION MODEL

In this chapter, it is studied whether HSM equations that have been calibrated to specific locations in the United States (in this case to Florida) are more transferable to Brazil instead of the equations directly out of the manual.

6.1 FLORIDA CRASH PREDICTION MODEL

Several investigations regarding Florida CPM transferability were done in Haas (2015), using different models. However, in a preliminary analysis, due to Brazilian data availability, only two of these models may be comparable.

The safety performance function was developed using negative binomial regression as shown in Chapter 2, Equation 2.2 and could be simplified as:

$$N_{KACBFL} = \exp(a + b\ln(AADT) + \ln(Lenght)) \qquad 6.1$$

where a and b are regression coefficients, *AADT* is the annual average daily traffic volume on the segment, and its *Length* in miles.

The crash estimation models developed for Florida condition sought to enhance some aspects raised after proceeding HSM calibration and locally developing SPFs in HSM analysis (Haas, 2015). The SPF's for Florida were settled using all available segments, rather than base conditions only (Srinivasan et al., 2011). The model was developed for Fatal and Injury (KABC) crashes and the obtained parameters are exposed in Table 6.1.

Table 6.1 - Florida and HSM model coefficients for Fatal and Injury (KABC) Crashes (Srinivasan et al., 2011)

Facility Type	a	b	Overdispersion Parameter	Calibration Factor (*Cr*)
Florida Rural Two-Lane	-9.012	0.964	0.549	N/A
HSM Rural Two-Lane	-9.364	1.000	0.236	1.039

As discussed in the previous chapter, since the calibration factor for rural TLHS was considerable higher than the HSM baseline, the evaluation of the applicability of the HSM calibrated model for Florida in Brazil did not add new information to the analysis. For this reason, the assessment of transferability considered the Florida model coefficients. Florida model could only be compared for Fatal and Injury (KABC) crashes. Still, the SPFs for Florida were obtained using all available segments, suppressing the need of CMFs application.

6.2 FLORIDA CPM APPLICATION RESULTS AND TRANSFERABILITY EVALUATION

The results of the application of Florida rural two-lane segments equation can be found in Table 6.2. All curved segments were removed from the Brazilian dataset because in Florida model development this characteristic was not addressed.

Table 6.2 – Examination of transferability of Florida crash model for KABC crashes

Calibration sample	States			
Description and results	SP	PR	MG	BR
Number of segments	49	163	60	272
Number of studied years	3	7	5	3-7
Total of observed KABC crashes non-curved segments	109	635	446	1190
Total of predicted KABC crashes non-curved segments	37.86	174.55	112.37	324.78
Mean absolute deviance (MAD)	0.73	0.62	1.38	0.77
Mean absolute percentage error (MAPE)	3.4%	3.9%	5.1%	4.1%
R^2 Efron's	0.148	0.611	0.671	0.628

Predicted crashes were around one third of observed Fatal and Injury crashes. The goodness-of-fit measures used to assess transferability suggested that even though there was a different scale regarding the absolute number, the average prediction has shown lower MAD's and MAPE's when contrasted with HSM application. Also, the R^2 indicated a good fit to values. The lowest R^2 from non-curved segments was for São Paulo State sample. In fact, the narrow range of AADT observed in São Paulo state sample is more likely the reason for the poor fit.

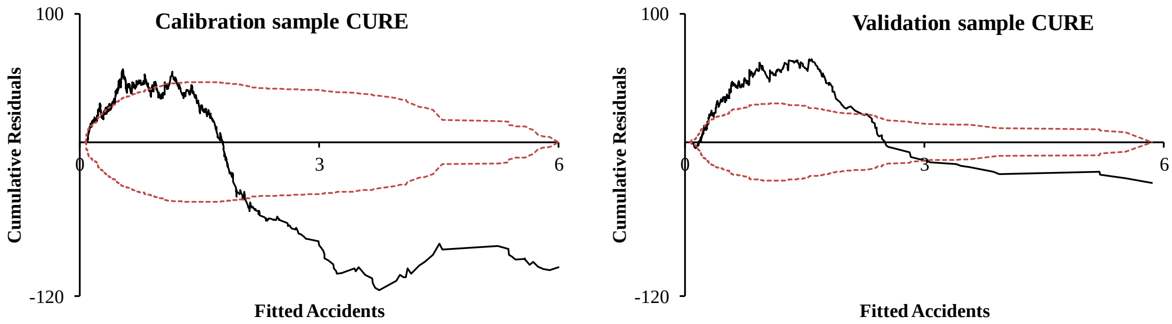
In addition, the validation sample parameters were calculated as presented in Table 6.3. The model has not achieved the sample performance for the validation sample as it did for the calibration set. However, the obtained values were considerable better than for HSM application in validation sample.

The crash prediction model overestimated the number of crashes for most segments, as can be seen in Figure 6.1. For validation sample, only few segments were between the range of two standard deviation boundary. This suggests that, despite the reasonable overall found GOF, the model could not reflect well the Brazilian sample crash KABC number.

Table 6.3 – Examination of transferability of Florida crash model for validation sample

Validation sample	States			
Description and results	SP	PR	MG	BR
Number of segments	23	74	24	120
Number of studied years	3	7	5	3-7
Total of observed crashes non-curved segments	44	327	121	492
Total of predicted crashes non-curved segments	17	77	40	133
Mean absolute deviance (MAD)	0.68	0.63	1.40	0.76
Mean absolute percentage error (MAPE)	4.0%	4.3%	4.4%	4.3%
R^2 Efron's	0.018	0.603	0.798	0.674

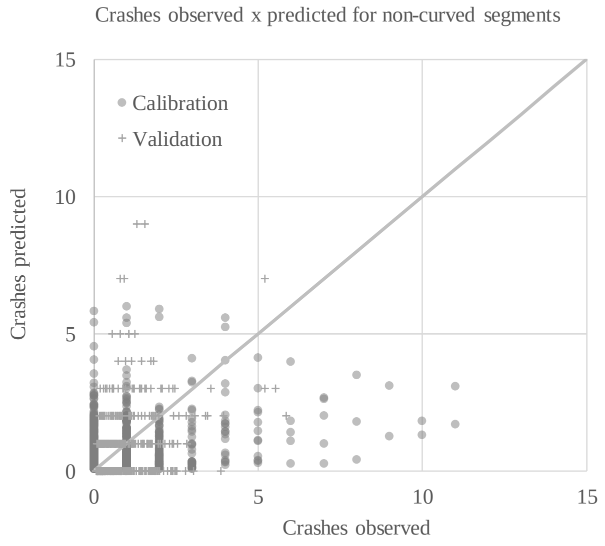
Figure 6.1 – CURE Plot for FI crashes model of non-curved segments



The plot of the predicted-versus-observed crashes is presented in Figure 6.2. The dispersion of data points suggests that the predicted number of crashes oscillated around the diagonal. Also, there was a trend of overestimating crashes in segments that presented more than five crashes/year.

The results of this section lead to recommending the use international crash prediction models in the Brazilian context with wariness. The analysis of the outlier points, associated to higher number of injuries, has shown that there is a significant influence of the roadside use in the segments. Most of these segments carries local traffic and lack proper lateral clearance.

Figure 6.2 – Predicted-versus-observed FI crashes



6.3 FINAL REMARKS

The question RQ8 could be addressed at the end of this chapter. The hypotheses that supported the conclusion reached in this work is that transferability evaluation depend on the application context.

The application of Florida FI crashes model presented reasonable measures to estimate this type of crashes on Brazilian Highways. However, due to the specificities of roadside use and other small differences combined, some locations could not be well represented by the model.

Establishing acceptable transferability measures involves a certain degree of professional judgment. Thus, the model can be applied with caution to specific conditions where the roadway characteristics are as close as possible to the model development features.

In this sense, the most adequate way to transfer a model should be by associating regions of same overall characteristics and proceeding its calibration/validation as well as evaluating its transferability. In addition, it may be appropriate to determine a scale of transferability, rather than binary (yes or no) output, as suggested by other researchers (Nowrouzian & Srinivasan, 2012).

7 BUILDING A BRAZILIAN CRASH PREDICTION MODEL

The results of the previous sections revealed that the transferability of HSM and Florida model to Brazilian two-lane highways is only possible to an extent. Thus, it is paramount, to further improve crash prediction on Brazilian context, developing a model that can reflect its singularities. Hence, in this section a general-purpose model was estimated.

7.1 CHOOSING THE FUNCTION FOR PREDICTING ACCIDENTS

The choice of the objective function was made regarding the characteristics of the Brazilian two-lane highway sample. This sample were mostly composed by low volume road segments with highly heterogenous features.

Some traffic influences areas (TIA's) were established to represent the entire segment, which implied in a limited range. Since the AADT is an important variable in a safety performance model, to link same AADT with segments with varied features could jeopardize any attempt to estimate a model. Another common variable placed into a simple model is the segment length (L). The combination of AADT and L is related to exposure to risk, as aforementioned. Both variables can be used in primary models that do not have a large dataset.

Ultimately, as a first approach, the negative binomial (NB) was chosen to fit a general-purpose model, consistent to the studied models of HSM and Florida. The SPFs for Brazilian sample were developed using all available segments for each year, rather than base conditions only, such that the application of CMFs is not necessary for crash prediction. Furthermore, since the presence of curved segments have shown a poor quality of fit and could not be plainly estimated for that sample, an additional model without curved segments was developed.

7.2 OBTAINING BRAZILIAN SPF

In order to obtain a general-purpose model that could dismiss the use of CMF´s, a negative binomial (NB) regression fit was performed, similar than Equation 6.1, developed for Florida conditions. The model was made using all crashes for several periods. The inputs of the model were based on the average values of AADT, average observed crash frequency and segment length.

The model to be fitted is shown in Equation 7.1 (Hauer, 2015).

$$N_{BR-prev} = \beta_0 L^{\beta_1} AADT^{\beta_2} \tag{7.1}$$

with $N_{BR\text{-}prev}$ is the predicted number of accidents/year, L is the length in miles and *AADT* is the Annual Average Daily Traffic. β_0, β_1 and β_2 are calibration parameters related to elasticity of crashes due to these characteristics.

The model was calculating by maximizing log-likelihood function using a GRG non-linear algorithm. The obtained model for Brazilian conditions was developed for average crashes in all segments, as presented in Equation 7.2. An additional model for non-curved segments was developed since previous diagnosis indicates this feature deserves special attention, as Equation 7.3.

$$N_{BR-prev} = 0.000086 L^{0.766} AADT^{1.265} \tag{7.2}$$

$$N_{BR-prev(non-curved)} = 0.000072 L^{0.766} AADT^{1.265} \tag{7.3}$$

As the parameters β_1 and β_2 were close to 1, it is possible that accidents could be proportional to the Length and AADT. As expected, it can be noticed that the scale of non-curved segments is lower than all segments that included curve features, suggesting that a specific study for curved segments is desirable.

7.3 Application Results

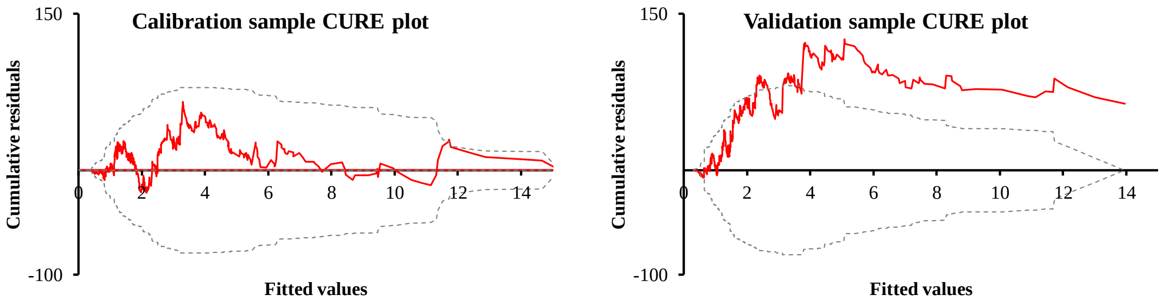
The obtained model was applied in the calibration/validation sample to evaluate its performance. In the Table 7.1 the statistics of the application are presented. Overall, the model for non-curved segments performed better than general model, including for the validation sample.

Table 7.1 – Results Brazilian Crash Prediction Model for two lane highway

Sample	Description and results	Segments Non-curved	All
Calibration	%/Number of segments	70%/605	
	Mean absolute deviance (MAD)	0.56	1.58
	Mean absolute percentage error (MAPE)	38%	105%
	R2 Efron's	0.63	0.35
Validation	% Number of segments	30%/258	
	Mean absolute deviance (MAD)	0.49	1.49
	Mean absolute percentage error (MAPE)	26%	68%
	R2 Efron's	0.62	0.28

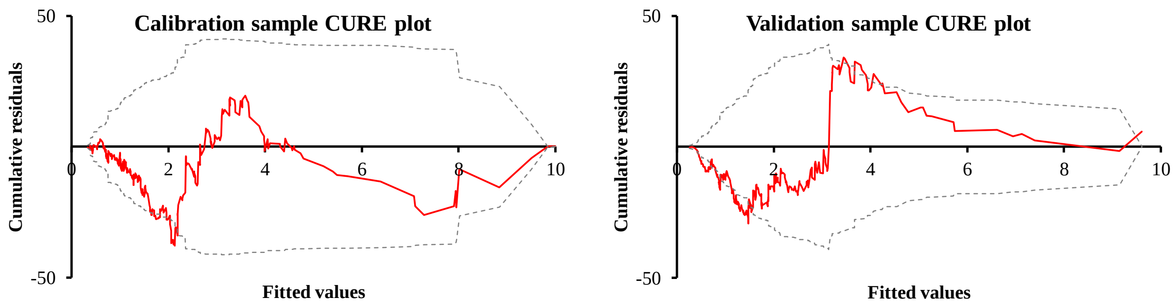
The CURE plot for all segments was mapped in Figure 7.1. For calibration sample, the cumulative residuals oscillated around the horizontal axis, which indicates a good fit of the model. The cumulative residuals remained inside the limits (within the 2σ boundary) for calibration sample. Even so, there is a bias-in-fit due to the existence of drifts up and down. However, the same performance could not be fully observed for the validation sample that the model tended to underestimate crashes where the fitted values are higher than 4.

Figure 7.1– Results all segments



For non-curved segments, the results were in general better, as shown in Figure 7.2. The cumulative residuals remained within the 2σ boundary, which is a good indication for calibration/validation sample. Nevertheless, a bias-in-fit can be noticed since there are consistently drifts up or down. In that case, some evaluation of the outlier (where the cumulative residual line seems to be nearly the vertical drop) could help to enhance the analyses. Also, a bigger sample could further improve the results.

Figure 7.2 – Results non-curved segments



7.4 FINAL REMARKS

As a result of this chapter, two novel models for Brazilian two-lane highways segments were estimated. The model developed for Brazilian condition showed better results for non-curved segments in calibration/validation sample. Thus, for a general analysis purpose of non-curved segments this model can be used.

It is useful to note that this approach was developed to average crashes since there were different period of analysis in each Brazilian state. It would be more suitable to make forecasts for multiple future years and evaluate the contrast between predicted crashes and the observed crashes over the longer time horizon.

Factors contributing to crash frequency could also vary across Brazil due to the land usage, diversity of driver behavior, weather conditions and specific factors other than could be pointed in this research. No examination of the existence of such variations was proceeded due to dataset limitations. This implies that it would be useful to calculate calibration factors in certain areas if significant differences exist. Also, the application of this model in Brazilian States, other than the studied ones, should be investigated regarding its transferability for different conditions.

An enhancement of the quality of the parameter of curved segments is recommended to create specific models or CMF's more adequate to local conditions. An increased crash number was noticed in curved areas and should be investigated in a larger dataset.

Also, due to data limitations some separated model for each state was not performed in this chapter. However, the presented results indicated that the general model for non-curved segments can produce better approaches in terms of crashes for the Brazilian States (MG, PR e SP) than the calibrated SPF of HSM and Florida.

Finally, the combination of this model with EB method could produce better results even though this application was not within the scope of this research. For future crash prediction models' development, other evaluations are desirable.

8 CONCLUSIONS AND RECOMMENDATIONS

The objective of this work was to evaluate crash prediction model procedures. The first method used was the HSM method since its publication changed the baseline of safety evaluation. The second one applied robust models (e.g. Florida's) in Brazilian context to take advantage of their development effort. Finally, the transferability of different models was assessed.

Since the analysis of Brazilian two-lane highways features realized on Chapter 3 revealed their heterogeneity, the sample was split in curved and non-curved segments. In addition, available Florida data and model have not considered curved segments, which meant that the comparison between those two models naturally would require such division.

Other recurrent difference between Brazilian and Florida highways was the relationship between crashes and exposure. Most of the analysis in Chapter 4 and 5 have shown that Brazilian highways are more prone to accidents. Even lower traffic led to more accidents, which highlighted the safety problem in Brazil, as discussed in Chapter 1. As a result of this discrepancy the values of the calibration factor for the HSM application were three times higher than those found for other calibration efforts worldwide.

In that sense, the improvement of safety analysis practices in Brazil is highly recommended. Even if some differences regarding the transferability of models were found in this research, its use in Brazilian context is promising to an extent. There are many factors that cannot be measured by a single model and no perfect model would reflect road safety for various condition. However, a model can provide a better start point in safety road analysis. The use of Empirical Bayes method can produce even fitter results.

A summary of studied safety performance function and the calibration factor obtained as results of this research are exposed in Table 8.1. Most of the analyzed models could not represent SP conditions, probably due to the small sample and homogeneous traffic. For PR and MG better approaches were found for non-curved segments.

Apropos of the posed Research Questions in Chapter 1, a better understanding of crash prediction model in the Brazilian context was provided. The answers were discussed in the ending of each chapter as Final Remarks. RQ2 to RQ5, addressed in Chapter 3, were related to data collection for Brazilian conditions and how to prepare the resulting database to use in model development for different places. The Brazilian two-lane highway sample presented more diverse characteristics when compared to Florida.

Table 8.1 – Summary of studied SPF in Brazilian TLHS

State	Analyzed models (SPF)***	Calibrated for local condition	Calibration Factor (Cr) [I]		
			All segments	Non curved segments	Curved segments
SP	$N_{SPF\ rs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}$	HSM-Yes	3.67	3.73	3.24
	$N_{KACB} = \exp(-9.012 + 0.964 \ln(AADT) + \ln(L))$	FL – No	1.00	1.00	-
PR	$N_{SPF\ rs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}$	HSM-Yes	3.77	3.11	4.38
	$N_{KACB} = \exp(-9.012 + 0.964 \ln(AADT) + \ln(L))$	FL – No	1.00	1.00	1.00
MG	$N_{SPF\ rs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}$	HSM-Yes	2.60	2.47	2.65
	$N_{KACB} = \exp(-9.012 + 0.964 \ln(AADT) + \ln(L))$	FL – No	1.00	1.00	-
BR	$N_{SPF\ rs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}$	HSM-Yes	3.10	2.88	3.24
	$N_{KACB} = \exp(-9.012 + 0.964 \ln(AADT) + \ln(L))$	FL – No	1.00	1.00	-
	$N_{BR-prev} = 0.000086 L^{0.766} AADT^{1.265}$	BR -Yes	1.00	-	-
	$N_{BR(non-curved)} = 0.000072 L^{0.766} AADT^{1.265}$	BR -Yes	-	1.00	-

*** Analyzed model exposes the model that was applied in each state using a specific calibration factor or not depending on its availability. L is the length in miles. I – Blanc fields means that this condition was not addressed by the model.

Aspects related to RQ1, RQ6, RQ7 were exposed on Chapter 5. It was concluded that the segmentation characteristics have an important role in crash prediction models, as well as the observed crash frequency. Moreover, the indiscriminate use of the HSM crash prediction model is not recommended. Also, the transferability was evaluated for some GOF applied in past research related to safety analysis. Finally, the answer for the posed questions directed for a proposed method in which a unified SPF are developed for accounting for different conditions. However, it was not exhaustive whereas the potential for further enhancements exist.

The last question RQ8 was addressed on Chapter 6, suggesting that the model can be applied with caution to specific conditions where the roadway characteristics are as close as possible to the model development features. In that sense, the goals of this research were accomplished, which does not mean there are no space for further improvements.

The results of this research were limited mostly to low volume two lane highway segments. Even though a great effort was done for collecting data, the sample of TLHS should be extended. A larger sample could allow for the consideration of the impact of different highway characteristics. Still, intersection evaluation can rise the quality of the model for safety analysis purposes, which was not considered in this study.

Finally, there is the opportunity for future work branching from the conclusions developed herein. Some aspects related to curved segments can be addressed to reflect this element in crash prediction. Moreover, modeling the combination of grades and curves should be accounted for. Still, the role of the ostensive signalization used as a low-cost measure to reduce crashes in highways could be soon understood.

REFERENCES

AASHTO. (2010). *Highway Safety Manual (HSM)*. (American Association of State Highway and Transportation Officials, Ed.) (1st ed.). Washington, DC.

Ackaah, W., & Salifu, M. (2011). Crash prediction model for two-lane rural highways in the Ashanti region of Ghana. *IATSS Research*, *35*(1), 34–40. http://doi.org/10.1016/j.iatssr.2011.02.001

Al Kaaf, K., & Abdel-Aty, M. (2015). Transferability and Calibration of Highway Safety Manual Performance Functions and Development of New Models for Urban Four-Lane Divided Roads in Riyadh. *94th Annual Meeting, Transportation Research Board, Washington D.C.*, (January), 1 to 18. http://doi.org/10.3141/2515-10

Andrade, G. R. de, & Setti, J. R. (2011). Método para caracterização e classificação de trechos homogêneos rodoviários. In ABCR (Ed.), *VII Congresso Brasileiro de Rodovias e Concessões*. Foz do Iguaçu, Brazil.

Andrade, G. R. de, & Silva, K. C. R. (2018). Estimation of Geometry Input Data for Operations and Safety Analysis from GPS and GIS. In *97th TRB Annual Meeting* (pp. 1–17). 97th TRB Annual Meeting.

Banihashemi, M. (2011). Highway Safety Manual, New Model Parameters vs. Calibration of Crash Prediction Models. In *90th Annual Meeting of the Transportation Research Board*. Washington DC,USA: 90th Annual Meeting of the Transportation Research Board.

Barber, P. (2014). Calibration of the Highway Safety Manual Models for Québec. In M. des transports du Québec (Ed.), *Measurement* (pp. 710–714). Montréal, Québec: 2014 Transportation Association of Canada Conference.

Bastos, J. T. (2014). *Análise Estratégica da Segurança viária no Brasil: Pesquisa de índices e Indicadores*. Universidade de São Paulo e Hasselt University.

Bezerra, B. S., Silva, K. C. R., Bastos, J. T., & Ferraz, A. C. P. (2011). A tale of two cities: Some empirical evidences of how urban and transportation planning can influence accidents at intersections. In *XV Congreso Chileno de Ingeniería de Transporte*. XV Congreso Chileno de Ingeniería de Transporte.

Cafiso, S., Di Graziano, A., Di Silvestro, G., La Cava, G., & Persaud, B. (2010). Development of comprehensive accident models for two-lane rural highways using exposure, geometry, consistency and context variables. *Accident Analysis and Prevention*, *42*(4), 1072–1079. http://doi.org/10.1016/j.aap.2009.12.015

Cafiso, S., Di Silvestro, G., & Di Guardo, G. (2012). SIIV - 5th International Congress -

Sustainability of Road Infrastructures Application of Highway Safety Manual to Italian divided multilane highways. *Procedia - Social and Behavioral Sciences*, *53*, 910–919. http://doi.org/10.1016/j.sbspro.2012.09.940

Caliendo, C., Guida, M., & Parisi, A. (2007). A crash-prediction model for multilane roads. *Accident Analysis and Prevention*, *39*(4), 657–670. http://doi.org/10.1016/j.aap.2006.10.012

Cunto, F., Sobreira, L., & Ferreira, S. (2013). Assessing the Transferability of the Highway Safety Manual Predictive Method for Urban Roads in Fortaleza City, Brazil. *Road Safety and Simulation*, *141*(1), 4014072. http://doi.org/10.1061/(ASCE)TE.1943-5436.0000734

D'Agostino, C. (2014). Investigating transferability and goodness of fit of two different approaches of segmentation and model form for estimating safety performance of motorways. *Procedia Engineering*, *84*, 613–623. http://doi.org/10.1016/j.proeng.2014.10.478

DATASUS. (2015). Óbitos por Causas Externas -Brasil. Retrieved February 27, 2017, from http://datasus.saude.gov.br/

Dinu, R. R., & Veeraragavan, A. (2011). Random parameter models for accident prediction on two-lane undivided highways in India. *Journal of Safety Research*, *42*(1), 39–42. http://doi.org/10.1016/j.jsr.2010.11.007

Dixon, K., Monsere, C., Xie, F., & Gladhill, K. (2012). *Calibrating the Highway Safety Maual Predictive Methods for Oregon Highways*.

DNIT. (2015). *Anuário Estatístico das Rodovias Federais 2010*. *República Federativa do Brasil*.

Elvik, R. (2008). The predictive validity of empirical Bayes estimates of road safety. *Accident Analysis and Prevention*, *40*(6), 1964–1969. http://doi.org/10.1016/j.aap.2008.07.007

Elvik, R., Hoye, A., Vaa, T., & Sorensen, M. (2009). *The Handbook of Road Safety Measures* (Second edi). Howard House, Wagon Lane, Bingley, UK: Emerald Group Publishing Limited.

Farr, T. G., & Kobrick, M. (2000). Shuttle radar topography mission produces a wealth of data. *Eos*, *81*(48), 583–585. http://doi.org/10.1029/EO081i048p00583

FGDL. (2017). Florida Geographic Data Library. Retrieved July 20, 2010, from https://www.fgdl.org/

FHWA. (2012). Toward Zero Deaths: A National Strategy on Highway Safety. Retrieved December 1, 2016, from https://safety.fhwa.dot.gov/tzd/

FHWA. (2017). Crash Modification Factors Clearinghouse. Retrieved May 22, 2017, from http://www.cmfclearinghouse.org/

Google. (2015). Google Earth Pro 7.1.5.1557. GoogleEarth. Retrieved from kh.google.com

Haas, P. (2015). *An examination of the spatial and temporal transferability of crash prediction models in Florida*. Universiy of Florida.

Haas, P. (2016). Crash Prediction Method for Freeway Segments with High Occupancy Vehicle (HOV) Lanes, 1–17.

Harwood, D., Council, F., Hauer, E., Hughes, W. E., & Vogt, a. (2000). Prediction of the expected safety performance of rural two-lane highways, (December), 197. http://doi.org/FHWA-RD-99-207

Hauer, E. (2010). On prediction in road safety. *Safety Science*, *48*(9), 1111–1122. http://doi.org/10.1016/j.ssci.2010.03.003

Hauer, E. (2015). *The art of regression modelling in road safety* (1st ed.). Springer International Publishing Switizerland. http://doi.org/10.1007/978-3-319-12529-9

Hauer, E., Harwood, D., Council, F., & Griffith, M. (2002). Estimating Safety by the Empirical Bayes Method: A Tutorial. *Transportation Research Record*, *1784*(1), 126–131. http://doi.org/10.3141/1784-16

Jovanis, P. P., & Chang, H.-L. (1986). Modeling the relationship of accidents to miles traveled. *Transportation Research Record 1068,* 42–51.

Koorey, G. (2010). Calibration of Highway Crash Prediction Models for other Countries - a Case Study with IHSDM, *2010*, 16p. Retrieved from https://trid.trb.org/view/1098932

Koppelman, F. S., & Wilmot, C. G. (1982). Transferability Analysis of Disaggregate Choice Models. *Transportation Research Record*, (895), 18–24. http://doi.org/10.1016/S0065-2113(08)60255-2

La Torre, F., Domenichini, L., Corsi, F., & Fanfani, F. (2014). Transferability of the Highway Safety Manual Freeway Model to the Italian Motorway Network. *Transportation Research Record: Journal of the Transportation Research Board*, *2435*, 61–71. http://doi.org/10.3141/2435-08

Lee, R. J., Sener, I. N., & Mullins III, J. A. (2016). An evaluation of emerging data collection technologies for travel demand modeling: from research to practice. *Transportation Letters: The International Journal of Transportation Research*, *7867*(April). http://doi.org/10.1080/19427867.2015.1106787

Lord, D., & Mannering, F. (2010). The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. *Transportation Research Part A: Policy and Practice*, *44*(5), 291–305. http://doi.org/10.1016/j.tra.2010.02.001

Lord, D., & Persaud, B. N. (2000). Accident Prediction Models With and Without Trend: Application of the Generalized Estimating Equations (GEE) Procedure. *Transportation Research Board Annual Meeting*, (0), 1–19. http://doi.org/10.3141/1717-13

Lubliner, H. (2011). Evaluation of the Highway Safety Manual Crash Prediction Model for rural two-lane highway segments in Kansas.

Martinelli, F., La Torre, F., & Vadi, P. (2009). Calibration of the *Highway Safety Manual's* Accident Prediction Model for Italian Secondary Road Network. *Transportation Research Record: Journal of the Transportation Research Board*, *2103*, 1–9. http://doi.org/10.3141/2103-01

McCullagh, P., & Nelder, J. A. (1989). Generalized Linear Models. *Journal Of The Royal Statistical Society Series A General*, *37*(3), 0. http://doi.org/10.2307/2344614

Metha, G., & Lou, Y. (2013). Safety Performance Function Calibration and Development for the State of Alabama: Two-Lane Two-Way Rural Roads and Four-Lane Divided Highways. *Transportation Research Board*, *4*. http://doi.org/10.3141/2398-09

Miao, S.-P. (1993). The relationship between truck accidents and geometric desig of road sections: poisson versus negative binomial regressions. *Accident Analysis and Prevention 26 (4)*, 471–482.

Miaou, S.-P., & Lord, D. (2003). Modeling Traffic Crash-Flow Relationships for Intersections: Dispersion Parameter, Functional Form, and Bayes Versus Empirical Bayes Methods. *Transportation Research Record*, *1840*(1), 31–40. http://doi.org/10.3141/1840-04

NHTSA. (2016). Traffic Safety Facts Research Note. Report No. DOT HS 812 318. *National Highway Traffic Safety Administration. U.S. Department of Transportation*, pp. 1–9. Washington, DC. Retrieved from http://www-nrd.nhtsa.dot.gov/ departments/nrd-30/ncsa/STSI/USA WEB REPORT. HTM

Nowrouzian, R., & Srinivasan, S. (2012). Empirical Analysis of Spatial Transferability of Tour-Generation Models. *Transportation Research Record: Journal of the Transportation Research Board*, (2302), pp-14–22. http://doi.org/10.3141/2302-02

Persaud, B., Saleem, T., Faisal, S., & Lyon, C. (2012). Adoption of Highway Safety Manual Predictive Methodologies for Canadian Highways. *Conference of the Transportation Accosiation of Canada Fredericton, New Brunswick*, 1–17. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/cbdv.200490137/abstract%5Cnhttp://www.tac-atc.ca/english/annualconference/tac2012/docs/session15/persaud.pdf

Sacchi, E., Persaud, B., & Bassani, M. (2012). Assessing international transferability of highway safety manual crash prediction algorithm and its components. *Transportation Research Record*, (2279), 90–98. http://doi.org/10.3141/2279-11

Saito, M., Brimley, B. K., & Schultz, G. G. (2011). Transportation Safety Data and Analysis Volume 2 : Calibration of the Highway Safety Manual and Development of New Safety Performance Functions. *UT-10.12b*, *2*(March 2011).

Saito, M., Knecht S, C., Schultz G, G., & Cook A, A. (2015). Crash Prediction Modeling for Curved Segments of Rural Two-Lane Two-Way Highways in Utah, 83p. Retrieved from http://www.udot.utah.gov/main/uconowner.gf?n=26397103967317288%5Cnhttps://trid.trb.org/view/1394588

Silva, K. C. R. (2012). *Aplicação do modelo de previsão de acidentes do HSM em rodovias de pista simples do estado de São Paulo.* Universidade de São Paulo.

Solomon, D. . (1964). Crashes on main rural highways related to speed, driver and vehicle. *Bureau of Public Roads*.

Srinivasan, R., & Bauer, K. (2013). Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs, (September), 1–47.

Srinivasan, R., Colety, M., Bahar, G., Crowther, B., & Farmen, M. (2016). Estimation of Calibration Functions for Predicting Crashes on Rural Two-Lane Roads in Arizona. In *Annual Meeting of Transportation Research Board* (pp. 1–14). Annual Meeting of Transportation Research Board. http://doi.org/10.3141/2583-03

Srinivasan, S., Haas, P., Dhakar, N. S., Hormel, R., Torbic, D., & Douglas, H. (2011). *Development and Calibration of Highway Safety Manual Equations for Florida Conditions*. *Final Report (FDOT BDK77 977-06 12)* (Vol. 6).

Strauss, J., Miranda-Moreno F, L., & Morency, P. (2016). Speed, Travel Time, and Delay for Intersections and Road Segments in Montreal Using Cyclist Smartphone GPS Data, 19p. Retrieved from https://trid.trb.org/view/1392769

Sun, C., Brown, H., Edara, P., Claros, B., & Nam, K. (Andrew). (2013). *Calibration of the Highway Safety Manual for Missouri*. *Report No. cmr14-007*.

Sun, X., Li, Y., Magri, D., & Shirazi, H. (2006). Application of Highway Safety Manual Draft Chapter: Louisiana Experience. *Transportation Research Record*, *1950*(1), 55–64. http://doi.org/10.3141/1950-07

Venkataraman, N. S., Ulfarsson, G. F., & Shankar, V. N. (2014). Extending the Highway Safety Manual (HSM) framework for traffic safety performance evaluation. *Safety Science*, *64*, 146–154. http://doi.org/10.1016/j.ssci.2013.12.001

Vogt, A., & Bared, J. G. (1998). Accident Models for Two Lane Roads. *Publication No. FHWA RD 98-133*, (October 1998), 1–209.

Waihrich, D. R. L. da S. (2015). *Calibração do método de previsão de acidentes do Highway Safety Manual (HSM) para trechos rodoviários de pista dupla no Brasil*. Universidade de Brasília.

Washington, S., Persaud, B., Lyon, C., & Oh, J. (2005). Validation of Accident Models for Intersections, (May).

WHO. (2015). *Global Status Report on Road Safety 2015*. *WHO Library Cataloguing-in-Publication Data Global*. Retrieved from http://www.who.int/

Williamson, M., & Zhou, H. (2012). Develop Calibration Factors for Crash Prediction Models for Rural Two-Lane Roadways in Illinois. *Procedia - Social and Behavioral Sciences*, *43*, 330–338. http://doi.org/10.1016/j.sbspro.2012.04.106

Xie, F., Gladhill, K., Dixon, K. K., & Monsere, C. M. (2011). Calibration of Highway Safety Manual Predictive Models for Oregon State Highways. *Transportation Research Record*, (2241), 19–28. http://doi.org/10.3141/2241-03

Zegeer, C. V, J. Hummer, D. Reinfurt, L. Herf, and W., & Hunter. (1987). *Safety Effects of Cross-Section Design for Two-Lane Roads*. Washington, D.C.

Zuo, Z. (2016). Transfer Mode Choice Probability Prediction Model for Urban Rail-Transit Terminal Area : A Case Study in China. In *The 95th Annual Meeting of the Transportation Research Board* (pp. 1–12). Washington, D.C.: TRB 2016 Annual Meeting.