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The severity and spatial pattern mapping of crashes and safety performance evaluation of two-way two-lane rural roads geometric design: A case of Oromia, Ethiopia

Dissertation

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Dedication

To

My mother, Erkinesh Getachew,

who has committed her entire life to me,

My father, Mulugeta Tola,

who always there for me,

Yisalemush Demissie, my grandmother,

and my lovely wife, Bezawit Wondimagegnehu,

who has been all my life and the one who always encourages me.

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Executive Summary

Despite being the backbone of every country's socioeconomic development, road transportation is engaged in traffic collisions that kill millions of people throughout the world. In the developed countries, there is a burgeoning body of scientific studies and technological advancements aimed at improving the effectiveness of safety interventions; however, little is known in Ethiopia about the spatial analysis of crashes, the safety performance of roadway geometric features, and the relative safety impact of design alternatives.

This dissertation is concerned with the application of cutting-edge crash mapping techniques as well as the assessment of the safety performance of roadway geometric design in Ethiopia with a particular emphasis on the Oromia region. It focuses on two aspects that have heretofore been overlooked in the study region: analyzing the severity and spatial pattern of crash incidents to identify crash hotspots, and evaluating the safety performance of rural two-way two-lane roadways using a predictive approach after developing a jurisdiction-specific crash distribution dataset.

To achieve the dissertation’s main objectives, three scientific studies were carried out. In this study, data from the respective offices on crash incidents, AADT and the as-built geometric design of roads, as well as on-site observations of road conditions (sites closer to Addis Ababa, especially those identified as hazardous road segments in this study) and satellite imagery, were utilized. To examine the spatial patterns of Road Traffic Crashes (RTCs) and identify crash hotspots in Ethiopia, the spatial autocorrelation of crashes and Getis Ord Gi^* statistics tools in ArcGIS were used. Moreover, the Crash Prediction Model (CPM) of the predictive approach in the Highway Safety Manual (HSM) and Interactive Highway Safety Design Model (IHSDM) has been exploited to evaluate the safety performance of rural roads and quantify the safety effects of road design improvements made to existing roads.

The scientific findings underlined the importance of identifying locations with safety problems based on crash severity and spatial attributes, as well as safer road provisions by adopting safety performance-based road designs for sustainable traffic management strategies in Ethiopia. According to the study, employing GIS in Ethiopia offers a considerable advantage when it comes to identifying potential locations for safety improvements. The mapping of crash hotspots using ArcGIS software discovered that Addis Ababa, Oromia region and zones in Oromia that were closer to, as well as the entry to Addis Ababa (i.e., East Shewa zone, Burayu town, North Shewa zone, West Shewa zone, Adama town and South-West Shewa zone), are the crash hotspot areas with Z-Score of more than 2.00.

In this work, Oromia's Crash Distribution Dataset (CDD) was also developed and validated for its integration into the predictive approach of CPM. The developed CDD, when compared to the default HSM dataset, predicts crash severity proportions and collision type percentages much closer to the observed values. For instance, for Fatal plus all Injury crashes (F+I), the calibration factors for the developed and HSM configurations are 1.018 and 1.915, respectively. Both configurations underpredict Fatal plus all Injury crashes, with the Oromia configuration underpredicting in 1.8% and the HSM configuration underpredicting in 91.5%. Furthermore, the study assessed the safety performance of rural two-way, two-lane roads by incorporating the developed CDD, and the study's results demonstrated the efficacy of performance-based road safety evaluation and design in identifying inconsistencies in a roadway network and providing safer roadway infrastructure. Engineering mitigations applied to identified hazardous road segments, for example, have resulted in total crash frequency (crashes/yr) being reduced by 17.18%, crash rate (crashes/km/yr) being reduced by 58.94%, and travel crash rate (crashes/million veh-km) being reduced by 58.86%.

Keywords: Crash distribution dataset; Crash prediction model; Getis Ord Gi*; HSM; IHSDM; Road traffic crash (RTC)

Zusammenfassung

Obwohl der Straßenverkehr das Rückgrat der sozioökonomischen Entwicklung eines jeden Landes ist, sind Millionen von Menschen auf der ganzen Welt in Verkehrsunfälle verwickelt. In den Industrieländern gibt es eine Vielzahl wissenschaftlicher Studien und technologischer Fortschritte, die darauf abzielen, die Wirksamkeit von Sicherheitsmaßnahmen zu verbessern. In Äthiopien ist jedoch nur wenig über die räumliche Analyse von Unfällen, die Sicherheitsleistung geometrischer Fahrbahnmerkmale und die relativen Sicherheitsauswirkungen von Entwurfsalternativen bekannt.

Diese Arbeit befasst sich mit der Anwendung modernster Unfallkartierungstechniken sowie mit der Bewertung der Sicherheitsleistung der Straßengeometrie in Äthiopien, wobei der Schwerpunkt auf der Region Oromia liegt. Der Schwerpunkt liegt auf zwei Aspekten, die bisher in der Studienregion übersehen wurden: die Analyse der Schwere und des räumlichen Musters von Unfallereignissen, um Unfallschwerpunkte zu identifizieren und die Bewertung der Sicherheit ländlicher zweispuriger Straßen mit einem prädiktiven Ansatz nach der Entwicklung eines gerichtsspezifischen Datensatzes zur Unfallverteilung.

Um die Hauptziele der Arbeit zu erreichen, wurden drei wissenschaftliche Studien durchgeführt. In dieser Studie wurden Daten der zuständigen Ämter über Unfallereignisse, die AADT und die geometrische Gestaltung der Straßen im Ist-Zustand sowie Vor-Ort-Beobachtungen des Straßenzustands (Standorte in der Nähe von Addis Abeba, insbesondere die in dieser Studie als gefährlich eingestuften Straßenabschnitte) und Satellitenbilder verwendet. Zur Untersuchung der räumlichen Muster von Straßenverkehrsunfällen und zur Identifizierung von Unfallschwerpunkten in Äthiopien wurden die räumlichen Autokorrelationen von Unfällen und Getis Ord Gi^*-Statistikwerkzeuge in ArcGIS verwendet. Darüber hinaus wurde das Crash Prediction Model (CPM) des prädiktiven Ansatzes im Highway Safety Manual (HSM) und das Interactive Highway Safety Design Model (IHSDM) genutzt, um die Sicherheitsleistung ländlicher Straßen zu bewerten und die Auswirkungen von Verbesserungen der Straßengestaltung auf die Sicherheit bestehender Straßen zu quantifizieren.

Die wissenschaftlichen Ergebnisse unterstreichen die Bedeutung der Identifizierung von Orten mit Sicherheitsproblemen auf der Grundlage von Unfallschwere und räumlichen Attributen sowie von sichereren Straßen, indem sicherheitsorientierte Straßendesigns für nachhaltige Verkehrsmanagementstrategien in Äthiopien eingesetzt werden. Der Studie zufolge bietet der

Einsatz von GIS in Äthiopien einen erheblichen Vorteil, wenn es darum geht, potenzielle Standorte für Sicherheitsverbesserungen zu identifizieren. Die Kartierung der Unfallschwerpunkte mit Hilfe der ArcGIS-Software ergab, dass Addis Abeba, die Region Oromia und die Zonen in Oromia, die näher an Addis Abeba liegen sowie die Einfahrt nach Addis Abeba (d. h. die Ost-Shewa-Zone, die Stadt Burayu, die Nord-Shewa-Zone, die West-Shewa-Zone, die Stadt Adama und die Süd-West-Shewa-Zone), die Unfallschwerpunkte mit einem Z-Score von mehr als 2,00 sind.

In dieser Arbeit wurde auch Oromias Crash Distribution Dataset (CDD) entwickelt und für die Integration in den prädiktiven Ansatz von CPM validiert. Der entwickelte CDD-Datensatz prognostiziert im Vergleich zum Standard-HSM-Datensatz den Anteil der Unfallschwere und den Prozentsatz der Kollisionsarten viel näher an den beobachteten Werten. So liegen beispielsweise die Kalibrierungsfaktoren für tödliche Unfälle und Unfälle mit Verletzten (F+I) für die entwickelte und die HSM-Konfiguration bei 1,018 bzw. 1,915. Beide Konfigurationen unterschätzten tödliche Unfälle und Unfälle mit Verletzten, wobei die Oromia-Konfiguration 1,8 % und die HSM-Konfiguration 91,5 % unterschätzte. Darüber hinaus bewertete die Studie die Sicherheitsleistung ländlicher zweispuriger Straßen mit Gegenverkehr unter Einbeziehung des entwickelten CDD. Die Ergebnisse der Studie zeigten die Wirksamkeit der leistungsbasierten Bewertung und Gestaltung der Straßensicherheit bei der Identifizierung von Unstimmigkeiten in einem Straßennetz und der Bereitstellung einer sichereren Straßeninfrastruktur. Die technischen Abhilfemaßnahmen, die auf die identifizierten gefährlichen Straßenabschnitte angewandt wurden, führten beispielsweise dazu, dass die Gesamtunfallhäufigkeit (Unfälle/Jahr) um 17,18 %, die Unfallrate (Unfälle/km/Jahr) um 58,9 % und die Reiseunfallrate (Unfälle/Millionen Fahrzeugkilometer) um 58,86 % gesenkt werden konnte.

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List of Acronyms

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AA-Ch	Addis Ababa to Chacha
AA-D	Addis Ababa to Dillela
AA-M	Addis Ababa to Modjo
ANRAM	Australian National Risk Assessment Model
ASL	Above Sea Level
AU	African Union
BSL	Below Sea Level
CAD	Computer-Aided Design
CDD	Crash Distribution Dataset
CMF	Crash Modification Factor
CPM	Crash Prediction Model
CSR	Complete Spatial Randomness
CSV	Comma Separated Values
EB	Empirical Bayes
ECA	Economic Commission for Africa
EGIA	Ethiopian Geospatial Information Agency
ERA	Ethiopian Roads Authority
ETSC	European Transport Safety Council
FHWA	Federal Highway Administration
GDP	Gross Domestic Product
GI	Global Indexes
GIS	Geographical Information System
GPS	Global Positioning System
GSA	Geo-Statistical Analysis
HSM	Highway Safety Manual
IDA	International Development Association
IHSDM	Interactive Highway Safety Design Model
KDE	Kernel Density Estimation
KIoT	Kombolcha Institute of Technology

LI	Local Indexes
MAD	Mean Absolute Difference
MoT	Ministry of Transport
NRSC	National Road Safety Council
NSMA	Non-Spatial Model Analysis
OECD	Organization for Economic Cooperation and Development
PI	Point of Intersection
PRM	Policy Review Module
RHR	Roadside Hazard Rating
ROR	Run-Off-Road
RSA	Road Safety Audit
RSDP	Road Sector Development Programme
RTC	Road Traffic Crash
SA	Spatial-Autocorrelation
SD	Sight Distance
SMAPE	Symmetric Mean Absolute Percentage Error,
SPF	Safety Performance Function
SSD	Stopping Sight Distance
UNECA	United Nations Economic Commission for Africa
UNECE	United Nations Economic Commission for Europe
USD	United States Dollar
UTM	Universal Transverse Mercator
vpd	Vehicle per Day
V_D	Design Speed
V_{85}	Operating Speed
WGS84	World Geodetic System 1984
WHO	World Health Organization

CHAPTER 1

Introduction

1.1. General

Highway infrastructures play a central role in countrywide economic growth and development policies. The significance of road transportation in achieving economic development goals in middle and low-income nations is now widely acknowledged. The fatalities and injuries caused by vehicle travel, on the other hand, are one of the most substantial issues associated with this mode of transportation. The primary goal of road transportation is to ensure the safety and efficient movement of goods and people. Road transportation is akin to war and drug use due to the problem of safety (Lamm, R., Psarianos, B., Mailaender, 1999). Road Traffic Crashes (RTCs) are a common cause of mortality and injury around the world, mostly affecting children and young people, and they place a significant financial and social burden on individuals and nations (Paris & Van den Broucke, 2008). While most RTCs happen in urban, rural roads have a higher rate of fatalities. RTC is the eighth-most cause of mortality for all age categories, according to the World Health Organization, killing 1.35 million people each year (WHO, 2018).

1.1.1. Global traffic crash statistics

Road Traffic Crash (RTC) is one of the humanitarian crises where society and decision-makers tend to recognize massive fatalities and disabilities as inevitable (Mohan, 2019). In many countries, road transportations made by automobiles facilitates social and economic development. Despite this, these automobiles are involved in traffic collisions that result in 1.35 million deaths of people globally and 20 to 50 million injuries each year (WHO, 2018). Daily, nearly 3,700 people die in traffic crashes, with pedestrians, motorcyclists, and cyclists accounting for more than half of those killed (WHO, 2018). According to the (WHO, 2018) statement of the Global Status Report on Road Safety, traffic crashes are indeed the leading cause of deaths among children and young adults aged 5–29 worldwide and for all age groups, it is estimated to be the eighth predominant cause of fatalities. *Figure 1* depicts the number of fatalities in RTCs and the death rate per 100,000 population from 2000 to 2016 consecutive years.

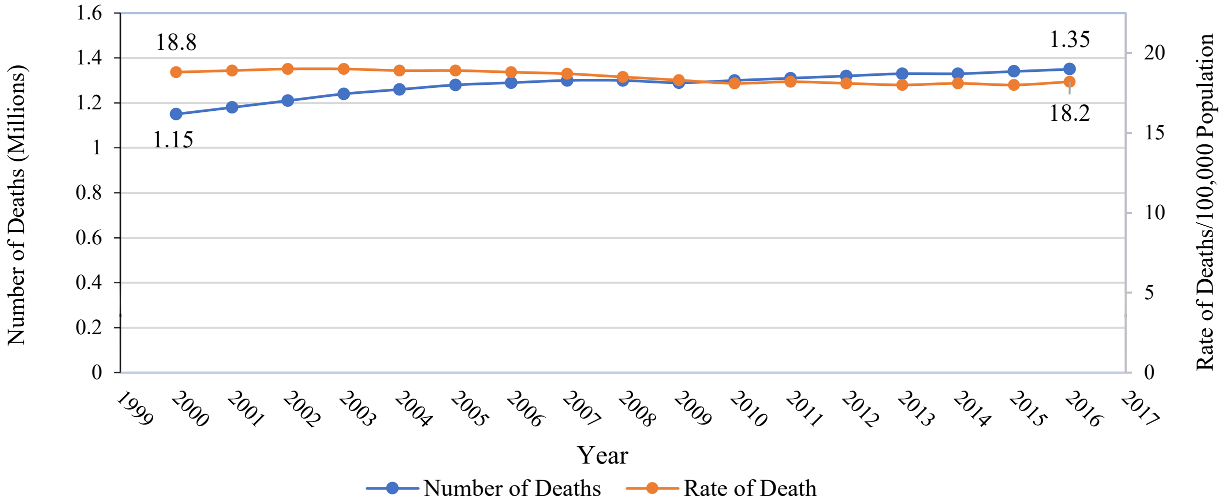


Figure 1: The number of fatalities due to RTCs and death rate per 100,000 population (WHO, 2018)

Traffic crashes now kill more people than HIV/AIDS and tuberculosis. Furthermore, it is estimated that RTC fatalities and injuries will cost the global economy nearly $1.8 trillion (in 2010 USD) between 2015 and 2030 (Chen et al., 2019). This equates to a 0.12% annual tax on global GDP (Chen et al., 2019). In low-income countries, the RTC death rate is more than three times that of high-income countries. The global death rate ranges from 9.3 to 26.6 per 100,000 population, and *Figure 2* depicts a summary of the WHO regions for 2013 and 2016 years. Despite accounting for 60% of the world's registered vehicles, low and middle-income countries account for more than 90% of all RTC fatalities in 2015 (Chen et al., 2019). From 2013 to 2016, there were no reductions in the number of crash deaths in any low-income country (WHO, 2018). The economic cost of traffic crashes is also substantial in low and middle-income countries (Gorman, 2006; Jacobs et al., 2000). It is approximated that low and middle-income countries will incur $834 billion economic losses (in 2010 USD) as a result of fatal and crash injuries between 2015 and 2030 (Chen et al., 2019). According to a World Health Organization report (WHO, 2018), overall RTCs in low and middle-income countries affect 2% to 7% of the countries' GDP.

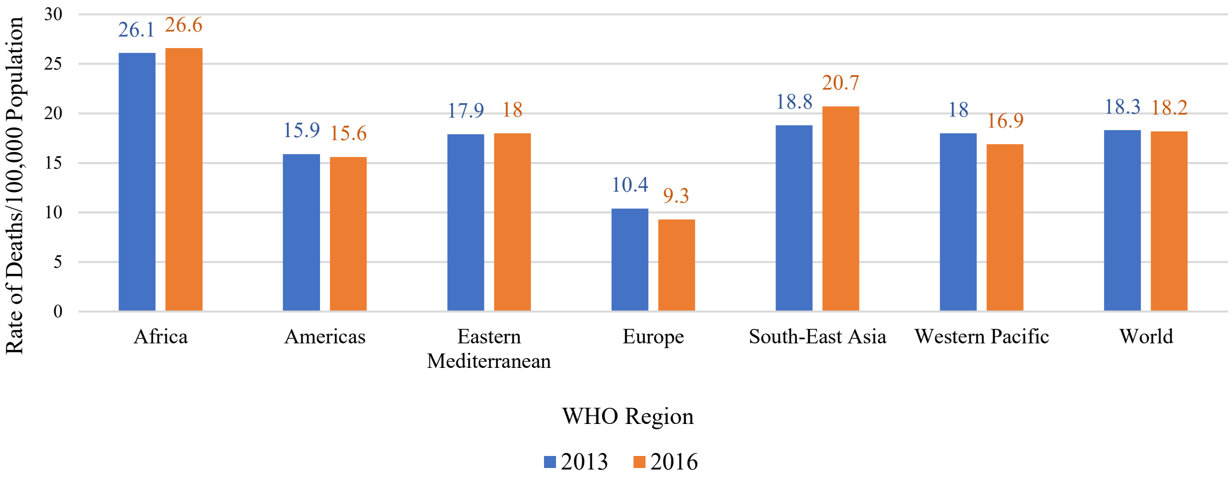


Figure 2: Rate of road traffic deaths/100,000 population by WHO regions for 2013 and 2016 (WHO, 2018)

Nowadays, urbanization inspires a new global economy and vice versa. This collaborative intervention will, in reality, change the face of the planet. Cities today host a large percentage of the global population. Between 2010 and 2050, the global population is expected to increase by 33% (United Nations, 2009). The rapid growth of motorization can be attributed to a combination of increasing urbanization and a greater desire for car ownership in developing countries (Gakenheimer, 1999). While public transportation is important in other countries, urban population growth coincides with a significant increase in public transportation trips (World Bank, 2002). However, in developing countries, a lack of strong traffic management systems, performance-based roadway designs, and thorough maintenance puts additional strain on the increasing traffic flows and crashes, resulting in congestion, pollution, unsafe mobility, and a poorer level of service highways (Cohen, 2006; Gakenheimer, 1999; Gwilliam, 2003; Rust et al., 2008).

1.1.2. Background of the study

Defective road infrastructures and traffic management can lead to RTCs, but proper engineering and management can considerably reduce the frequency and severity of crashes (Chandler & Anderson, 2010). Because the roadways influence how road users perceived their surroundings and convey directions on what they should do through signs, traffic regulations, and roadway geometry, good road design can improve traffic safety. Most traffic control and road safety engineering strategies function through influencing human (driver and pedestrians) psychology. Reducing the occurrence of traffic crashes has long been one of the most important responsibilities of highway engineers and road safety practitioners across the world. One of the major aims of transportation engineering is to improve the safety of road infrastructure. Decades of study and experience show that employing a scientific, systematic, consistent, and proactive approach to highway planning and design could greatly improve highway safety. Individual designers, transportation agencies, and concerned organizations should all work together to provide safe, efficient, and sustainable road transportation in order to achieve a significant reduction in road traffic crash fatalities and severe injuries. Predicting the number of crashes that may occur as a result of a given roadway design feature is critical for evaluating various alternatives in design and safety improvements. As a result, to be effective in improving road safety, safety engineers must understand the relationships between traffic crashes and roadway features. Road safety studies have underlined the opportunities as well as safety challenges on highways (Burgess, 2005; Chandler & Anderson, 2010; Tang et al., 2018; Tola & Gebissa, 2019b).

The safety of victims' mobility on roadways can be improved by constructing new infrastructure. However, this takes a long time and is expensive. It is feasible to improve the existing infrastructures through engineering mitigations as well traffic management as a short-term solution (Gakenheimer, 1999). The most important tasks for an effective road safety practice are identifying crash hotspots based on a spatial pattern analysis of crashes and an evaluation of crash spatial relations with neighboring areas, as well as developing safety mitigations by assessing crash contributors and the safety performance effects of road geometric characteristics. While high-income countries with proactive safety implementations have seen a steady decrease in the rate of crash fatalities, developing countries have poorer road quality, engineering mitigations, traffic safety management, and regulation (Dahdah, 2008; Gwilliam, 2003). To support road safety improvement in developing countries, both proactive and reactive road safety approaches should be exercised. Such as hazardous segment or crash hotspot management, network safety management, road safety performance evaluation, Road Safety Audit (RSA) assessment, and road safety inspection, the first two of which are reactive approaches and the latter proactive (Dahdah, 2008).

In Ethiopia, the majority of road safety analysis methodologies employed by transportation authorities and safety specialists are classic descriptive approaches focused on quantifying and summarizing crash data. This dissertation aims, first and foremost, to analyze the severity and spatial pattern of crash incidents, as well as to map crash hotspots in Ethiopia using the most up-to-date analytical techniques. While crashes are random incidences that occur in space and time, they also reflect spatial dependency and spatial autocorrelation, which should be taken into account while analyzing them (Yao et al., 2016). Most of the traditional approaches of crash analysis focus on the time dimension, nowadays the spatial dimension of traffic crashes has got more attention from researchers (Yao et al., 2016; Yuan et al., 2020). Emerging technologies to study, interpret, and improve safety are becoming available as Geographical Information System (GIS) technology advances and precise data is gathered for each crash incidence. Even though a comprehensive review and evaluation of analytical approaches have been conducted (Lord & Mannering, 2010a), numerous research has demonstrated that spatially enriched crash analysis shows potential in establishing a better insight into road safety (Mannering & Bhat, 2014; G. S. Mehta, 2014). Thus, based on the literature reviewed, the GIS software was used in this study to analyze, map, visualize, and interpret crash spatial patterns and severity due to its ability to integrate advanced statistical and spatial analysis.

Second, using the predictive approach of Safety Performance Function (SPF), the study evaluated the safety performance of rural two-way two-lane roads, and the relative safety effects of design alternatives were quantified. Current road safety studies have centered on more advanced and statistically verified techniques for improving roadway safety. The three well-known predictive tools capable of defining a new paradigm in road safety are the Highway Safety Manual (HSM), the Interactive Highway Safety Design Model (IHSDM), and SafetyAnalyst (Alluri et al., 2014). The analysis of roadway safety performance in this dissertation focuses on the two effective and advanced proactive tools of the HSM and IHSDM.

1.2. Problem statement

In terms of crash prevention programs, there are minimal indications regarding road safety measures being implemented in low and middle-income countries (Lagarde, 2007), where the majority of crashes occur. Ethiopia, a low-income country, has already identified road safety as one of its key priorities. Ethiopia, along with Uganda, Bangladesh, and Vietnam, is among the four nations in the world with an exceptionally high health concern, with more than 1,000 fatalities per 100,000 motorized vehicles (Elvik et al., 2009). It is fact that a larger frequency and severer crashes occurring year to year on the Ethiopian roads. Traffic crashes occurred on Ethiopian roads kill 4,732 citizens each year, which means that every day, nearly 13 Ethiopians do not come back home as a result of Road Traffic Crashes (RTCs) (UNECE, 2021).

According to the World Bank (Peden, 2004) and the WHO reports (WHO, 2015), there is a significant gap in understanding the burden of RTCs and their intervention strategies in low and middle-income countries compared to high-income countries. A Systematic Review and

Meta-Analysis carried out on traffic crash mitigation studies in low and middle-income countries by Staton et al. (2016) discovered only 18 studies from low and middle-income countries out of 8,560 total articles searched from electronic databases of EMBASE, Global Health, Lilacs, MEDLINE, Scielo, Scopus, TRID, and Web of Science (Staton et al., 2016). According to their findings (Staton et al., 2016), only four of these were from Sub-Saharan Africa, and only one of them focused on road improvements (The review was based on articles from the electronic databases EMBASE, Global Health, Lilacs, MEDLINE, Scielo, Scopus, TRID, and Web of Science). This gap motivates this research to study the safety performance of Ethiopian, Sub-Saharan Africa, road geometric features to add scientific and proactive roadway safety improvement strategies.

Understanding why RTCs occur and how to prevent them from happening again is a fundamental task of improving safety in any industry. Acquiring this knowledge necessitates determining why a specific combination of events, conditions, and actions leads to a definite outcome, such as crash analysis (Hollnagel et al., 2008). Crash severity and spatial pattern analysis can be utilized to determine where safety measures should be implemented. The crash causality model and crash analysis are important tools to get a better understanding of this issue (Underwood & Waterson, 2013). A conceptual representation of crash causality is observed from the analysis model whereas, the techniques made for analysis provide a means of applying this theory (Underwood & Waterson, 2013).

Since a better understanding of the factors that cause crashes enhances the ability of safety engineers to identify and implement effective safety measures, researchers have continued to be interested in investigating these factors. Several studies have been undertaken over the last few decades to investigate the relationships between contributing factors to crashes and crash attributes, including roadway characteristics, traffic characteristics, socioeconomic, and environmental factors (Dissanayake et al., 2009; Emer Tucay & Teyba, 2017; Golob et al., 2004; Graham & Stephens, 2008; Kononov et al., 2008; Lord et al., 2005; J.-L. Martin, 2002; Noland & Karlaftis, 2005; Ossiander & Cummings, 2002; Priyantha Wedagama et al., 2006; Quddus, 2008; Wier et al., 2009). Some safety practitioners have focused their efforts on exploring the effect of road safety measures on the occurrence of traffic crashes (Allpress & Leland, 2010; Galante et al., 2010; Hirst et al., 2005; Jones et al., 2008). While such safety models based on roadway performance measures are essential for determining effective safety mitigations to improve road transportation, no substantial investigations have been conducted in the current study region.

Recent advancements in artificial intelligence, sensor fusion, and algorithms have brought about the introduction of a proactive safety management system closer to reality. The basic prerequisite for developing such a system is to have a reliable crash prediction model that takes real-time traffic data as input and evaluates their association with crash risk (Hossain et al., 2019). Thus, motivating the current study to investigate the safety performance of roadway designs using the predictive approach of the crash prediction model to quantify the safety effects of various geometric design alternatives, as well as to study the spatial pattern and severity of crash incidents to identify crash hotspots and guide decision-makers where and when to implement preventive measures (i.e. enforcement, engineering, and education). As noted earlier, there has been a dearth of significant studies conducted to address the impact of road geometric design characteristics on road safety in low and middle-income countries (such as Ethiopia); the safety and operational effects of various road geometric designs in Ethiopia must be researched and quantified. The motivations presented in this sub-section give rise to the following research questions (*Section 1.3*) and study objectives (*Section 1.4*).

1.3. Research Questions

- Where are the traffic crash hotspots in Ethiopia as well as Oromia region?
- How effective is it to develop a jurisdiction-specific Crash Distribution Dataset (CDD)?
- What are the advantages of using a predictive approach of HSM and IHSDM to evaluate the safety performance of rural roads in Ethiopia?

1.4. Study objective

1.4.1. General Objective

The general objective of the study is to contribute scientific, consistent, and engineering proactive approaches to improving road safety in Ethiopia by analyzing the severity and spatial pattern of crash incidents and evaluating the safety performance effects of road geometric design. This general objective is attained through the specific objectives outlined in *Section 1.4.2* below.

1.4.2. Specific Objectives

- To analyze the severity and spatial pattern of crashes, as well as the spatial dependency of crashes with neighboring areas using GIS.
- To develop a jurisdiction's Crash Distribution Dataset (CDD) using local crash data for crash prediction model evaluation.
- To evaluate the safety performance of rural two-way, two-lane roadway geometry in Ethiopia and quantify the safety effects of design alternatives.

1.5. Significance of the study

The primary objective of the research is to address a knowledge gap in the study region about exploring roadway segments with safety concerns by analyzing the spatial pattern and severity of crash events, as well as assessing the safety performance of rural roads' geometric design features. While some researchers have studied road safety in Ethiopia (Abegaz & Gebremedhin, 2019; Berhanu, 2004; Eckersley et al., 2010; Fekadu & Quezon, 2016; Persson, 2008; Salmon & Eckersley, 2010; Getu Segni Tulu et al., 2015), none have used the advanced safety tools and techniques utilized in this study. Hence, by calibrating and integrating the advanced and well-known safety tools and techniques such as GIS, IHSDM, and HSM to Ethiopian road safety improvement strategies, the current study has the significance of:

- Addressing "*safer roads through better design*" for safety improvements.
- Contributing to the knowledge gap in using performance-based roadway designs and safety evaluations in Ethiopia.
- Demonstrating the advantage of using the spatial autocorrelation and statistical tools of GIS to identify crash-intensive prone zones.
- Revealing the facts regarding the basic cause of road traffic crashes on Ethiopian roads and locations with high crash frequency and severity (crash hotspots).
- Evaluating the effectiveness of HSM and IHSDM model for use in Ethiopia.
- Providing the developed and validated crash distribution dataset for Ethiopian rural two-way two-lane roads.
- Exploring the safety benefits of design changes or alternative designs.
- Quantifying the safety effects of roadway improvements and safety mitigations made.
- Assist agencies in determining how to best invest limited resources to improve roadway safety performance.

1.6. Dissertation layout

The dissertation is structured into seven chapters, including the one at hand. This is the introductory chapter, which describes the global crash burden, the study's background, the problem statement, the objectives, and the study's significance. There is one review chapter (*Chapter 2*), one for the study area description (*Chapter 3*), three scientific investigation chapters (*Chapters 4–6*), and a concluding chapter (*Chapter 7*). The content of each chapter is summarized below.

The second chapter (*Chapter 2*) includes a review of the literature on the factors that contribute to traffic crashes, as well as methodologies that have been used by scholars for crash analysis and road safety performance evaluations, along with their applications to safety improvements. *Chapter 3* presents the background of the study area (Ethiopia) as well as the country's road safety overview in terms of road infrastructure development, vehicle ownership rate, and crash trends.

Chapter 4 presents, severity, spatial pattern, and statistical analysis of traffic crashes. The study used ArcGIS software to analyze and identify crash hotspots throughout Ethiopian regions, as well as zones and towns in the Oromia region, based on four years of crash data. In *Chapter 5*, a jurisdiction-specific Crash Distribution Dataset for Ethiopia's Oromia region is developed using local crash data. Using observed crash incidents, the developed local crash distribution dataset is validated and compared to the default HSM configuration. A predictive approach of CPM is applied in *Chapter 6* to identify road segments with safety issues. The chapter also explores how modifications in road geometric design based on the safety performance effects of design alternatives enhance road safety in Ethiopia.

Chapter 7 concludes with a summary, the study's limitations, and some recommendations and prospective research directions.

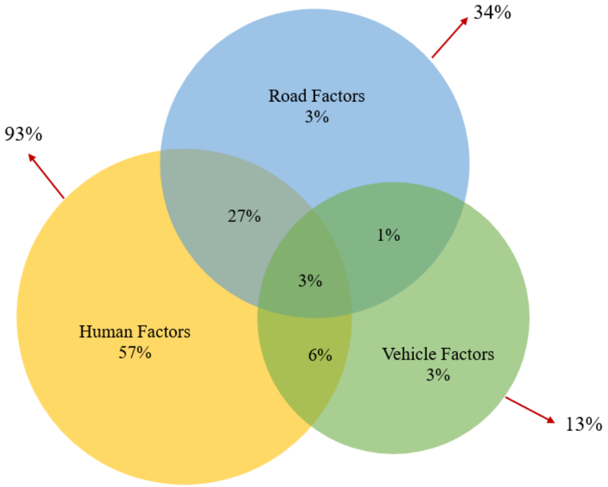
CHAPTER 2

Literature Review

This chapter presents a comprehensive review of the literature on road safety to provide insight into the factors that contribute to traffic crashes, as well as the systematic and analytical approaches established in the past road safety studies. Road traffic safety analysis has been employed to save the loss of lives by understanding the cause of traffic crashes and coming up with safety mitigations. The analysis aims to investigate pieces of information needed by decision-makers to apply suitable safety measures to mitigate and minimize the occurrence and severity of traffic crashes (Li et al., 2007). Factors influencing traffic crashes have been the subject of extensive research in transportation studies over the last decade. When conducting a road safety study, it is critical to understand and investigate these factors. The first section provides a brief overview of the numerous factors influencing the severity and frequency of traffic crashes, followed by a review of the literature on traffic crash analysis and the most up-to-date techniques for evaluating roadway safety performance.

2.1. Major traffic crash contributors

Whereas it is usual to state the causes of crashes, most crashes cannot be correlated to a single contributory event. Crash events, rather, are the result of the integral of a series of events that are associated with several causal factors (i.e. driver speed, driver attention, vehicle condition, roadway design features, weather condition, etc.). These causal factors have an impact on the sequence of events that occur *pre-crash, crash phase*, and *post-crash* (AASHTO, 2010). *Pre-crash* event studies expose factors that influenced the likelihood of a crash incidence, as well as how the crash could have been mitigated. During the pre-crash phase, all mitigation strategies that prevent the occurrence of a crash must be selected. *During-crash* incidents indicate factors that contributed to the severity and incidence of the crash as well as how technological advances or engineering mitigations are capable of reducing crash incidence and severity. Finally, the *post-crash* events show factors that affect the crash's result, as well as how developments in emergency service and hospital care may have lessened injures. In connection to the human, vehicle, and road & environment, William Haddon (Haddon, 1980) established a matrix that detects influencing factors pre-crash, during-crash, and post-crash. The established matrix is a diagnostic tool that may be used to determine all of the contributors to a crash. Countermeasures can be devised and prioritized for application over short- and long-term timeframes once the several factors correlated with a crash have been revealed and analyzed. Treat's (Treat et al., 1979) study based on relative percentages of influencing factors found that relative percentages are much more meaningful than actual values, the summary is shown in *Figure 3*.



NB: The numbers in the overlapping regions represent the interaction of the three contributing factors, whereas the numbers in the circles that are not overlapping represent the individual contribution. To obtain the overall percentage contribution, add the values in the circle (overlapping and non-overlapping) (i.e. 57%+27%+3%+1%+3%+6%+3% = 100%). The values outside the circles are the relative percentages of the factors determined by aggregating individual contributions and percentage interactions with other factors.

Figure 3: The relative percentages of contributing factors to traffic crashes (source: Treat et al., 1979)

Even though the human factor has been noted as a leading cause of traffic crashes, it is practically difficult to foresee and plan for the driver's attitude as well as the physical situation. The highway designer has minor influence over driver decisions at curves and junctions and has no control over alcohol consumption or seat belt use. Consistent geometric design, on the other hand, could help to regulate operating speeds and improve safety caused by improper roadway environments or geometry. Even so, several factors have been recognized that contribute to crash incidences: road user characteristics, road infrastructure and environmental factors, and vehicle factors are the fundamentals.

2.1.1. Road users and traffic characteristics

The characteristics of the driver, including consciousness, fatigue, experience, and risk-taking attitude, are being studied as significant contributing factors to the occurrence and severity of crashes. In most countries, driver fatigue is one of the major contributors to traffic crashes, particularly those on rural roads. Scholars have conducted research to estimate the contribution of driver fatigue to crash incidences, such as Philip et al. (Philip, 2001), who found that fatigue was a contributory cause in nearly 10% of crashes. The European Transport Safety Council

(ETSC) (Etsc, 2001) reported that the proportion of fatal crashes involving fatigue or sleeping varied between 16-19%, and Amundsen & Sagberg (Amundsen & Sagberg, 2003) proved that 15-20% of fatal crashes were fatigue-related.

The skill of the driver to handle both speed and direction is crucial in Run-Off-Road crashes. When a driver is confronted with a sudden or uncommon situation, he or she will interact at a significant angular position, resulting in a Run-Off-Road crash. This is caused by the driver's characteristics, such as driving under the influence of alcohol or drugs, interruptions, being ill or blacked out, overspeeding, being unfamiliar with the street, and disobeying traffic rules (Garber & Hoel, 2002). The age of a driver also influences crash incidence: from the viewpoint of an older driver, aging-related declines in perceptive and psychomotor abilities enhance their susceptibility to driving off the road (Spainhour & Mishra, 2008).

Speed, flow, and density are the traffic characteristics that influence the incidence and severity of traffic crashes. Several studies have been conducted to investigate the impact of speed (Ossiander & Cummings, 2002; Treat et al., 1979), flow (Golob et al., 2004; Lord et al., 2005; J.-L. Martin, 2002), and congestion (Kononov et al., 2008; Noland et al., 2008; Wier et al., 2009) on crash incidence and severity. Regardless of the results of the various studies, it is clear that traffic characteristics can have a significant influence on the incidence as well as the severity of crashes. A thorough understanding of how these factors interact can assist traffic management, reducing both the severity and frequency of traffic crashes.

2.1.2. Vehicle characteristics

Vehicle deficiencies and equipment malfunctions are may also cause traffic crashes. Defective vehicles not only cause traffic crashes, but they might also lead to fatal or severe injuries, even in minor collisions. The ability of a vehicle to safeguard (i.e., seatbelts, airbags, seatbacks & booster seats, motorcycle helmets, energy-absorbing steering columns, and other safety features) its occupants in the event of a collision has a significant impact on the result of traffic crash injuries. Weakness in seatbacks and faulty seat belts can increase injury levels during the crash event (Smith, 2021). At the time of crash events, the seatback is designed and provided to sustain the passenger's chest and back, even at a higher vehicle speed. Another key aspect that plays an important role in crash incidence and severity is vehicle mechanical issues (Garber & Hoel, 2002). Malfunction of brakes or steering, worn tires, inadequate headlights, overburdening, and reflecting loads all have an impact on vehicle control, especially at higher speeds (Smith, 2021). Tire tread rupture and tire blowout in high-speed motor vehicles induce failure in vehicle control, which often leads to crashes. The wear resistance induced by vehicle and road surface interaction is crucial in preventing vehicles from encroaching on off-roadway components such as the median, shoulder, as well as other traffic signs (Saravade, 2005).

2.1.3. Roadway and Environment

Traffic crashes don't occur uniformly across the road network; instead, they might exist in clusters at certain locations, on specific roadway segments, or across entire residential areas, particularly in aspects of society with poverty (WHO, 2006). Whilst road infrastructure can significantly reduce the incidence and seriousness of crashes, it is a factor that potentially causes traffic crashes. Most traffic management and safety engineering interventions function by influencing drivers' behavior through road infrastructure, which influences crash risk by impacting the road user's perception of the road environment and providing guidelines on how they use the road (WHO, 2006). Roadway infrastructure as a contributing factor to traffic crashes includes those in which an inconsistent roadway causes a crash, where a certain road feature misleads a driver and thus leads to a fault, or where a geometric design modification to the roadway could have mitigated the incidence as well as the severity of a crash.

Horizontal curvature, sight distance, road length, roadside characteristics, cross-section elements (i.e. lane width and shoulder-width, widening), vertical curvature, and vertical grade are the key road design elements that may have contributed to traffic crashes. Horizontal curves are among the most significant risk factors of roadway elements, and they've gotten a lot of press in the safety research. Because of the additional burden put on the driver due to the existence of centrifugal forces at the curved sections, crashes are more probable to happen on curves than on tangents. A vehicle entering and leaving a horizontal curve should therefore properly shift its turning radius as well as varied side friction. As a result, effective maneuvering on a curve requires the selection of appropriate speed, suitable deceleration, and proper turning through the curve (Oxley et al., 2004). On curves, crash rates are reported to be 1½ to 4 times larger than those on tangents (C. et al., 1991). According to Cairney's (P., 1998) research, segments that have 5°-10° of curvature would have had at least two times the crash rate of segments with a curvature of 1°-5°, and segments with a curvature of between 10°-15° have four times the crash rate; and in aspects of curve radius, 200 m appears to be the reference below that the crash rate dramatically increases. Anderson and Krammes (I. B. Anderson & Krammes, 2000) looked at the association between average crash rate and mean degree of curvature, and discovered that horizontal curves that demand speed reductions have greater crash frequencies than curves that don't. The average crash rate has increased linearly with the mean speed reduction, according to their findings. The study by Lamm et al. (R. et al., 2000) discovered a substantial increase in crash and severity with rising curvature changes, notably for curves with rates larger than 200 gon/km, that correlate to radii below 320 m without considering curves changeover.

The relevance of sight distance, which is determined by both horizontal and vertical alignments, has also an influence on traffic crashes. A study was conducted in New Zealand (A.J. & J.N., 2000) to investigate the effects of sight distance on driver speeds. According to the study, a large proportion of drivers (44% to 82%) were riding too fast to stop within the accessible sight distance. Crash numbers have also been linked to locations where speeds were detected to be extreme for the accessible sight distance. Several studies have been conducted to investigate the impact of lane and shoulder-width on the crash frequency and severity (Bester & Makunje, 1998; Directorate, 2001; Hauer, 2000). Researchers examined the relationships between traffic crashes and roadway design elements. Using negative binomial models, (M. A. Abdel-Aty & Radwan, 2000) evaluated the frequency of crash incidence on a major arterial in Central Florida. They emphasized the importance of road infrastructure characteristics such as the degree of horizontal curvature, the number of lanes, shoulder widths, and the length of the road section, stating that drivers on roads with narrow lane and shoulder widths, decreased median width, and an increased number of lanes are more vulnerable to crashes (M. A. Abdel-Aty & Radwan, 2000). According to a study conducted by (Noland, 2003), certain changes in roadway design elements (variables included are lane width, number of lanes for different types of roads, and the proportion of each type of road) in the United States between 1984 and 1997 increased the absolute total number of traffic casualties. On the other hand Noland and Oh (Noland & Oh, 2004) concluded in their study that a higher number of lanes, widened lane widths, and reduced outside shoulder width have been associated with higher crash frequency.

Furthermore, the surrounding environmental conditions are the most challenging crash contributing factor that must have to be considered in road safety. Unfavorable and poor weather, such as heavy rain, windy, foggy, and storms, can significantly impair drivers' vision (Aron et al., 2015; Jaroszweski & McNamara, 2014). Several studies conducted over the last decades concluded that heavy rain is one of the significant environmental factors causing traffic crashes (Asefa et al., 2015; Wang et al., 2011), whereas others identified that snowfall has been a major contributor to crash incidence in countries with four seasons (Wang et al., 2011; Xi et al., 2014), and the rest revealed that dust storms as an environmental factor also have influenced traffic crashes (Lankarani et al., 2014; Tezangi, 2016).

2.2. Road safety improvement studies and interventions

The reduction of traffic crashes, as well as their socio-economic consequences, has become the world's most pressing problem. Road safety improvement continues to be a primary concern for transportation agencies, policymakers, and safety practitioners. Traffic crash fatalities and injuries can be prevented by establishing a road safety management system that includes all key participants and implementing fundamental safety mitigations systematically. The scientific approach to road safety management acknowledges traffic safety as a collective responsibility of all road safety stakeholders. As a result, this systematic approach to road safety management is then used by a community that adheres to risk-aversion norms of behavior established through education, policies, and enforcement. Furthermore, as an integral part of the system, road designers and engineers play a critical role.

Considering the crash contributory factors and the time frame of a crash event improves the identification of effective crash mitigation measures. Improvements in road user behavior, road infrastructure, and the surrounding environment, technology design and maintenance (i.e., vehicle, roadway, and environmental technology), the allocation of emergency medical treatment and post-crash recovery, and travel exposure can all play a significant role to reduce the crash frequency and severity. These improvements can be facilitated through the following road safety strategies (AASHTO, 2010):

- Design, Planning, and Maintenance: Consistent geometric design, improving and timely maintenance of the transportation system (i.e., modifying signal phasing, rehabilitation of deteriorated road so on), engineering mitigations (i.e., rumple stripe, use of median barriers to prevent head-on collisions);
- Education: Public awareness campaigns, driver training programs, and training of engineers and doctors;
- Policy/Legislation: prohibit cell phone use while driving, require minimum design standards, and mandate the use of helmets or seatbelts;
- Enforcement: penalizing illegal behavior, such as excessive speeding and drunken driving;
- Advances in Technology: electronic stability control systems in vehicles improve the driver's ability to maintain control of a vehicle. The introduction of "Jaws of Life" tools (for removing injured persons from a vehicle) has reduced the time taken to provide emergency medical services;

- Demand Management/Exposure: increasing the availability of mass transit reduces the number of passenger vehicles on the road and therefore a potential reduction in crash frequency may occur because of less exposure.

While all of the aforementioned strategies are important in reducing the frequency and severity of crashes, the current literature concentrates on road safety improvement strategies in which the roadway infrastructure is believed to be the main contributor, either alone or in combination with other factors. Since traffic safety study is such an important activity for improving roadway safety, it has been extensively researched in the academic press. Despite the lack of consensus on road safety studies, researchers and experts have developed various strategies and engineering mitigations in which safety can be enhanced on-road transportations. One of the most cost-effective road safety interventions is to eliminate the so-called black spots, that is, to remedy crash-intensive prone locations along the roads. There are no universally acknowledged procedures to identify black spots (also called hazardous road locations, crash hotspots). Some safety researchers prioritize sites by crash rate (i.e. crashes per vehicle-kilometers for segments and crashes per entering vehicles for intersections), others use crash frequency (i.e. crashes per year), some use spatial analysis of crashes, and others adopt the integration of the above and the rest uses regression modeling (i.e. the predictive approach of Crash Prediction Model, CPM) (Geurts & Wets, 2003).

The most important activity for an effective road safety practice is to identify hazardous roadway locations and coming up with appropriate mitigations. This in general comprises the following road safety management tasks (AASHTO, 2010; General Directorate of Highways, 2001):

- Identify the black spots: detecting and prioritizing sites with a potential of safety improvements or in need of immediate mitigations;
- Learning the problems of each spot (diagnosis): evaluating crash data, historic site data, and field conditions to identify crash patterns (i.e collision diagrams, condition diagrams, and crash mapping using Geographic Information Systems (GIS) tools);
- Design appropriate safety mitigations: identifying factors that may contribute to crashes at a site, and selecting possible countermeasures to reduce the average crash frequency;
- Estimate their effects Evaluating the benefits and costs of the possible countermeasures, and identifying individual projects that are cost-effective or economically justified;

- Set priorities: evaluating economically justified improvements at specific sites, and across multiple sites, to identify a set of improvement projects to meet objectives such as cost, mobility, or environmental impacts;
- Implement, and finally, follow up and evaluate safety effectiveness: evaluating the effectiveness of a countermeasure at one site or multiple sites in reducing crash frequency or severity.

There are a lot of road performance measures available to assess a site's potential for safety improvements among these crash frequency, crash rate, critical rate, relative severity index, probability of specific crash types exceeding a given normal threshold, predicted average crash frequency, and expected average crash frequency with EB adjustments are the commonly used. The following factors should be considered when selecting performance measures: data accessibility, regression-to-the-mean bias, as well as how the performance threshold is determined (AASHTO, 2010). The common data required are roadway data, crash data, and traffic volume and characteristics. The regression-to-the-mean impact is a statistical probability in which roads with an elevated crash frequency in a certain period are likely to have fewer crashes in the next year (Ogden, 2002), even though no actions are taken; this is due to random fluctuations in crashes frequencies. The threshold performance value could be a value that is subjectively presumed or one that is computed as part of performance measures methodology.

The most critical task for road safety engineers is determining where to apply safety preventative procedures. By prioritizing and detecting sites with safety issues, road safety engineers will be able to make technical and practically feasible safety mitigations. One of the most common goals of detecting sites with safety issues is to address a critical question in road safety practice: where are the crash hotspots or hazardous roadway segments? In general, scientific answers to these inquiries can be found in two categorized studies:

- By analyzing the observed crash severities and spatial patterns (Choudhary et al., 2015).
- By evaluating the safety performance estimates of the existing or newly constructed road geometric designs and traffic exposures (Montella, 2010).

2.2.1. Crash pattern analysis and mapping

Crash analytics, which can be used to evaluate the safety of road infrastructure, is one of the most popular scientific disciplines in the domain of traffic safety study. The straightforward method to evaluate crash data is detecting where the crash rate per unit exposure exceeds a given normal threshold (crash hotspots) (Taylor et al., 2017). Generally, the most frequently used methods of crash hot spot analysis can be categorized into two. These are:

- Non-Spatial Model Analysis (NSMA): which uses the traditional approaches of statistics such as regression models (Zhang & Ivan, 2005);
- Geo-Statistical Analysis (GSA): by analyzing the spatial units of crashes (i.e. Density Estimation) (Erdogan et al., 2008; Z. Xie & Yan, 2008) or spatial arrangement of each crash attribute value (i.e. Spatial-Autocorrelation, SA) (Anselin, 1995; Getis & Ord, 2010; Ord & Getis, 1995).

As compared to NSMA, Geo-Statistical crash hotspot analysis needs less data and is easier to apply due to the simplified mathematical calculations (Lee & Khattak, 2019) and its integration of crash incidence with spatial factors and also, the presentation of clear visualization in the result. The adoption of the spatial arrangement of attribute values from each unit is more advantageous than using a spatial unit of crashes due to its consideration of spatial dependence of attribute values and the geographical location of incident points (Levine, 2002).

The spatial study of crashes must be addressed by road safety researchers due to the existence of distance in the roadway transportation system. Spatial analysis is the inspection of crash occurrence patterns by considering their relative locations or zones. Traffic crashes meet the main characteristics of spatial heterogeneity and spatial dependence of point data. Spatial dependence belongs to the influence of events at a location by neighboring events while spatial heterogeneity happens when the spatial relationships among observed incidents and random parameters in the developed model are not established spatially (Dereli & Erdogan, 2017).

GSA can be further divided into two groups such as Global Indexes (GI) for instance Global *Moran's I* (Spatial-Autocorrelation), Getis-Ord G statistic and Geary's C; and Local Indexes (LI) these are Local Anselin Moran's I (Cluster and Outlier Analysis), planar Kernel Density Estimation (KDE), Getis Ord *Gi** and kriging. Except for kriging and KDE, the rest incorporates a procedure for testing the statistical significance of clustered incidents. In the global index analysis, the spatial pattern incidence of the entire network is assessed and it analyzes whether data is clustered in a group, dispersed, or randomly distributed, whereas the local indexes are used to study the microscopic pattern of incidents to determine the spatial location and extension of these clusters (Fu et al., 2011).

Several studies have used planar KDE (T. K. Anderson, 2009; Erdogan et al., 2008), which works by creating a continuous surface of total event density within a search bandwidth. While other researchers have used network space KDE (Z. Xie & Yan, 2008; Yamada & Thill, 2004), which is generalized to calculate the crash density over a distance unit rather than an area unit for crash hot spot identification. The major limitations of both planar and network space KDE's are the lack of statistical significance test in the analysis (T. K. Anderson, 2009; Plug et al., 2011; Z. Xie & Yan, 2008) and also, there are no criteria for prioritizing crash hot spots (Z. Xie & Yan, 2008). Researches develop and used KDE+ as an effective tool for crash hot spot identification and site prioritization to overcome the limitation of the network and planar KDE approach (Bíl et al., 2013, 2016). The KDE+ analysis works based on the standard KDE approach with the addition of statistical significance testing of clustered points.

Compared to KDE, for both *Moran's I* and Geary's C the statistical significance of clustered crashes is determined using Z-Score (Erdogan, 2009; Wong & Lee, 2005). Indeed, *Moran's I* and Geary's C follow the global statistics approach which is the measure of the whole study network. The local statistics approach (such as Getis-Ord *Gi** statistics (Getis & Ord, 2010) and local *Moran's I* (Anselin, 1995)) is superior to the global statistics system for studying spatial variance and spatial dependency. The Getis-Ord *Gi** statistic, in particular, has been validated to identify statistically significant values of crash hot spots or cold spots and has proven to be useful (Khan et al., 2008).

The emergence of GIS has provided a vital tool for community health study (Goodchild, 2015; Kwan, 2012; Neutens, 2015). Moellering used a Geographical Information System (GIS) to analyze traffic collisions for the first time in 1976 in his work of "*a computer-animated film in the analysis of geographical patterns of traffic crashes.*" (Moellering, 1976). Since then, the geographical information system has been used extensively in road traffic safety studies over the past five decades (Dereli & Erdogan, 2017; Mohaymany et al., 2013). Its application varies from simple mapping and visualization roles to further advanced methods such as spatial statistical models and the analysis of large data methods. Nowadays, the precise location of RTCs and their attributes are stored in the GIS database. GIS software allows us to gather spatial data in which we can store, manipulate, analyze and visualize it with ease (Lloyd, 2010).

Although most of the traditional approaches of crash analysis focus on the time dimension, nowadays the spatial dimension of traffic crashes has got more attention from researchers (Yao et al., 2016). This necessitates the application of GIS in the analysis of traffic crashes. In recent years, several RTC databases recorded the precise locations of crashes through the application of GPS devices hence, it is no longer necessary to identify the crash hot spot section of a road from aggregated data (Gundogdu, 2010; Li et al., 2007). By having these accurate locations of

RTC, road safety analysts can focus on the highly clustered crash locations. The advantage of using advanced GIS-based hotspot analysis is not limited to the simple presentation of perilous roadway areas; it also provides the ability to investigate the spatial dependency of crash incidents and spatial connections with other factors. For the past five decades, a GIS application in the field of traffic safety has aided in the advanced realization of crash characteristics, which is then used as a piece of information to improve traffic safety. Nowadays, Geographical Information systems (GIS) have become a more popular and preferable tool for crash hotspot identification. A GIS combines crash spatial attributes with statistical analysis which is the best way to understand crash patterns. The application of GIS is relatively easy and can convert raw statistical and geographical information into meaningful data for spatial analysis, mapping, and detecting any issues contributing to crashes (Choudhary et al., 2015).

2.2.2. Roadway Safety Performance evaluation

In the field of road safety, examining the safety outcomes for specific treatments is critical in improving highway safety. Current studies and practices have validated that highway planning and design that possess a scientific, consistent, and proactive approach can add a significant safety improvement. Developing correlations between crash frequency and traffic condition, roadway elements, and environmental condition is the conventional method to identifying sites with safety concerns and contributory factors of crash incidence. It is obvious that by assessing the relationship between the elements of the roadway geometric design and factors affecting road safety, additional findings can be derived. The differences can be observed in crash rates when the highway parameters like curvature, slope, sight distances, shoulder width, and lane numbers are altered, supporting further the argument that highway geometric characteristics do affect safety on the road. For instance, research made by Othman et al recommends that horizontal curves with high crash rates can be amended by restricting lane-changing maneuvers (Othman et al., 2009). Also, Ahmed et al support this argument by concluding that roadway sections with high degrees of curvature, wider medians, and surges in lane numbers are factors for reducing crash rates (Ahmed et al., 2011).

To be effective in highway safety improvements, safety engineers need to comprehend the associations between traffic crashes and roadway characteristics. The existing relationship between road safety and geometric design consistency characterize a key subject in current highway geometric design (NCHRP, 2003). The impacts of geometric design consistency on crash rates are an ongoing argument between academic researchers, safety engineers, and transportation bodies. A lot of road safety studies conclude that even though driver error is usually the major cause of a road traffic accident, the geometric design also plays a significant role in crash occurrence (Haghighi et al., 2018; Karlaftis & Golias, 2002; Semeida, 2013). Drivers are expected to select the safest speed on the roadway they are traversing depending on the appropriate speed for the surrounding roadway environment. However, drivers' perceptions can be affected by the road environment in both their speed and the appropriate speed for the roadway.

Geometric design consistency study has been conducted widely to improve the safety of the roads. Geometric design consistency can be demarcated as how a driver's expectations and the road's performance match up (i.e., when a road with a good consistency level matches a driver's expectations, the road user is not amazed while driving along with it) (Camacho-Torregrosa et al., 2013). Studies made in geometric design consistency attentive on quantifying measures of the design consistency and developing a model that best fits the local condition and evaluation measures to identify them. Generally, geometric design consistency measures are divided into four distinct categories and most of the research and development of design consistency measures focused on them (Awatta & Hassan, 2002; Ng & Sayed, 2004): Operating speed, vehicle stability, driver workload, and alignment indices.

A. *Operating speed:* Operating speed is defined as the vehicle speed selected by drivers when not restricted by other users and is generally represented by the 85th percentile operating speed (Lamm, R., Psarianos, B., Mailaender, 1999; Poe & Mason Jr., 2000). In geometric design consistency evaluation, operating speed (V_{85}) is the most widely used and straightforward criterion (Gibreel et al., 1999). The variation of vehicle speed along the roadway is a clear indicator of inconsistencies in geometric design (Nicholson, 1998). Operating speed can be used for consistency measure by examining the difference between operating speed (V_{85}) and design speed (V_D) or examining the variation of operating speed along continuous roadway section (ΔV_{85}) (Camacho-Torregrosa et al., 2013).

B. *Vehicle stability:* In the profession of highway geometric design, the most crucial feature of the road surface are its skid resistance. The centripetal force developed due to the horizontal curve can be counterbalanced by providing superelevation and also, used to reduce friction demand. Extreme centrifugal forces acting on vehicles moving on a horizontal curve may lead to skidding, rollover, and head-on collision. Hence, for consistent highway geometric design and vehicle stability, and driver comfort, side friction demand must have to be supplied in the balance of the centrifugal forces. Side friction is essential to horizontal curve design, but that the design values must be based on a realistic study of driver behavior and comfort tolerance of recent drivers (McLean, 1976). The design consistency assessment can be done based on a margin of safety of the variance among side friction supply and side friction demand on a horizontal curve. Road sections that do not provide vehicle stability can be considered as an inconsistent geometric design (Gibreel et al., 1999).

C. *Alignment indices:* Alignment indices are a simpler method to assess design consistency (Hassan, 2004), which are the quantitative measures of the general character of a roadway segment (I. B. Anderson et al., 1999). Alignment indices are not subjected to any evaluation measures; however, it is well known that road geometric inconsistencies may appear when the general character of the road alignment differs expressively (Fitzpatrick, Elefteriadou, et al., 2000; Hassan et al., 2001).

D. *Driver workload*: Driver workload is defined as "the time rate at which drivers must perform a given amount of work or driving task" (Messer, 1980). He indicated that driver workload increases with reductions in sight distance and increasing complexity of geometric features, as the complexity of highway geometric features increases, the time rate required to perform a given driving task is expected to increase also, consequently reflecting higher driver load. Also, Gibreel et al defined driver workload as the required rate of time that a driver must perform a given amount of driving task, which increases as long as the complexity in the highway geometric features increases (Gibreel et al., 1999). Driver workload might more interesting measure for detecting geometric design inconsistencies than operating speed since it is a pointer of the effort that the road needs from drivers, while the operating speed is only a quantifiable output of the driving task (Ng & Sayed, 2004). A lot of researchers have studied the effect of geometric design consistency on road safety (for instance, (I. B. Anderson et al., 1999; Cafiso et al., 2007; Ng & Sayed, 2004)).

In order to attain the primary goal of road transportation, such as safe mobility, road designers and their disciplines need to use different emerging technologies and techniques. The recent advancement in road safety research from descriptive techniques to more radical and statistically validated methods of predictive and quantitative approaches has piqued the interest of road safety practitioners. Descriptive analyses are used to summarize and quantify the observed crash data on a roadway (such as summarizing historic crash data using the different techniques). Predictive approaches are rather dedicated to predicting the average crash frequency and severity at sites that have similar geometric as well as operational characteristics.

The predicted or expected average crash frequency in proportion to the corresponding severity levels can be used to evaluate multiple design alternatives (AASHTO, 2010).

Safety evaluations based on expected safety performance are a valuable technique to identify hazardous road locations in a highway network as well as site-specific safety concerns, especially given the cost of engineering studies and limited budget (Qin et al., 2013a). The process of identifying hazardous road locations (also called blackspots, high-risk locations, hotspots, crash-prone zone, inconsistent, etc) is defined as the process by which a road network is screened to detect places that require safety inquiry (B. N. Persaud, 2001). It has a long history in traffic engineering and is considered the primary and most frequent activity in the road network safety management process (AASHTO, 2010; Hauer et al., 2002; Montella, 2010). Road locations with a higher number of crashes than other similar locations due to local risk factors are considered hazardous or high-risk locations (Elvik, 2007). This means that high-risk locations are places where the geometric design and traffic circumstances have a major impact on the crash occurrence and can be mitigated using engineering remedies. The list of hazardous sites is prioritized for additional engineering research (Hauer et al., 2002), and the most cost-effective projects are frequently selected to get the best outcomes with limited funds (Montella, 2005, 2010).

In practice, network screening and road safety performance evaluation are the mandates of the transportation agency; however, developing a model isn’t a simple task (Reurings et al., 2006), and it may be time-consuming regarding data requirements and staff qualification. Transportation agencies, including Australia (Thompson et al., 2010), Denmark (Greibe, 2003), Finland, and Lithuania (Peltola et al., 2013), have used a simple model that just requires basic data only. In the Highway Safety Manual (AASHTO, 2010), simple models are also utilized as base models; the predictive approach followed in this manual are developing baseline models for the specified base conditions, and in order to account for changes in geometric design and operational characteristics (deviations from the specified base condition), Crash Modification Factors (CMFs) are multiplied by baseline models.

Crash Prediction Models (CPMs) are widely used to evaluate the safety of roadway design alternatives. Crash prediction model development is a technique for congregating sophisticated interconnections in safety science while also incorporating engineering expertise and quantitative predictions of the crash's likelihood. In most cases, these models are developed and applied separately for road segments and intersections (AASHTO, 2010). A lot of statistical models have been developed to address a variety of data-related issues (comprehensive reviews are provided in (Ambros et al., 2018; Lord & Mannering, 2010b)). For instance, the Poisson and negative binomial regression models were used as base models in HSM's predictive approach (AASHTO, 2010). The most common method used in several studies is to find a connection between a wide range of variables (contributory factors) and the frequency or severity of crashes.

The CPM, in general, predicts the expected frequency of crashes for roadway segments and intersections using geometric design and traffic operational variables. CPMs can be used to perform a variety of road safety management procedures, including road network screening, the development of Crash Modification Factors (CMFs), road safety performance evaluations, and economic analysis of design alternatives. CPMs evaluates and expose possible safety concerns, as well as assist in identifying potential safety improvements and quantifying their benefits (Yannis et al., 2016). In recent decades, CPMs based on road geometric design and traffic exposure have become an essential scientific and proactive tool in quantitative road safety management and have been the cornerstone of the AASHTO Highway Safety Manual (HSM) and the Australian National Risk Assessment Model (ANRAM) (AASHTO, 2010; Jurewicz et al., 2014).

The Highway Safety Manual (HSM), published in 2010 by the American Association of State Highway and Transportation Officials (AASHTO), is a tool to support in achieving the goal of performance-based safety evaluation (AASHTO, 2010). HSM has become a well-known science-based decision-making tool that can perform statistical evaluations on safety and other roadway transportation performance indicators (such as traffic operations, environmental impact, and construction costs) (Ambros et al., 2018). Factors such as roadway characteristics, traffic volume and characteristics, and weather conditions are features that influence the expected number of crashes in the predictive analysis. Driver behavior, in which its data are not always accessible also influences the expected number of crashes. The driving behavior of the specific local jurisdiction can be studied from crash data information but ‘Driving simulator’ experiments and ‘Naturalistic driving’ studies may provide an accurate deep understanding of the contribution of driving characteristics on crash occurrences (Ahmed & Chalise, 2018). By using the predictive approach of HSM, agencies or safety practitioners can be well guided in the process of identifying road sections with safety issues, developing mitigations to address them, evaluating the safety outcome of those mitigations on resource allocation, and assessing the effectiveness of safety projects that have been built or implemented. Highway design and planning typically entails assessing a set of potential design alternatives to see how they affect a variety of aspects, such as safety, capacity, construction costs, societal expenses, environmental impacts, and so on. The HSM procedure can also be used to evaluate the safety implications of these design alternatives. Part C of the HSM's predictive approach (AASHTO, 2010) provides CPMs for various facility types (i.e., roadway segments and intersections) to estimate the expected crash frequency at a certain location considering its geometric and traffic characteristics.

For a limited fund and cost of engineering studies, road safety studies based on the expected safety performance function are a feasible way to identify potential roadway sites for improvement. The predictive models of HSM (*Equation 1*) detect roadway sites with great promise for the reduction of crash frequency and severity. For the specified analysis period, the predictive method of HSM presents an organized technique to predict the expected average crash frequency by their respective crash distribution dataset (i.e. categorized by overall crashes, crash severity proportions, and collision type distribution). The predictive approach of HSM has four main features these are; Safety Performance Functions (*SPFs*), Crash Modification Factors (*CMFs*), Calibration Factor (C_x) and Crash distribution dataset (AASHTO, 2010; Tarko et al., 2018). SPF is a statistical model that predicts the crash frequency of facilities based on the specified '*base conditions'* (HSMs specified base conditions). Safety Performance Functions (SPFs) utilize known information about a roadway, such as geometry and annual average daily traffic *(*AADT*)*, to estimate the average crash frequency for a facility type with specified '*base conditions*'.

$$N_{Predicted} = N_{SPF} \times C_x \times \left(CMF_1 \times CMF_2 \ldots \times CMF_n\right) \qquad 1$$

Where $N_{predicted}$ is the predicted average crash frequency of a site, N_{SPF} is the safety performance function (SPF) for '*base conditions'*, C_x is the calibration factor, and CMF_1, $CMF_2 \ldots CMF_n$ are Crash Modification Factors (CMFs) accounting for the variation in crash frequencies due to the safety treatments or site characteristics. Sites or locations with higher observed crashes than that of the predicted crash frequency needs additional investigations for the safety benefits.

Whenever the characteristics of site conditions *(condition 'b')* under the evaluation vary from the '*base conditions*' *(condition 'a')*, the corresponding CMFs are applied by multiplying them with the predicted crash frequency under '*base conditions*'. CMFs are used to address the effect of individual geometric design and traffic control features on the SPF estimate of predicted crash frequency, and their computation is given in *Equation 2*. A CMF has a value of *1.00* under *'base conditions'*, while values less than *1.00* imply that alternative treatment reduces the predicted crash frequency, and values greater than *1.00* indicate that alternative treatment increases the predicted crash frequency compared to the *'base condition'*.

$$CMF = \frac{Predicted\ average\ crash\ frequency\ with\ condition\ 'b'}{Predicted\ average\ crash\ frequency\ with\ condition\ 'a'} \qquad 2$$

A calibration factor *(C_x)* is also multiplied by the crash frequency predicted by the statistical base model to account for the differences in undetected crash frequency contributory factors (such as weather, road user characteristics, vehicle characteristics, and crash reporting thresholds) between the general local conditions (site-specific condition) and HSM conditions (states used to develop HSM) (AASHTO, 2010). Thus, applying the HSM predictive method to different geographic locations without calibration may result in erratic crash predictions, which are being investigated by some researchers (B. Persaud et al., 2002; Sawalha & Sayed, 2006). Whenever the observed number of crashes for the evaluation period is available, *Equation 3* can be used to compute the calibration factor *(C_x)*. Since HSM does not state any statistical techniques to check the validity of the calibration factor, safety practitioners should be careful during the application of the calibration procedure.

$$C_x = \frac{\sum_{All} Observed\ crashes}{\sum_{All} Predicted\ crashes} \qquad 3$$

Another part of the HSM CPM is the *Empirical Bayes (EB)* method. The empirical Bayes (EB) procedure is used in the predictive approach to computing the expected crash frequencies before and after safety mitigation has been applied at a certain site. The EB procedure comprises improving the precision of safety estimation and correcting '*regression-to-the-mean*' bias (Elvik, 2008; Li & Zhang, 2007). A '*regression-to-the-mean*' bias occurs when a site is observed with an unusually low or high crash frequency in one year, followed by a resume to a more usual crash frequency the succeeding year. The EB technique takes into account both the observed and predicted number of crashes at a site depending on the SPFs. The EB approach, which is based on the notion of weighted adjustment factor, has been commonly applied in several road safety investigations (Das et al., 2018; Pratt et al., 2018; X. Sun et al., 2014; Wu et al., 2018; Zou et al., 2018) and is endorsed by the HSM (AASHTO, 2010). To compute the expected average crash frequency ($C_{Expected}$), EB adopts a weighted adjustment factor (w) to integrate observed ($C_{Observed}$) and predicted crash frequencies ($C_{Predicted}$) as illustrated in *Equation 4*.

$$C_{Expected} = w \times C_{Predicted} + (1 - w) \times C_{Observed} \qquad 4$$

Where $C_{Expected}$ is the expected average crash frequency; $C_{Predicted}$ is predicted average crash frequency; $C_{Observed}$ is the observed crash over the analysis period and; w is a weighted adjustment factor as a function of the over-dispersion parameter (k):

$$w = \frac{1}{1 + C_{Predicted} \times k} \qquad 5$$

Where the over-dispersion parameter (k) in this equation represents the SPF model's over-dispersion. It is the presence of greater variability (statistical dispersion) in a data set than would be expected by a given statistical model.

2.2.3. Application of HSM and IHSDM

Due to its capacity to identify locations with safety issues, SPFs that precisely predict crash frequencies are worthwhile to transportation agencies. Thus, with the HSM, defining performance-based safety objectives and strategies have become more straightforward. The HSM has gained popularity, having been included in the Interactive Highway Safety Design Model (IHSDM) and subsequently implemented in the European crash prediction (Yannis et al., 2015), Australian ANRAM (Jurewicz et al., 2014) as well as New Zealand (NZTA, 2016). The SPFs proposed in the HSM have been developed using roadway facilities that are representative of the United States as a whole; however, local and international users are encouraged to calibrate the SPFs for their jurisdictions. Calibration procedures are presented in Appendix-A of HSM part C; they should be enhanced or adjusted considering the jurisdiction data availability including geometric data, traffic, and crash history.

HSM allows local agencies and safety practitioners to develop and calibrate the individualized predictive components (i.e. SPF, CMFs, and crash distribution datasets). Many techniques can be used to customize the predictive HSM by combining its major elements, for instance, the study by Dixon et al., has investigated the possible options associated with calibration factors and crash distribution percentages under the HSMs default SPFs (F. Xie et al., 2011). Since the introduction of the Highway Safety Manual, highway safety engineers do not only use it as a standard in the predictive approach but also it is adopted by local and state transportation agencies in the United States and many other countries (Sacchi et al., 2012). For instance, HSM has been calibrated and implemented by the highway safety engineers, local and state transportation agencies, in the United States; Alabama, Florida, Louisiana, Missouri, Oregon, South Dakota, Texas, Utah, and Virginia (M. A. Abdel-Aty et al., 2014; Brimley et al., 2012; Fitzpatrick et al., 2006; Kweon et al., 2014; G. Mehta & Lou, 2013; Qin et al., 2016; C. Sun et al., 2014; X. Sun et al., 2006; F. Xie et al., 2011) and in other countries such as Canada, Italy, and New Zealand (Koorey, 2010; Marchionna et al., 2012; Martinelli et al., 2009; B. Persaud et al., 2012). A study by Sacchi et al. (Sacchi et al., 2012) was made with a key objective of investigating the methodologies to assess the transferability of the overall HSM predictive algorithm and its components which are; the CMFs and baseline SPFs. The study was executed based on data conducted from rural two-lane undivided roads of Turin province in Italy. They compared the results of their studies with a similar study done in Canada as part of their study to amplify the conclusions on the transferability of the predictive HSM procedure in other countries (B. Persaud et al., 2012). The study result revealed the over-prediction of the HSM predictive model and suggesting the development of jurisdiction-specific SPFs and CMFs across Europe. The authors concluded the acceptability of using baseline SPFs and CMFs with local calibration factors by highlighting, the complexity of HSM transferability techniques and the need for substantial data and analysis.

Some of the studies have developed jurisdiction-specific Safety Performance Functions with locally available data in which it was found to give improved prediction estimates (Brimley et al., 2012; Kweon et al., 2014; G. Mehta & Lou, 2013). In Kweon et al.'s (Kweon et al., 2014) study, the SPF variables and equations in the predictive HSM were modified for crash estimates using Virginia highways and crash data. Variables newer to HSM predictive approach such as; truck proportion and speed limit were included in the study executed to develop jurisdiction-specific SPFs (Brimley et al., 2012; G. Mehta & Lou, 2013). In other studies, further inquiries have been discovered for instance; modeling lane width in non-linear form rather than a linear form in the equation of SPFs shows improved estimates (Park & Abdel-Aty, 2017) and the presence of an association between the shoulder and lane width as well as the necessity of including their correlation in SPFs model (Park & Abdel-Aty, 2017).

Since different highway geometric characteristics may affect crash type and severity proportions, the predictive method of HSM encourages users to predict crashes by their respective proportions of severity and collision type. Predictive models by crash proportions yield a better estimate than crash frequency predictions with overall crash types (Jonsson et al., 2009). Crash prediction models based on specific crash distributions (i.e. by severity level and collision type) explores the associations between roadway geometric features and their accompanying crash types thus, helping policymakers, road safety engineers, and practitioners in making effective improvements on the severer crashes. In comparison to Rear-end collisions, Head-on collisions create more severe damages (Jonsson et al., 2009) and Run-Off-road collisions are further associated with shoulder and lane widths than are Rear-end collisions (Zegeer et al., 1988). Roadway features significantly influence the number of crash types and their proportions. Persaud et al. employed an empirical Bayes before-after method by installing rumble strips on rural undivided highways (B. N. Persaud et al., 2004). Their study result discovered that the installation of rumble strips along the centerline has shown a reduction in all crash injuries and a significant reduction in opposite sideswipe and head-on crashes witnessed.

Because of the benefits of predicting average crash frequency in terms of crash severity and collision type proportion, the HSM predictive method provides default crash distribution datasets for rural two-way two-lane roadways (AASHTO, 2010). HSM endorses the necessity of replacing this default crash distribution dataset with the fraction of local crash distribution estimates as part of the calibration procedure. Numerous studies found that the replacement of the fixed default crash proportions by the local crash history could improve the accuracy of crash prediction significantly (Brimley et al., 2012). In contrast, some studies argued that the assumption of fixed crash distribution datasets might be not true. For example, strong relationships between highway features and the possibilities of different crash severities and collision types have been explored by related studies (M. Abdel-Aty & Keller, 2005; Haleem & Abdel-Aty, 2010; Huang et al., 2008). In (Qin et al., 2019) study, they presumed that a crash severity proportion as a function rather than as a fixed proportion might predict crash frequency pretty well with higher accuracy. However, according to the study's result, crash severity proportion as a function does not improve the prediction accuracy. Thus, their study guarantees the effectiveness of a fixed crash proportion approach in the development of a jurisdiction-specific crash distribution dataset.

Statistical software or spreadsheets are commonly used to carry out the HSM analytical procedures such as preparation of data, exploratory analysis, modeling, and computations. FHWA (The Federal Highway Administration) has been designated Highway Safety Design Practices and Criteria as the top research and development program (Paniati & True, 1996). The primary objective of this research program is to build a tool capable of evaluating the safety performance and cost-effectiveness of highway design alternatives in a CAD (Computer-Aided Design) interface. The project has been executed for a couple of years and a fully functional software known as the Interactive Highway Safety Design Model (IHSDM) has been developed. IHSDM evaluates the complete highway design, including both the highway alignments and cross-section as well as the roadside features. IHSDM is available now as a FREE software package and is used to estimate a project's substantive safety.

In addition to the predictive HSM, SafetyAnalyst and Interactive Highway Safety Design Model (IHSDM) are the key road safety improvement tools for making efficient and effective design decisions (Qin et al., 2013b). The crash prediction module of IHSDM, which is a faithful application of the predictive method of HSM in part C, has been used as a proactive road safety tool by providing the expected safety alternatives for the newly constructed highway (during the design phases) and existing roads (FWHA, 2019). Nowadays, CPM of the Interactive Highway Safety Design Model (IHSDM) software, which is developed by the Federal Highway Administration, is the commonly used predictive approach. IHSDM software incorporates the four predictive components of HSM, which are *(i)* safety performance function (SPF), *(ii)* crash modification factors (CMFs), *(iii)* calibration factor (C_x), and *(iv)* crash distribution dataset (Tarko et al., 2018). Thus, the constraints in the calibration of the predictive HSM components can be carried out by the application of the IHSDM tool (Tarko et al., 2018). Many studies were made to assess the applicability of CPM in IHSDM software. For instance, Dominguez et al (Dominguez-Lira et al., 2010a) calibrated CPM in IHSDM with jurisdiction data on three highway sections in Spain. The results of their study showed that the IHSDM crash prediction with a calibrated dataset performed significantly better. They concluded that even if the application and interpretation of the CPM in IHSDM needs attention and expertise in the field, its application could be essential for the evaluation of existing highways and roadway rehabilitation projects.

The IHSDM includes five evaluation modules (Crash Prediction, Design Consistency, Policy Review, Traffic Analysis, and Driver/Vehicle) as well as an Economic Analysis Tool. All of them are supplemented by nationally recognized research and design regulations (FWHA, 2019). The IHSDM Crash Prediction Module uses geometric design and traffic information to estimate the frequency and severity of crashes expected to occur on a given highway. *Part C* of the HSM is directly implemented by the IHSDM's crash prediction module (CPM), which integrates the most up-to-date analytical approaches to (FHWA, 2013; Office of Research and Technology, n.d.):

- Predict crash frequency along with roadway segments, intersections, and interchanges.
- Identify sites in a road network or facility that have safety issues.

- Assess the relative safety effects of design alternatives or improvements.
- Evaluate the safety and cost-effectiveness of roadway design.

Several case studies conducted using IHSDM software revealed the need for substantial data collection, model adjustment, and calibration (Chuo & Saito, 2009a; Conkin & Stamatiadis, 2004; Donnell et al., 2009; Maji et al., 2006). The default model must be updated and calibrated to realize the full potential of IHSDM for an accurate estimate of crash frequencies expected to occur on roadways with specific geometric design and traffic features. The calibration, if properly executed, can account for differences between the states used to develop the crash prediction model and local crash characteristics (Qin et al., 2013a). Koorey in his study concluded that IHSDM is a promising tool to evaluate the safety and operational effects of roadway alignments; additionally, its ability to integrate crash data into the analysis improves its crash predictions and eases calibration to local conditions (Koorey, 2015). IHSDM was used by Chua and Saito (Chuo & Saito, 2009b) to evaluate the safety performance of Utah's two-lane rural roads and identify alternative designs for road segments with safety concerns. Based on the findings of a study, they highlighted the predictive accuracy of IHSDM software and suggested its importance for application in road safety audits and evaluating the effectiveness of design alternatives. They also mentioned the need for expertise regarding road geometric design aspects to interpret the IHSDM results. Several studies utilizing IHSDM as a safety tool have been conducted, and most of them confirmed its ability to evaluate geometric design consistency and predict the average crash frequency of roadway sites after calibration to local conditions (Azevedo & Cardoso, 2010; Chai et al., 2009; Dominguez-Lira et al., 2010b; Levison et al., 2001; Meng et al., 2016).

2.3. Summary of literature review

While it is common practice to state the causes of crashes, the majority of crashes cannot be attributed to a single contributing event. Crash events, on the other hand, are the sum of a series of events that are linked to a variety of causal factors (i.e. driver speed, driver attention, vehicle condition, roadway design features, weather condition, etc.). Nonetheless, several factors have been identified as contributing to crash incidences: road user characteristics, road infrastructure, and environmental factors, with vehicle factors being the most important.

The most critical task for road safety engineers is determining where to apply safety preventative procedures. By prioritizing and detecting sites with safety issues, road safety engineers will be able to make technical and practically feasible safety mitigations. One of the most common goals of detecting sites with safety issues is to address a critical question in road safety practice: where are the crash hotspots or hazardous roadway segments? In general, scientific answers to these inquiries can be found in two categorized studies:

- By analyzing the observed crash severities and spatial patterns.
- By evaluating the safety performance estimates of the existing or newly constructed road geometric designs and traffic exposures.

Crash analytics, which can be used to assess the safety of road infrastructure, is a popular scientific discipline in the field of traffic safety research. The precise location of RTCs, as well as their attributes, are now stored in a GIS database. GIS software enables us to collect spatial data that we can easily store, manipulate, analyze, and visualize. Although most traditional approaches to crash analysis focus on the time dimension, researchers are now paying more attention to the spatial dimension of traffic crashes. However, there has been a dearth of significant studies in Ethiopia that have used a spatial pattern, severity, and statistical analysis using the GIS tool. To bridge this gap, the current study statistically analyzed the spatial pattern and severity of crash incidents for hotspot mapping.

Examining the safety performance of specific treatments is critical in improving highway safety in the field of road safety. Current studies and practices have validated that highway planning and design with a scientific, consistent, and proactive approach can significantly improve safety. The recent advancement in road safety research from descriptive techniques to more radical and statistically validated methods of predictive and quantitative approaches has piqued the interest of road safety practitioners. Safety evaluations based on expected safety performance are a valuable technique for identifying hazardous road locations in a highway network as well as site-specific safety concerns, especially given the cost of engineering studies and limited budgets. Crash Prediction Models (CPMs) are widely used to evaluate the safety of roadway design alternatives.

There had been no significant studies conducted in the study region (Ethiopia) for the evaluation of the safety performance of rural two-way two-lane roads using a predictive approach prior to the success of this report. The current study used the predictive approach of HSM that is incorporated into the CPM of IHSDM to evaluate the safety and operational performance of rural two-lane roadway characteristics in Ethiopia, due to its advantages of:

- Being enhanced with a quantitative approach to evaluating the safety of rural roads.
- Identifying roadway segments with safety issues.

- Supporting safety performance-based practical design.
- Assisting agencies in deciding how to best invest limited resources to improve safety performance.
- Evaluating the safety effects of highway improvements and treatments.

Allowing engineers to incorporate local data whenever developing jurisdiction-specific or calibrating the default HSM model, dataset, design policy, and so on.

CHAPTER 3

Background of the Study Area, Ethiopia

3.1. Introduction

Ethiopia is a focus of the current research. Ethiopia, a landlocked nation in East Africa (so-called the Horn of Africa), is the origin of the Blue Nile, the Nile's main headstream by volume. The country is almost twice as large as Kenya, France, or Texas, with a total surface area of 1,126,829 km^2 (One World-Nations Online, n.d.). Ethiopia shared a common border with Kenya in the south, Somalia and Djibouti in the east, South Sudan and Sudan in the west, and Eritrea in the north, with known coordinates between $3^0 – 15^0$ North, $33^0 – 48^0$ East and a mean altitude of 1,330 m ASL (*Figure 4*). The highest elevation is Ras Dashen, 4550 m ASL and the lowest is Danakil Depression with an elevation of 125 m BSL (CIA World Factbook, 2021). The country's climate is tropical monsoon weather, with vast elevation differences such as temperate in the highlands and tropical in the lowlands, hot season from October to May, and a rainy season from June to September. Ethiopia is Africa's second-most populated country, next to Nigeria, with an anticipated population of 114.9 million (in 2020) (One World-Nations Online, n.d.; *World Population Prospects 2019*, 2019). Ethiopia's economy grew at a 9.4% annual rate from 2010/11 to 2019/20, but since the outbreak of COVID, the gross domestic product (GDP) in 2019/20 has dropped to 6.1% (World Bank Group, 2021). It is, unfortunately, among the poorest country's, with an income per capita of 850 USD (World Bank Group, 2021). The country's global commerce is heavily reliant on the shipping ports of nearby countries, notably the Port of Djibouti. Ethiopia's economy is mostly centered on the agricultural industry, which accounts for more than 70% of the country's working population (One World-Nations Online, n.d.). The map of the study area is shown in *Figure 4*.

Ethiopia set a goal of reaching middle-income economic status by 2025 (World Bank Group, 2021); therefore, roads are a crucial backbone for a country like Ethiopia, which is landlocked and highly reliant on agriculture and is now progressively being pushed by an industrialization drive. Roadway transport is Ethiopia's most significant mode of transportation, providing access and mobility to people and products in both urban and rural areas. Improvements to the country's road transportation infrastructure have received greater attention from government officials. To tackle restraints in the infrastructure development, particularly low roadway coverage and poor transport infrastructure condition, the government established the Road Sector Development Programme (RSDP) in 1997 (ERA, 2015), which has been carried out over a twenty-four-year period, with four subsequent phases implemented and the fifth currently underway (ERA, 2019). The RSDP's primary goal is to develop road networks and consistency in design, as well as to boost institutional efficiency in road traffic operation and management.

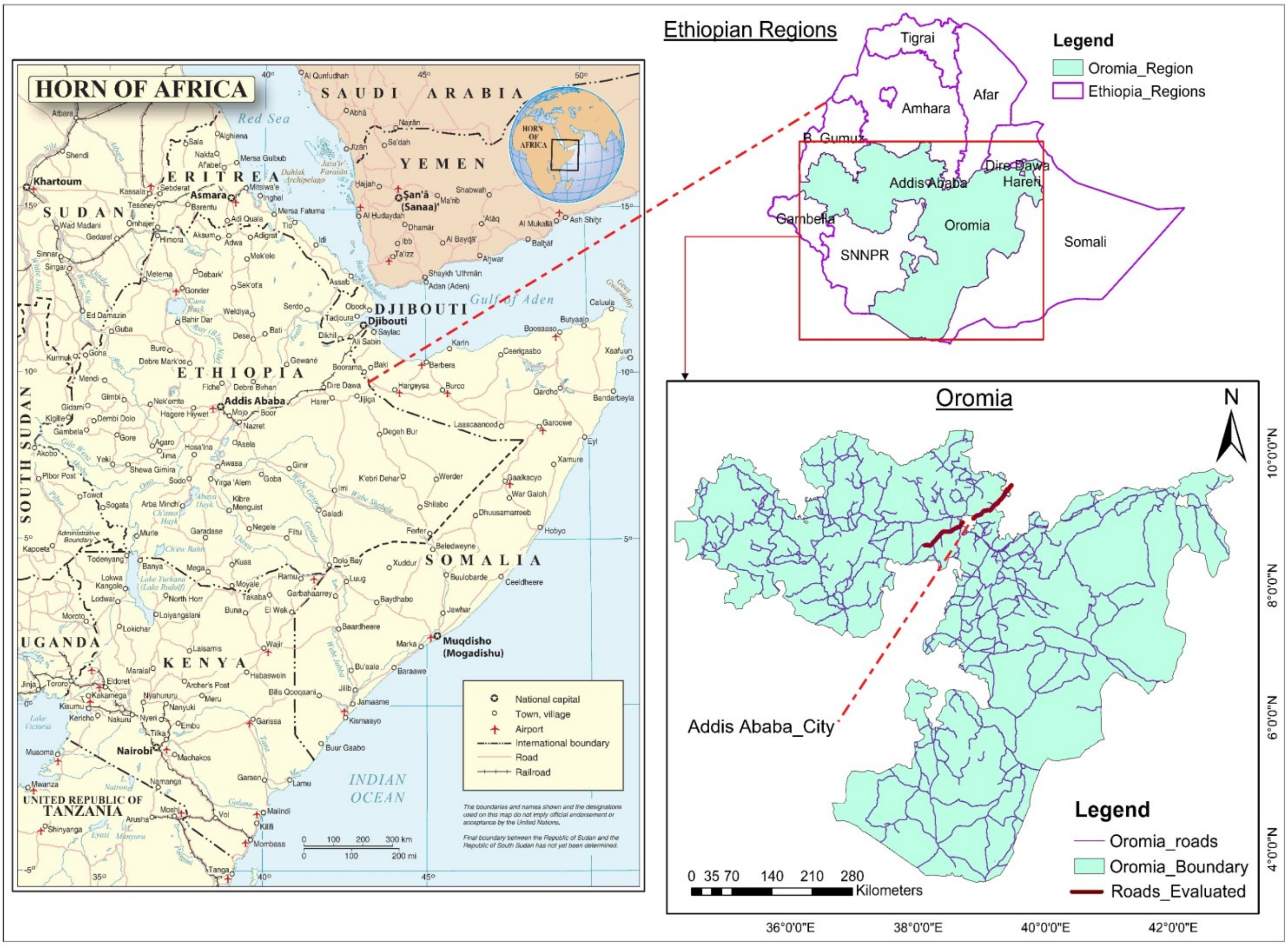


Figure 4: Map of the study area (The Horn of African Map is taken from UN (United Nations, 2012)*)*

The International Development Association (IDA), one of the largest official development aid organizations in Ethiopia (World Bank Group, 2021), also supplies analytical insights and consultancy services to assist with solid proof decision-making and improved management on a variety of development challenges. Road asset management (such as the implementation of road performance-based agreements), climate concern, strengthening road management agencies, developing the Expressway Development Program, and improving road safety are among the sectors where IDA has collaborated with other development partners, including the

European Union, African Development Bank, and other joint ventures, to support the country’s capacity. During the last two decades of the RSDP era, IDA has invested over 2 billion US dollars in the road infrastructure sector to support Ethiopia’s development strategy (World Bank Group, 2021). The road network in Ethiopia was 26,550 km in 1997 and increased to 126,773 km in 2018 with an average growth rate of 7.8% (ERA, 2019). As a consequence, road density per 1,000 square kilometers increased from 24.1 km in 1997 to 115.2 km in 2018, and the quality of the countrywide road infrastructure has improved significantly, with the share of the road network in good condition rising from 22% in 1997 to 73% in 2018 (ERA, 2019).

3.2. Road safety overview

In Ethiopia, as a low-income country aspiring to become a middle-income country, road infrastructure is essential to economic and social growth. However, the issue of road safety has already been identified as the top of its priority list (UNECA, 2009; UNECE, 2021). Low-income countries’ present road infrastructures are now incapable of ensuring safe mobility in the face of increasing motorized vehicles and a growing population. Ethiopia is seeing an upsurge in traffic crashes due to a population growth rate of about 3% and an anticipated yearly rise in the motor vehicle fleet of 10-15% (National Road Safety Council office of Ethiopia, 2018). Countrywide, vehicle ownership and travel distances in kilometers have grown significantly. In 2018, 1,071,345 vehicles have been registered and accessing the road, a 338.6% growth (Federal Transport Authority, 2019) from 244,257 in 2007 (WHO, 2009). These tendencies are affecting Ethiopia, and a new strategy to regulate road safety is required.

Ethiopia established the aim of the United Nations Decade of Action for Road Safety (2011-2020) to decrease traffic crash fatalities and injuries by half by 2020 (WHO, 2015); unfortunately, an assessment of Ethiopia’s road safety performance revealed that the country fell short of the target (UNECE, 2021). In contrast, throughout a similar time, road traffic deaths and serious injuries have risen year after year. Furthermore, relatively too little is known in Ethiopia regarding road safety expertise, attitude, and road users characteristics, as well as the contributory factors of traffic crashes and potential interventions (UNECA, 2009). According to Boesen and Brand (Boesen & Brand, 2008), although much emphasis has been placed on the “hard” parts of the road transportation sector (especially road infrastructure building and maintenance), the “softer” parts (such as road traffic management and operation, safety and monitoring tasks) have received insufficient attention. Road traffic crashes are a major problem in Ethiopia, threatening both the country's economic development and the health of society (Persson, 2008).

There are several discrepancies and shortcomings in the implementation and enforcement of traffic safety and management system across Ethiopia's regional states and administrative cities. This can be justified by the lead agency's weak competence to develop a strategic plan, manage, coordinate, and review road safety on a regular schedule. The Ethiopian National Road Safety Council (NRSC) is the country's principal agency for road traffic safety, with the principal goal of developing a road traffic safety plan and coordinating the execution of that policy. Multiple governments and private parties manage Ethiopia's NRSC. The Ministry of Transport, Ethiopian Roads Authority, Federal Transport Authority, Federal Police Commission, Ministry of Health, Ministry of Finance, Ministry of Education, as well as private and public transportation associations lead the Council. The Ministry of Transport is the principal ministry in charge of road safety in the country, and the NRSC reports directly to it. The Minister is in charge of the Council's day-to-day operations. Road safety councils are supervised by their relevant Bureaux in the regional states and administrative cities. The Transport Bureau, in particular, is in charge of road safety initiatives in each region and city. However, the NRSC's connection with regions and administrative cities' road safety units is weak (National Road Safety Council office of Ethiopia, 2018; Persson, 2008). Ethiopia also isn't a signatory to either of the United Nations Conventions on Road Safety or the African Road Safety Charter (UNECE, 2021).

From the standpoint of a road network infrastructure, the notion of road safety is not properly included in all levels of road project design and management. Designers, constructors, and road asset managers have minimal awareness of traffic safety due to their poor expertise (UNECE, 2021). The majority of roads in the country are currently two-way, two-lane, with numerous inconsistent roadway segments (such as poor or lack of traffic lights, which would be a significant issue for traffic safety, the lack of traffic signs and road markings, and geometric design constraints) (UNECE, 2021). But per the "Safer Systems" perspective, safer road design and road infrastructure construction have a significant impact on road safety, reduce the likelihood of traffic crashes, and thereby safeguard citizens' lives. Infrastructure should be consistent in design in order to decrease the crash frequency and injury severity, taking into account the incidence of road users' imperfection, and should meet the transportation demands of both motorized vehicles and vulnerable road users. However, Ethiopia's road safety and traffic management efforts are unable to keep up with the ever-rising crash frequencies and devastating conditions caused by imbalanced road network development and population and traffic flow increase (UNECA, 2009). Indicating the importance of significant attention by

Ethiopia's competent councils and ministries in establishing an effective strategy for safer road network development, efficient traffic and operational management, and better road user characteristics.

3.3. The burden of traffic crashes in Ethiopia

Ethiopia, alongside Bangladesh, Uganda, and Vietnam, is among the four countries of the world with insanely substantial traffic crash fatalities; it has more than 1,000 fatalities per 100,000 vehicles (Elvik et al., 2009). Every day in the national news media, there are terrible tales of traffic crashes and the resulting fatality, injury, and property damage.

In Ethiopia, the number and severity of traffic crashes have been increasing year over year, pointing to a major impact of traffic crashes on the country's economy, social, and communal health. According to the Ethiopian Federal Police Commission, there were 2,161 road traffic fatalities countrywide in 2007, which increased to 4,597 in 2018 with a more than doubling tendency (Federal Police Commission, 2011, 2019). In 2018, about 43 citizens were killed per 10,000 vehicles. As a result of underreporting and misclassification of deaths due to road traffic crashes, true fatality statistics may be substantially higher than those published by the Ethiopian Federal Police Commission. For illustration, in 2016, the WHO projected 27,326 traffic crash fatalities, a much more than six-fold increase above what the country's police reported in the same year such as 4,352 (WHO, 2018). This number should be evaluated in the context of the country's considerable underreporting of crashes, and it should be rectified.

Crash severity is increasing over time with the growth in the population, road network, vehicle number, and vehicle kilometers traveled. Between 2016 and 2018, the total number of fatalities in traffic collisions in Ethiopia was 14,194, the number of serious injuries was 22,647, and the number of minor injuries was 21,159 as a whole country (Federal Police Commission, 2019). This implies that almost 4,732 people are killed each year, or that 13 Ethiopians do not come back home every day, or that one person is killed on the roads every two hours as a consequence of traffic crashes (UNECE, 2021).

According to official road traffic collision data, passengers are the most vulnerable road users in Ethiopia, sharing for 52% of all road fatalities in 2018 (UNECE, 2021). Walking is the most common form of road transit in Ethiopia, both in urban and rural areas. In metropolitan locations, the majority of traffic collision casualties are pedestrians rather than motor vehicle occupants (UNECE, 2021). Walking, for example, constitutes 55-60% of total road transit in Addis Ababa (G.S. Tulu et al., 2013). The distribution of fatal crashes by road type; paved roads accounted for 79% of fatal crashes, while gravel and earth roads accounted for just 19%, with the remaining undetermined. In 2018, buses and commercial vehicles or trucks were concerned with a relatively higher number of crash fatalities, accounting for about 65% of all fatal crashes in the country (UNECE, 2021). Despite a worrisome increase in traffic crash frequency and severity, the government has not prioritized road safety as it does other industries. This might be due to a lack of expertise and weak leadership, as well as obstacles in obtaining long-term funding (UNECE, 2021).

CHAPTER 4

Crash Severity and Spatial Pattern Analysis

4.1. Introduction

Despite the fact that GIS's ability to incorporate severity, spatial pattern, and statistical analysis of traffic crash events and output the results as a single map for ease of comprehension, GIS is not commonly used in Ethiopia for crash data recording and detecting RTC hotspot locations. A GIS-based spatial analysis has been a promising and commonly utilized approach for identifying RTC hotspots (T. K. Anderson, 2009; Vemulapalli et al., 2017). A GIS-based hotspot analysis result is clearly provided on a single map with the relevant attribute data of each RTC, which may increase road safety experts' comprehension of the reasons for each crash occurrence (Le et al., 2019). This analysis aims to address a gap in the application of GIS to identify crash hotspots in Ethiopia and illustrate its applicability by utilizing four-year crash data from Ethiopian regions as well as zones and towns in Oromia.

4.2. Methods and Materials

4.2.1. Study Area and Data Collection

This research was carried out in Ethiopia to identify and prioritize Road Traffic Crash (RTC) hotspot regions, with a particular emphasis on the Oromia region (see *Figure 4*). RTC data of Ethiopia was obtained from the Ethiopian Federal Police Commission, traffic police division. The commission records crash data for all regions and federal territories. Crash data of four consecutive years (from 2014/15 to 2017/18) was used for crash severity analysis and hotspot identification. The Ethiopian Geospatial Information Agency (EGIA) provided a map of Ethiopia divided into regions and federal territories, as well as a map of the Oromia region, divided into zones and towns. In these maps, roadway networks and other important features were included as a shapefile.

4.2.2. Methods

For RTC hotspot identification, this study used the spatial statistics toolbox of ArcGIS 10.5. Supportive tools such as Google Earth and Google Maps were also utilized. For RTC hotspot identification, the procedure used in this study can be divided into the following steps:

i. Projecting the map;
ii. Computing the severity value of each crash;

iii. Analyzing the spatial pattern of RTCs to measure the fluctuating threshold distance of RTC clustering by using *Moran's I* index of incremental spatial autocorrelation tool; and
iv. Identifying and prioritizing highly clustered RTCs or hotspot zones. The detailed steps and the theoretical basis are discussed as follows.

The map utilized to locate crash hotspots was a Projected Coordinate System rather than a Geographical Coordinate System. The map dataset provided by the Ethiopian Geospatial Information Agency (EGIA) was in geographic coordinates. Since distance is one of the parameters evaluated in crash hotspot analysis (Tola & Gebissa, 2019a), the examined maps were projected in World Geodetic System WGS84 using the UTM (Universal Transverse Mercator) coordinate system.

4.2.2.1. Crash Severity

Crash hotspot zones are classified based on their severity index, in addition to crash rates. A single crash's weight is determined by the crash severity index. As a result, to accurately identify high or low clustering zones, the crash severity index must be included in hotspot analysis. Based on the expenditures, the crash severity index assigns higher values to more severe crashes. Numerous previous research used crash severity weights in crash hotspot analysis, for example, Geurts et al. (Geurts et al., 2004) used a Belgian government severity index with values of 5, 3, and 1 for fatal, serious injury, and slight injury, respectively. Because Ethiopia lacks a traffic crash costing platform for particular crash severity levels, the crash severity index developed by the Roads and Traffic Authority of New South Wales (NSW Road Safety and Traffic Management Directorate, 1999) was utilized in this study. In this system, each crash incident is provided a value of 3.0 for fatal, 1.8 for serious injury, 1.3 for slight injury, and 1.0 for property damage only crashes (*Equation 6*).

$$SI = 3.0 \cdot X_1 + 1.8 \cdot X_2 + 1.3 \cdot X_3 + 1.0 \cdot X_4 \tag{6}$$

where; SI is the severity index, X_1 is fatal crashes, X_2 is serious injury crashes, X_3 is possible injury crashes, X_4 is Property-damage-only crashes.

*4.2.2.2. Getis Ord Gi**

Spatial analysis using local spatial autocorrelation is preferred for identifying RTC hotspots. *Local Moran's I* is a well-known local spatial autocorrelation method that is frequently used in motor vehicle crash hotspot analysis (Mitra, 2009). The Moran indices, on the other hand, do not distinguish between hot and cold spots. Getis Ord *Gi** is thus more suited because it differentiates between clusters with high and low feature attribute values among local events. In this study, Getis Ord *Gi** statistics method was used to identify RTC hotspots.

*Gi** statistics devoted to investigating the existence of a spatial pattern for an arbitrary variable *X*, where a selected event (with a value of x_i) is autonomously connected to the field. As a result, if x_i is analogous to adjacent regions, it can be seen that variable *X* has spatial autocorrelation over area *i*. A simple form of *Gi** statistics is defined as *Equation 7*, which is derived by dividing the study zone into *n* indefinite extent of regions, each with accurate Cartesian coordinates and a central point *i* (*i=1, 2, 3… n*) (Getis & Ord, 2010).

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_i}{\sum_{j=1}^{n} x_j} \qquad 7$$

where; *Gi** is a statistic that describes the spatial dependency of feature *i*, x_j is the value of variable *X* at feature location *j*. w_{ij} is the spatial weight between feature *i* and *j*.

The conceptualized-spatial relationship around distance *d* (for instance Cartesian distance) is used to calculate w_{ij}. The result of *Gi** statistics may vary based on the choice of *d*. The value of d is a user-defined threshold. The most straightforward way to think about w_{ij} is in binary form, with 1 indicating inclusion and 0 indicating exclusion of the association between *i* and *j* events. However, w_{ij} can have non-binary values (as they did in this study), and the total weights (W_i) are expressed in *Equation 8*.

$$W_i = \sum_{j=1}^{n} w_{ij} \qquad 8$$

therefore the expectation of *Gi** is:

$$E\left(G_i^*\right) = \frac{W_i}{n} \qquad 9$$

where; *E(Gi*)* is the expectation of *Gi**, *n* is the total number of features and then the variance of *Gi** stated as:

$$Var\left(G_i^*\right) = \frac{s^2}{x} * \frac{W_i\left(n - W_i\right)}{n-1} \qquad 10$$

thus, the sample mean and variance for the variable *X* can be defined as in *Equation 11*.

$$\bar{x} = \frac{\sum_{j=1}^{n} x_j}{n} and; s^2 = \frac{\sum_{j=1}^{n} x_j^2}{n} - \bar{x}^2 \qquad 11$$

*Gi** statistics are generally standardized using the sample mean and variance for a normal asymptotical condition, as seen in Equation 12:

$$Z\left(G_i^*\right)=\frac{\sum_{j=1}^{n} w_{ij} x_j-\bar{x}\sum_{j=1}^{n} w_{ij}^2}{s\sqrt{\frac{n\sum_{j=1}^{n} w_{ij}^2-\left(\sum_{j=1}^{n} w_{ij}\right)^2}{n-1}}} \tag{12}$$

This standardized *Gi** statistics is a Z-score that corresponds to the statistical significance of each target location. The Getis Ord *Gi** hotspot analysis tool's null hypothesis is that crashes are occurred by Complete Spatial Randomness (CSR) or are distributed randomly. While running Getis Ord *Gi** statistics tool, the resulting Z-score and P-values will tell you whether to reject or accept the null hypothesis. The P-value for spatial pattern analysis is the likelihood that the observed crash incidents occurred arbitrarily. When the P-value obtained from the hotspot analysis tool is very small, it is very unlikely that the observed crash event occurred at random, and so the null hypothesis can be rejected. The tails of the typical normal distribution curve have extremely low P-values and extremely high absolute Z-scores. When the Z-score is closer to zero, it indicates that the spatial events in the region are distributed randomly. The maximum absolute values of *Gi** statistics, on the other hand, represent clusters of low-valued events for negative or high-valued events for positive.

The Getis Ord *Gi** hotspot analysis tool in ArcGIS incorporates the *Gi** statistics index to identify a significant hot/cold region based on nearby attribute values. Hotspots (regions with statistically significant positive Z-scores) are surrounded by neighbors with high feature values, whereas coldspots (regions with statistically significant negative Z-scores) are surrounded by neighbors with low feature values. A statistically significant Z-score is obtained if the local aggregate of the target area and its nearby values differs significantly from the expected local value to be random distribution.

The final statistical significance for hotspot identification has been adjusted by taking multiple testing and spatial dependency into account and has taken the form of *Equation 13*. This final equation is incorporated in ArcGIS' Getis Ord *Gi** hotspot analysis tool to identify and prioritize crash hotspots. Thus, the final form of statistical significance for hotspot identification (in *Equation 13*) was used in this study by running ArcGIS' Getis Ord *Gi** hotspot analysis tool.

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j - \left(\frac{\sum_{j=1}^{n} x_j}{n} \right) * \sum_{j=1}^{n} w_{ij}}{\sqrt{\frac{\sum_{j=1}^{n} x_j^2 - \sum_{j=1}^{n} x_j}{n}} * \sqrt{\frac{n \sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij} \right)^2}{n-1}}} \tag{13}$$

4.2.2.3. Spatial Autocorrelation

The distance methods adopted in the spatial planar analysis are Manhattan or Euclidean. The choice of conceptualization of the spatial connection of crash events in the analysis of spatial autocorrelation could be based on the understanding of the interactions among the features to be investigated. Fixed distance, inverse distance, inverse squared distance, K-nearest neighbors, the zone of indifference, the space-time window approach, and contiguity edges and corners are all ways to understand the spatial relationship between events. By applying Anselin *Local Moran's I* to aggregated traffic crashes, the result of the crash hot spot from global spatial autocorrelation and Getis Ord *Gi** can be enhanced (Erdogan et al., 2015). The choice of acceptable spatial correlations between features for use in local spatial autocorrelation analysis may aid in reflecting the distributional and spatial situation of definite target features (O'Sullivan & Unwin, 2010). In this study, the fixed distance method was used to conceptualize the spatial association between events.

The incremental spatial autocorrelation tool in ArcGIS 10.5 was used in this study to ascertain the fluctuating value of spatial autocorrelation as a distance threshold. The Global *Moran's I* index approach is used in this tool to estimate the distance bandwidth (i.e. the distance at which maximum crash events are clustered (Maingi et al., 2012)) throughout the entire area. The equations of *Moran's I* index (I), the expected value (*E[I]*), variance (*V[I]*), and Z-score (Z_Score) are presented in *Equation 14 to Equation 17* respectively:

$$I = \frac{n}{\sum_{i=1}^{n} \sum_{i=1}^{n} w_{i,j}} * \frac{\sum_{i=1}^{n} \sum_{i=1}^{n} w_{i,j} \left(x_i - \overline{X} \right) \left(x_j - \overline{X} \right)}{\sum_{i=1}^{n} \left(x_i - \overline{X} \right)^2} \tag{14}$$

$$E[I] = \frac{-1}{(n-1)} \tag{15}$$

$$V[I] = E\left[I^2 \right] - E[I]^2 \tag{16}$$

$$Z\_Score = \frac{I - E[I]}{\sqrt{V[I]}} \tag{17}$$

where; x_i is an attribute value of target feature at location i, x_j is an attribute value of neighboring feature at location j, w_{ij} is the spatial weight between features at location i and j.

A statistically significant Z-score (peaked) shows a critical distance threshold at which spatial autocorrelations are highly clustered. The first peak was used as the distance threshold in this study because it tends to best describe the spatial variation analysis and is recommended for use when there are multiple peaks (Blank et al., 2016).

4.3. Results and Discussions

This section presents crash fatality statistics as well as crash hotspot mapping results for Ethiopian regions and federal territories, as well as Oromia zones and special towns, followed by discussions.

4.3.1. Death rate and trend of traffic crashes in Ethiopia

The investigation was conducted over an eight-year (2010/11-2017/18) period to determine the trends in fatalities caused by RTCs in Ethiopia. According to crash data provided by the Ethiopian Traffic Police Commission, there were 2,541 fatalities as a result of traffic crashes in 2010/11 (the detail is shown in *Figure 5*). There was a slight increase in fatalities until 2013/14, then a significant increase in 2014/15, when the number of people killed in crashes shockingly reached 4,883. Even if a slight decrease was seen in 2015/16, it increased again, and finally, 5,118 deaths were recorded in 2017/18. As per the Ethiopian Roads Authority (ERA) (ERA, 2019), between 2009 and 2017, 77,980 kilometers of total roadways (asphalt and gravel) were newly constructed, with an annual growth rate of 13.08%. Despite the Ethiopian government's attempts to improve road users' access and mobility, the significant growth of motor vehicles was a contributing factor to the increase in traffic fatalities. The motor vehicle registration record of the Ethiopian Federal Transport Authority disclosed that in 2009 the number of vehicles in Ethiopia was about 276,794 in which had exceeded 831,000 motor vehicles in 2017 with an annual average growth rate of 15.28% (Federal Transport Authority., 2019). The Ethiopian Police Commission-Department of Traffic Police reported that the day-to-day increase of RTC fatalities caused by alcohol use has become their main concern. As previously stated, the reasons for the increase of fatalities may be attributed to a significant growth rate of motor vehicles relative to road networks (the road network's growth rate is 13.08%, while motor vehicles' growth rate is 15.28%) and alcohol consumptions of drivers. The detail of these trends is presented in *Figure 5*.

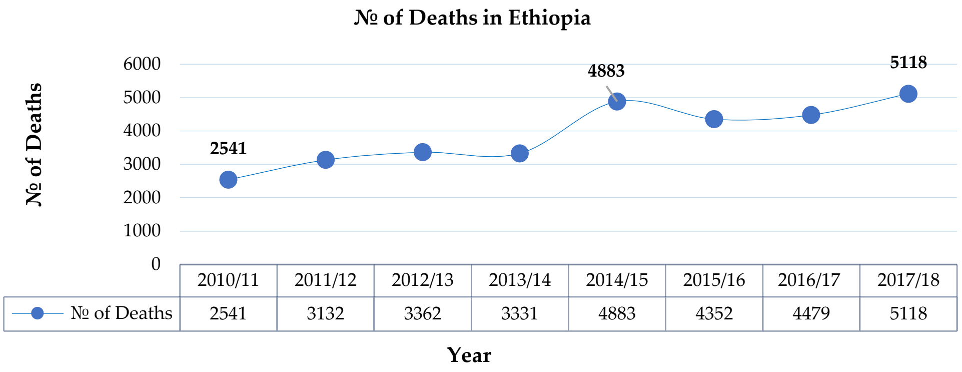


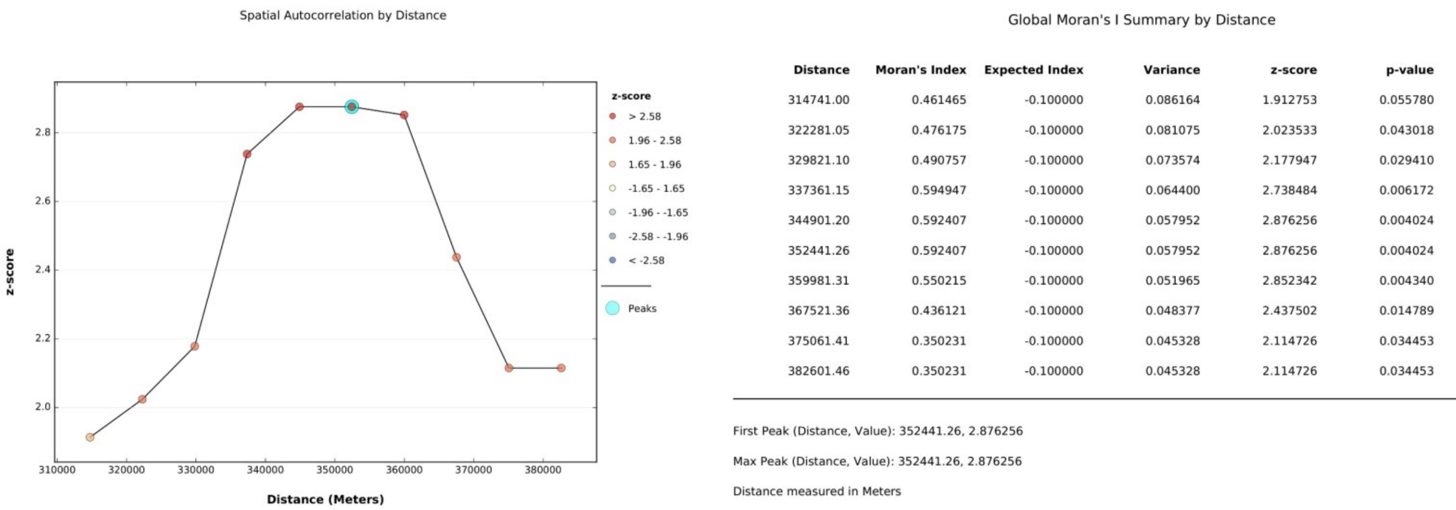
Figure 5: Number of crash fatalities recorded in Ethiopia from 2010/11-2017/18

4.3.2. Crash hotspot mapping of Ethiopian regions and towns

Crash hotspot analysis was performed at the regional level using a polygon feature dataset and the computed crash severity values from each region in the attribute table. The distance bandwidth was determined using ArcGIS's incremental spatial autocorrelation toolbox, and the results are demonstrated in *Figure 6*. The highest and first peak distance obtained from incremental spatial autocorrelation analysis was 352.441 kilometers, implying that RTC incidents are extremely clustered at a distance band of 352.441 kilometers with a statistical significance of 0.01 (the P-value obtained is 0.402% < 1%, noting a confidence level of 99 %). This value was used as the threshold distance in Getis Ord *Gi** crash hotspot mapping. As a result, crash hotspots in Ethiopian regions and federal territories were identified and ranked by taking into account the spatial patterns and spatial dependencies of crashes. *Figure 7* and *Table 1* depict the results of the Getis Ord *Gi** crash hotspot analysis.

Addis Ababa and the Oromia region were identified as crash hotspots, with confidence intervals of 99% and 95% respectively. Furthermore, two federal territories, 'Dire-Dawa' and 'Harari', were identified as low clusters of crash severity zones or cold spots with a 90% confidence interval. Crash hotspot zones are typically defined as densely clustered areas with a high concentration of pedestrians, traffic volumes, populations, and intersections. Ethiopia's capital city, Addis Ababa, was discovered as the first crash hotspot. Among numerous factors, the city's stress can be justified as a factor in this result. The city is home to the African Union (AU), the Economic Commission for Africa (ECA), and over a hundred (100) embassies from various countries. Ethiopia's financial and administrative capital city, Addis Ababa, is experiencing persistent growth and transformation. The city is transitioning from its current administrative center to a central business district and an industrial center. Because of all this transformation and rapid growth, there is an excessive transportation demand for the mobility of goods and people, as well as a higher attraction of people to the city, which has a population of 3.6 million in 2013 and is expected to increase to about 10 million by 2037 (World Bank, 2015). Whereas the city's efficient proportion of roadway infrastructures in land use demands 20% to 25%, the existing share is just 7% (Ethiopian Roads Authority (ERA), 2005), showing that the city's road transportation system is insufficient.

The city’s modernization, combined with an increase in motor vehicle ownership, increases the number of vehicles in the city; for example, of all registered motor vehicles in Ethiopia, 77% are found in Addis Ababa, with a yearly growth rate of 5.8% (Samson & Chandra, 2006). This rapid increase in motor vehicles (i.e., higher AADT) leads to higher crash rates in Addis Ababa. Moreover, even though walking (pedestrians) constitutes a significant portion of Addis Ababa's transportation modes, accounting for more than 60% of daily journeys (Getu Segni Tulu et al., 2017), the city's walking facilities are seen as inadequate. This high proportion of pedestrian road users in the city, combined with limited sidewalk facilities (such as crowded sidewalks, unpaved or inaccessible sidewalks), increases the number of pedestrian-related crashes. This is demonstrated by the fact that about 89% of the city's recorded crash causalities were pedestrian-related (World Bank Group, 2002).



Global Moran's I Summary by Distance

Distance	Moran's Index	Expected Index	Variance	z-score	p-value
314741.00	0.461465	-0.100000	0.086164	1.912753	0.055780
322281.05	0.476175	-0.100000	0.081075	2.023533	0.043018
329821.10	0.490757	-0.100000	0.073574	2.177947	0.029410
337361.15	0.594947	-0.100000	0.064400	2.738484	0.006172
344901.20	0.592407	-0.100000	0.057952	2.876256	0.004024
352441.26	0.592407	-0.100000	0.057952	2.876256	0.004024
359981.31	0.550215	-0.100000	0.051965	2.852342	0.004340
367521.36	0.436121	-0.100000	0.048377	2.437502	0.014789
375061.41	0.350231	-0.100000	0.045328	2.114726	0.034453
382601.46	0.350231	-0.100000	0.045328	2.114726	0.034453

First Peak (Distance, Value): 352441.26, 2.876256

Max Peak (Distance, Value): 352441.26, 2.876256

Distance measured in Meters

(a) (b)

Figure 6: (a) Result of spatial autocorrelation; (b) Attribute table result of spatial autocorrelation

Addis Ababa City, the first-ranked crash hotspot zone, has a radial-shaped road network with five major roadways radiating in and out of the city's central business and administrative district. All traffic flows entering and leaving the city via these five roadways pass through the

Oromia region, which was prioritized as the second crash hotspot area. High traffic volumes entering and leaving Addis Ababa have an impact on the Oromia region, which shares a common periphery on all sides with Addis Ababa (Finfinnee). Oromia was prioritized as the second hotspot due to higher traffic volumes, spatial dependence with Addis Ababa, larger size (inland coverage, roadway length, and population number), and unsustainable traffic management in the region.

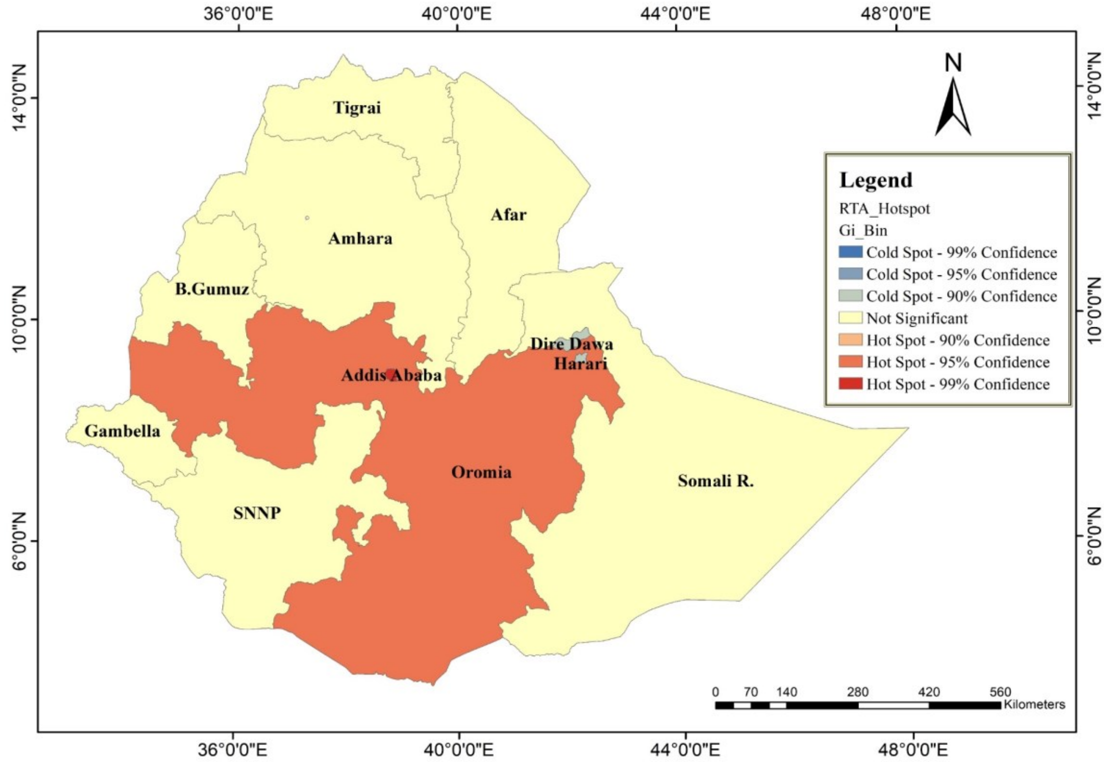


Figure 7: RTC Hotspot map of Ethiopia regions and federal territories

*Table 1: Crash Hotspot result of Getis Ord Gi**

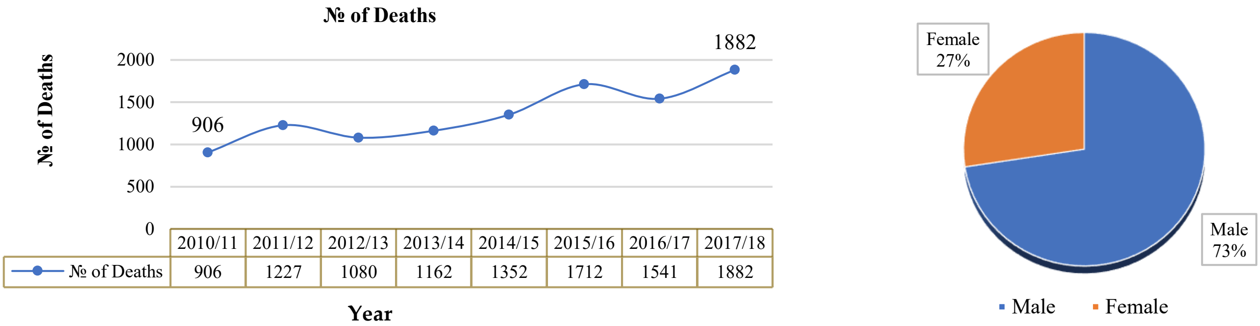
OBJ _ID	Crash Severity	Shape_L. (m)	Shape_A. (m^2)	GiZScore	GiPValue	NNeighbors	Region_Names
1	109518	106098	525638401	2.87230	0.00407	3	Addis Ababa
8	30661	6403850	355423484208	2.55848	0.01051	3	Oromia
9	11192	2806015	117263152867	0.85676	0.39158	3	SNNP
2	19831	2689742	153443579103	0.49482	0.62073	5	Amhara
11	8201	1580725	56451528629	-0.07804	0.93780	3	Tigrai
4	1477	1630480	48889173519	-0.54855	0.58331	3	B_Gumuz
6	845	908665	25649364273	-0.86238	0.38848	3	Gambella
3	1693	1920341	95242894663	-0.94792	0.34317	5	Afar
10	2179	3677531	278073581426	-1.40998	0.15855	3	Somali R.
5	2780	215410	1507085646	-1.77287	0.07625	4	Dire-Dawa
7	8201	93895	394011903	-1.77287	0.07625	4	Harari

4.3.3. Crash analysis of Oromia region

4.3.3.1. Fatalities due to RTCs in the Oromia region

According to crash data collected from the Oromia Traffic Police Bureau over eight years (2010/11-2017/18), fatalities caused by RTCs increased year after year. Notwithstanding population growth, the number of traffic fatalities more than doubled from 906 in 2010/11 to 1,882 in 2017/18 (see *Figure 8(a)*). According to the Ethiopian Federal Transport Authority, there has been tremendous expansion in motor vehicles in the Oromia region (Federal Transport Authority., 2019), which has a significant correlation with the increased fatalities. As per the Oromia's Traffic Police Bureau crash recording information (Oromia Traffic Police Bureau, 2019), denying priority for pedestrians pass, risky vehicle passing, driver's alcohol and drug consumptions, overspeeding, driver workload, insufficient vehicle following time, and vehicle mechanical problems are the recognized significant factors for the increasing number of crash fatalities in Oromia. This increase in crash fatalities in the region indicates the impact of road traffic crashes on the socio-economic well-being of the country as a whole and the Oromia region in particular. The Oromia transport bureau, traffic management, traffic police, road authority, and concerned governmental and non-governmental organizations should all work together to address this serious issue. *Figure 8(a)* depicts the number of RTC fatalities in the Oromia region over eight consecutive years.

Male fatalities were 2.7 times higher than females *(Figure 8(b))*. According to the population census commission's 2007 survey, the percentage of males and females in Oromia was nearly equal (Central Statics Agency, 2012); moreover, males accounted for 73% of the region's road traffic crash victims (*Figure 8(b))*. This can be explained by the fact that, in comparison to females, males have greater exposure to road transportation as drivers and passengers for a variety of reasons. For example, males are over-represented in professional driving careers (i.e. jobs in remote areas, operators, taxi, nighttime driving, and so on) and females are under-represented in self/paid employment or outdoor activities in Ethiopia (Quisumbing & Yohannes, 2005), which could reduce female vulnerability to RTCs. Furthermore, males are more likely than females to engage in risky driving behaviors such as careless overtaking, the use of alcohol, impatience, exceeding posted speed limits, and having a lower risk perception (Al-Balbissi, 2003; Cordellieri et al., 2016). As compared to females, males' higher use of two-wheeled motor vehicles and bicycles for transport can also affect their susceptibility to traffic crashes (J. L. Martin et al., 2004).



(a) (b)

Figure 8: (a) Total lives lost due to RTCs; (b) Percentage deaths (Female versus Male)

4.3.3.2. Crash severity

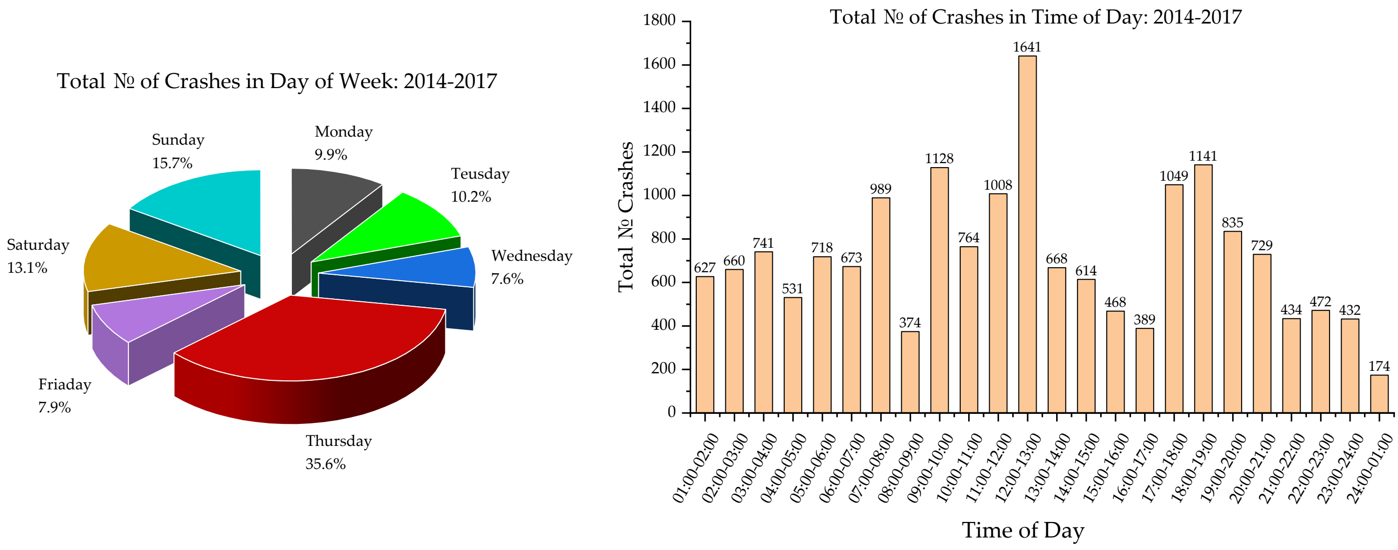
Table 2 shows that there were 17,259 traffic crashes in the Oromia region during the last four years, from 2014/15 to 2017/18.

Table 2: Four years traffic crash frequencies reported in their respective severity level

Year	Fatal	Serious Injury	Slight Injury	PDO	Total
2014/15	1310	901	1100	1722	5033
2015/16	1356	623	515	1446	3940
2016/17	1188	568	518	1626	3900
2017/18	1319	729	532	1806	4386
Percentage (%)	29.97	16.35	15.44	38.24	100

4.3.3.3. Crashes in the Day of Week and Time of Day

RTCs occur more frequently on Thursday and then on Sunday in a week and from 12:00 to 13:00, 18:00 to 19:00 and 09:00 to 10:00 in a day. I recommend that the Oromia region's traffic management, transportation authority, and traffic police bureau intervene and monitor traffic flows during peak crash days and times when a higher number of crashes are likely to occur. The details are demonstrated in *Figure 9*. Thursday is more likely associated with a market day in the Oromia region, when a large number of people may travel from place to place, and Sunday is an off-day, but most of the society and road users may prefer to consume alcohol, resulting in more traffic crashes. Crash rates were higher from 12:00 to 13:00 and 09:00 to 10:00 during the day, and these are the times when higher traffic flows are observed (peak hours), so the risk of RTC could be increased. Another critical time revealed was 18:00 to 19:00. This was most commonly related with nighttime crashes as a result of insufficient lighting for perception.

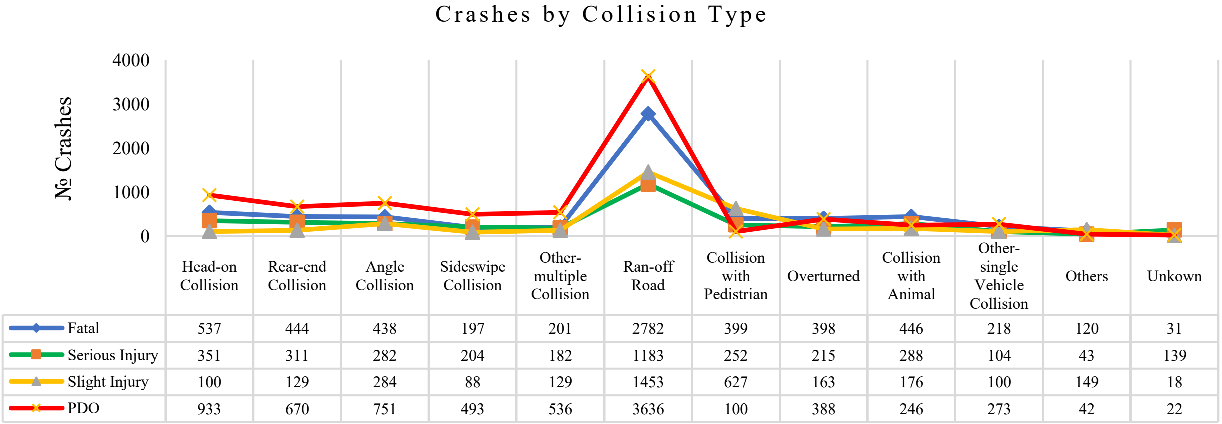


(a) (b)

Figure 9: (a) Crashes occurred in a day of the week: from 2014/15-2017/18; (b) Crashes occurred in the time of the day: from 2014/15-2017/18

4.3.3.4. Crashes by collision type

Collision types of '*Ran-Off-Road (ROR)*' were more likely to occur in Oromia, as shown in *Figure 10*. A run-off-road (ROR) collision occurs when a moving vehicle overturns on the inaccessible ground or exits the roadway and collides with an object. Over 95% of the critical reasons for ROR crashes were driver-related (Liu & Ye, 2011). The internal condition (i.e. heart attack or other health deficiency), driving too fast for over-compensation, speeding on curves, and napping or 'fatigued driving' were among the prominent driver-related factors that contributed to ROR crashes in descending order (Liu & Ye, 2011). However, a thorough investigation into the factors that contribute to the frequency of higher ROR collisions in the Oromia region is needed.



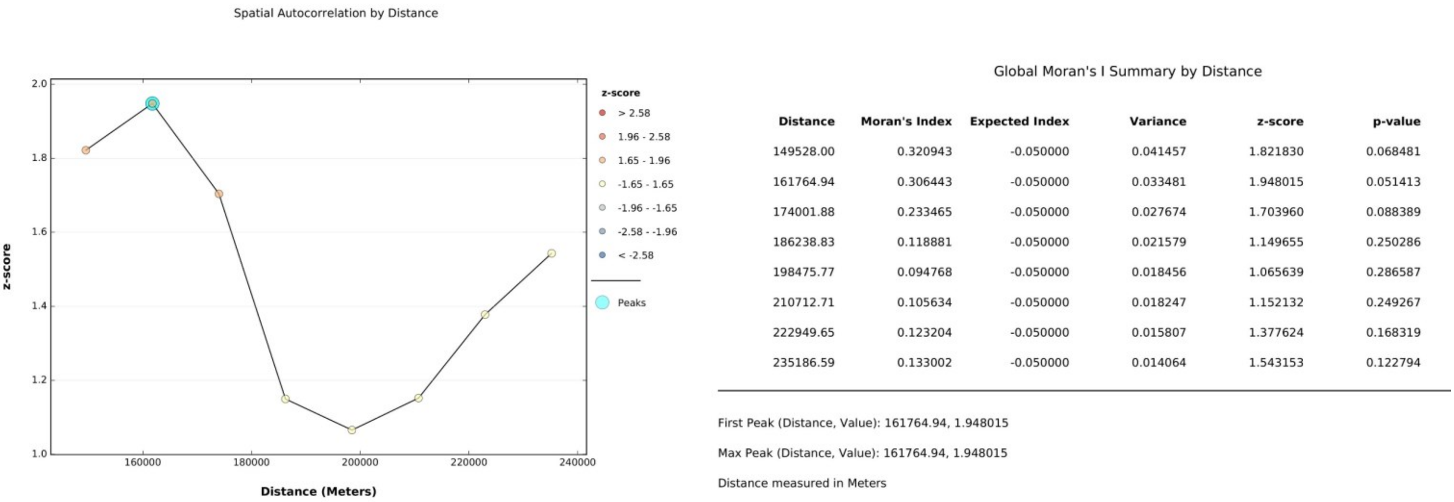
	Head-on Collision	Rear-end Collision	Angle Collision	Sideswipe Collision	Other-multiple Collision	Ran-off Road	Collision with Pedistrian	Overturned	Collision with Animal	Other-single Vehicle Collision	Others	Unkown
Fatal	537	444	438	197	201	2782	399	398	446	218	120	31
Serious Injury	351	311	282	204	182	1183	252	215	288	104	43	139
Slight Injury	100	129	284	88	129	1453	627	163	176	100	149	18
PDO	933	670	751	493	536	3636	100	388	246	273	42	22

Figure 10: Crashes analyzed by collision types: 2014/15-2017/18

4.3.3.5. Crash hotspot mapping

Moran's I spatial autocorrelation analysis results were used to estimate the threshold distance for identifying crash hotspots, the analysis result is illustrated in *Figure 11*. The Getis Ord *Gi** crash hotspot analysis threshold distance is the distance at which crashes are densely clustered. As a consequence, the Oromia region's incremental spatial autocorrelation study gave a threshold distance of 161.764 kilometers with a statistical significance level of 0.10 (such that the P-value obtained is 5.14% < 10% thus, the confidence level is 90%). *Figure 12* and *Table 3* show the results of Getis Ord *Gi** statistics for identifying crash hotspots in the Oromia region. Getis Ord *Gi** statistics' crash hotspot analysis identified six hotspots, which are listed in the attribute table's result (*Table 3*). The rankings were based on each zona's computed Z-score.

According to the findings, the East 'Shewa' (E. Shewa) zone and 'Burayu' town (Burayu T.) have the highest values of crash severity clusters and are ranked as priority crash hotspot areas across the Oromia region with a confidence interval of 99%. As noted previously, Addis Ababa has been linked to other cities by five radiating major roadways, which are locally named: 1) 'Ambo-Ber', 2) 'Tarma-ber', 3) 'Jimma-Ber', 4) 'Gojjam-Ber', and 5) 'Kality-Ber' or 'Bishoftu-Ber'. The estimated AADT for freight vehicles entering and leaving Addis Ababa is 10,725 and 12,890, respectively (Kebede & Gebresenbet, 2017). More than 70% of these incoming and outgoing freight vehicle shares have passed through Gate-5 (Bishoftu-Ber) (Kebede & Gebresenbet, 2017), which is located in the East Shewa zone, Oromia's first-ranked crash hotspot. 'Bishoftu-Ber' is also a major entry point for import and export freight trucks between Addis Ababa and the port of Djibouti. Thus, the East 'Shewa' zone has been demonstrated to have a higher crash rate, severity, and frequencies as a result of larger traffic volumes and freight trucks. As compared to others, the second crash hotspot zone, 'Burayu town', was mostly associated with poor roadway infrastructure (such as narrow lane width, deteriorated pavement, lack of pedestrian walkway, and so on).



Global Moran's I Summary by Distance

Distance	Moran's Index	Expected Index	Variance	z-score	p-value
149528.00	0.320943	-0.050000	0.041457	1.821830	0.068481
161764.94	0.306443	-0.050000	0.033481	1.948015	0.051413
174001.88	0.233465	-0.050000	0.027674	1.703960	0.088389
186238.83	0.118881	-0.050000	0.021579	1.149655	0.250286
198475.77	0.094768	-0.050000	0.018456	1.065639	0.286587
210712.71	0.105634	-0.050000	0.018247	1.152132	0.249267
222949.65	0.123204	-0.050000	0.015807	1.377624	0.168319
235186.59	0.133002	-0.050000	0.014064	1.543153	0.122794

First Peak (Distance, Value): 161764.94, 1.948015

Max Peak (Distance, Value): 161764.94, 1.948015

Distance measured in Meters

(a) (b)

Figure 11: The spatial autocorrelation of Oromia in (a) Graph and (b) Attribute table

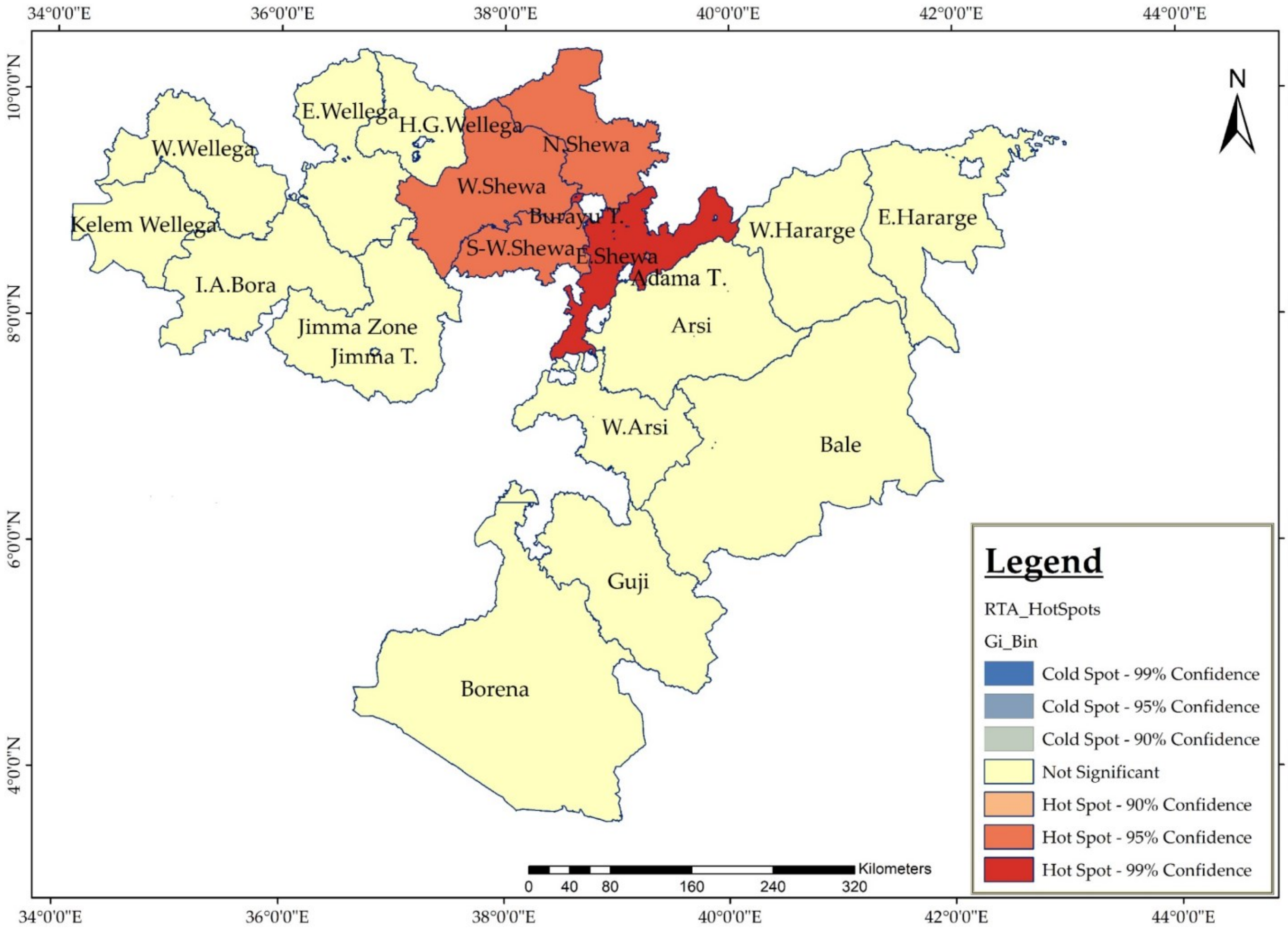


Figure 12: Crash hotspot map of Getis Ord Gi statistics of Oromia region*

*Table 3: The attribute of crash Hotspot result of Getis Ord Gi**

OBJ_ ID	Crash Severity	Shape_L. (m)	Shape_A. (m^2)	GiZScore	GiPValue	NNeighbors	Zone_Names
7	1520	1269948	9892678054	2.90573	0.00366	8	E.Shewa
20	429	60226	85906978	2.80042	0.00510	7	Burayu T.
6	1501	913429	11530834348	2.13166	0.03303	7	N.Shewa
5	1488	1577743	14806415071	2.01316	0.04410	7	W.Shewa
15	712	25993	29858260	2.01316	0.04410	7	Adama T.
13	1154	681347	6508288032	2.00548	0.04491	8	S-W.Shewa
19	149	756608	8097272756	1.59692	0.11028	5	H.G.Wellega
17	885	1080199	11776723820	1.31245	0.18937	4	W.Arsi
10	1155	1390038	18239926953	0.80006	0.42367	2	E.Hararge
9	724	768631	16523003204	0.73969	0.45949	4	W.Hararge
8	798	909816	20696957154	0.41390	0.67895	7	Arsi
4	634	1009026	18075624315	-0.19253	0.84733	5	Jimma_Zone
2	597	980901	13830420375	-0.19309	0.84689	6	E.Wellega
14	649	985714	18577054735	-0.43489	0.66364	3	Guji
16	303	38118	50520944	-0.72780	0.46674	3	Jimma_City
12	246	3121707	45463584611	-0.82827	0.40752	2	Borena
18	352	642890	9851170119	-0.83608	0.40311	3	Kelem_Wellega
1	507	892523	12744967754	-0.86970	0.38446	4	W.Wellega
3	632	999481	16516931736	-1.24901	0.21166	6	I.A.Bora
11	218	1434621	44912392310	-1.49546	0.13479	3	Bale

4.4. Conclusions

The primary goal of crash hotspot mapping is to answer a critical question in road safety practice: where are the hazardous spots located? This inquiry is addressed scientifically by studying the spatial pattern and severity of crashes. The advantage of using advanced GIS-based hotspot analysis is not limited to the simple presentation of hazardous roadway areas; it also provides the ability to investigate the spatial dependency of crash incidents and spatial connections with other factors. For the past five decades, a GIS application in the field of traffic safety has aided in the advanced realization of crash characteristics, which is then used as a piece of information to improve traffic safety.

The objective of this chapter was to demonstrate a GIS application for identifying and evaluating statistically significant spatial patterns based on crash frequency and severity. Crash hotspots were identified based on the severity of the crashes applying the integration of spatial autocorrelation of crashes and Getis Ord *Gi**. Spatial autocorrelation provides the added benefit of allowing statistical analysis of crash spatial patterns. *Gi** statistics' ability to distinguish high crash clusters from low crash clusters makes them a better technique for finding crash hotspots than *Moran's I* index. Rather than the overall frequency of crashes, crash counts and severity values were used in this analysis.

Following an evaluation of crash spatial autocorrelation, *Gi** statistics were used to identify high and low crash severity clusters. The first crash hotspot identification study result for all Ethiopian regions and federal territories revealed Addis Ababa and Oromia region as high crash severity clusters, with confidence intervals of 99% and 95%, respectively. Second, by combining spatial autocorrelation with *Gi** statistics, six statistically significant crash hotspots in Oromia were identified. The quantitative results of Z-Scores highlighted East 'Shewa' zone and 'Burayu' town as the most crash hotspots with a confidence level of 99%. The six identified crash hotspot zones and towns are all located around the entrance to Addis Ababa, Ethiopia's capital city. Five major routes connect Addis Ababa to other towns, zones, and regions, and all of these linking roads pass through the identified crash hotspots in Oromia. It can be concluded that the identified crash hotspot locations are along the entrance and exit of Addis Ababa city; thus, the responsible bodies and traffic management agencies should give these areas top priority and conduct a thorough study in order to reduce the socio-economic impact of traffic crashes.

The study’s findings confirmed that the used approach of crash hotspot identification can evaluate spatial patterns of crashes and identify highly clustered crash severity with statistical significance. The study found that adopting GIS in Ethiopia has a considerable advantage when it comes to identifying promising spots for safety improvements. Thus, the use of GIS in crash hotspot analysis must be investigated and employed as a tool for road safety research in Ethiopia in the future.

CHAPTER 5

Developing Jurisdiction-Specific Crash Distribution Dataset

5.1. Introduction

As previously discussed (in *Literature Review*), roadway designs and evaluations based on the predictive approach of Safety Performance Function (SPF) or CPM is an effective and economically feasible method with a limited budget. This predictive technique serves as the foundation for the HSM's *Part C*. However, driving behavior, roadway characteristics, the environment, weather conditions, and other scenarios differ significantly between Ethiopia and the states used to develop HSM. Thus to ensure accurate and consistent crash predictions, the SPFs and Crash Distribution Datasets (CDDs) of HSM must be calibrated to Ethiopian conditions. Appendix A of the manual outlines the HSM calibration procedures (AASHTO, 2010). "*To exercise the full potential of IHSDM for a realistic and reliable estimate of crashes for local roads with certain geometric and traffic characteristics, the tool needs to be adjusted and calibrated*" (Qin et al., 2013b). An appropriate calibration is capable of inferring the difference between the jurisdictions' crash prediction models as well as local crash histories. Calibrating the crash prediction model of IHSDM is fundamentally the same as calibrating the predictive approach of HSM.

The main objective of the current scientific study is to evaluate the effectiveness of developing a fixed jurisdiction Crash Distribution Dataset (CDD) using the locally collected crash data on rural two-way two-lane roads. To meet the study's objective, both the HSM's default values and the developed Oromia's-fixed CDDs have been compared for the trustfulness of crash predictions in terms of crash distribution. Thus, for the evaluation of the estimates by the developed local CDDs, the study presumes taking the default SPF models and CMFs (or with a calibration value of 1.0) of HSM in crash prediction analysis.

5.2. Study area and dataset

5.2.1. Study area description

For many decades, the safety problems on rural roads have been a principal issue globally. From the overall roadway safety issues, a significant share has been taken by rural roads. For instance, according to data from Organization for Economic Cooperation and Development (OECD), the "*average fatal crash rates per vehicle kilometer can be up to 6 times higher on 2-lane rural roads than on motorways*" ("Towards Zero: Ambitious Road Safety Targets and the

Safe System Approach,” 2008). Even though crash rates or the number of crashes in urban roadways are higher than in rural roads; due to higher traffic flows and the number of intersections, rural road crashes are more severe than urban ones. Poor roadway characteristics, reduced traffic enforcement, riskier roadside hazard ratings, and higher operating speeds on rural roads are the main factors that increased crash severity as compared to urban roads (Oxley et al., 2004). Thus, improving traffic safety on rural road segments is the prime most duties of safety engineers. The current study was done in the Oromia region focusing on undivided rural two-way two-lane roads. The study area is shown in *Figure 4*.

5.2.2. Data preparation

The procedures for data collection and preparation for analysis are described in this section. The study was carried out using primary data collection and other supplementary information. To acquire the study objectives, the requested data, which are crash data and highway data (i.e. horizontal and vertical alignments, roadway cross-section, and traffic volume), were collected and these are outlined as follows.

5.2.2.1. Crash data

Crash data on rural two-way two-lane roads were collected from the Oromia Traffic Police Bureau for the development of a fixed Oromia’s CDD. Furthermore, two years of observed crash data from 2017/18 to 2018/19 were used for validation and comparison of the developed CDD prediction. Crashes on one-way and divided roadways were omitted in order to extract crashes that occurred on undivided rural two-way two-lane roads (*Table 4*).

The KABCO scale is a severity level used in both the HSM and the IHSDM predictive method to classify various crash types. The five KABCO's severity levels are K: Fatal injury, A: Incapacitating Injury, B: Non-incapacitating Injury, C: Possible Injury, and O: No Injury crashes (PDO) (AASHTO, 2010). In Oromia, however, there are only four crash severity levels such as; Fatal, Serious Injury, Slight Injury, and Property Damage Only (PDO). This means that while IHSDM has three severity levels (ABC), Oromia only has two (Serious Injury and Slight Injury). To make the computation easier, the percentage of C (Possible injury) for Oromia's crash data has been set to zero. This implies that the Oromia injury crashes (Serious Injury and Slight Injury) are assumed to be comparable to their equivalent IHSDMs injury crashes (Incapacitating injury, Non-incapacitating injury, and possible injury).

The nine collision types in HSM are *Collision with Animals*, *Collision with Bicycles*, *Collision with Pedestrians*, *Overturned*, *Run-Off-Road*, *Angle Collision*, *Head-on Collision*, *Rear-end*

Collision, and *Sideswipe collisions*. Except for *Collisions with Bicycles*, all collision types are available and were obtained from the Oromia Traffic Police Bureau. The cumulative crash data (2010/11-2016/17) obtained from Oromia Traffic Police Bureau is presented in *Table 4*.

Table 4: Aggregated crash data by roadway types: From 2010/11-2016/17

Roadway Type	Fatal	Serious Injury	Slight Injury	PDO
One-way *(A)*	2334	1206	1427	2542
Two-way Undivided *(B)*	2724	1591	1704	2968
Divided *(C)*	1525	836	1147	2970
Painted with Passing Restricted *(D)*	907	604	534	1799
Broken-line Painted *(E)*	319	666	505	1494
Total for Undivided Rural Two-way Two-lane *=B+D+E*	3950	2861	2743	6261

5.2.2.2. Highway data

The essentials among the required data for Crash Prediction Model (CPM) evaluation are highway geometric data (i.e. horizontal curve data and tangents, vertical curves and grades, and roadway cross-sections) and general highway environments (i.e. terrain types, traffic volume, and design/posted speeds). The Ethiopian Roads Authority (ERA) provided the as-built geometric design and general roadway conditions for the road from 'Addis Ababa' to 'Chacha' for comparison and validation of the CDD prediction. The road was selected based on the availability of data. Rural and urban/suburban roads have been distinguished based on the cross-section types and demographics of rural and urban areas. As a result, twelve undivided rural two-way two-lane road sections (*71.03km*) are identified as undivided rural two-lane roads and their geometric design and surrounding conditions have been imported to IHSDM. IHSDM provides several options to import or create highway alignments, from these IHSDM users:

- Can manually enter roadway data using Highway Editor Tool,
- Can import highway alignment using CSV (comma separated values) format,
- Can import highway data in LandXML format from other software (i.e. MX-Road, Geopak, AutoCAD Civil 3D, and others).

The geometric data of the isolated twelve undivided rural two-way two-lane highways on the road from 'Addis Ababa' to 'Chacha' were imported into IHSDM using *AutoCAD Civil3D* software.

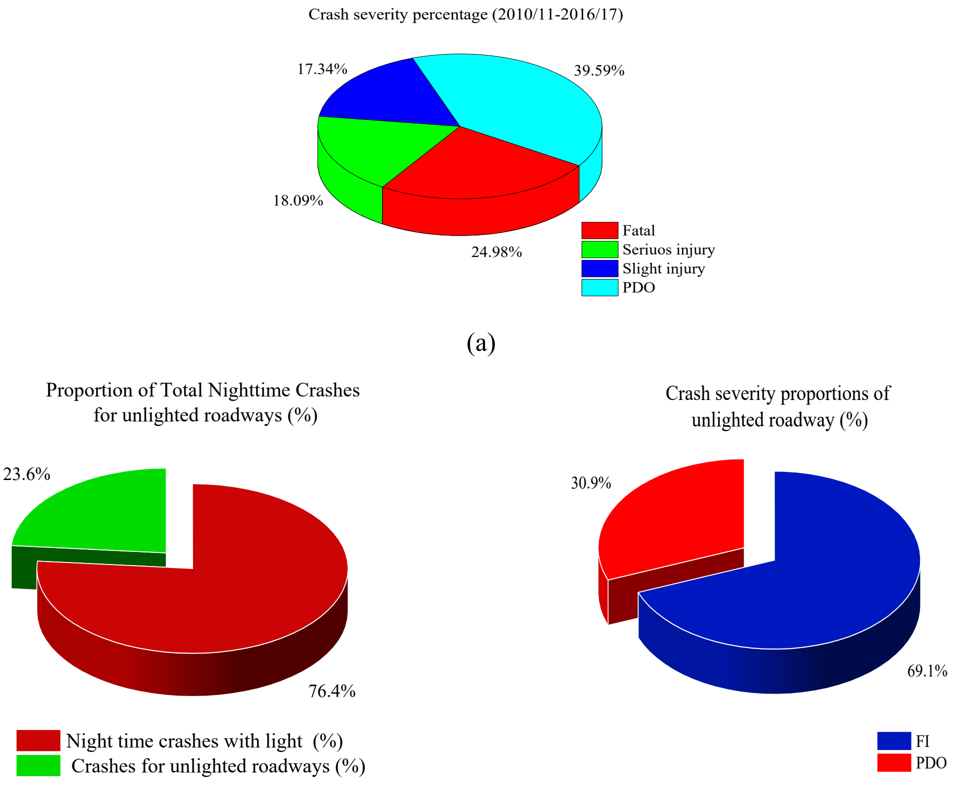
5.3. Methods

The goal of this study is to develop a jurisdiction-specific CDD using crash data collected on rural two-way two-lane roadways in the Oromia region. HSM *Appendix C* lists five sets of default CDDs for rural two-way two-lane roads that HSM users should modify (AASHTO, 2010). These are *i)* Crash severity proportions, *ii)* Collision type proportions, *iii)* The ratio of driveway-related crashes to overall crashes of roadway segments, *iv)* Nighttime crash proportions of roadway segments, and *v)* Intersection nighttime crash proportions. Except for intersections' nighttime crash proportions, all of the above-listed default crash distribution datasets were updated in this study, and a fixed crash distribution dataset for the Oromia region was finally developed. The study validated the developed CDD estimates using HSM's default SPF and CMFs.

5.3.1. Crash Distribution Dataset, CDD: Development

A seven-year (2010/11-2016/17) crash data of the Oromia region was used to compute the crash severity percentages, which were divided into four severity categories; Fatal (F), Serious Injury (SeI), Slight Injury (SI), and Property Damage Only (PDO). The computed result is presented in *Figure 13(a)*. According to the findings, Fatal plus all Injury crashes (F+I) that were occurred in Oromia are higher, accounting for 60.41% of all crashes, while the default HSM values based on crash data from the states used to develop HSM are 32.10%. This demonstrates that the crashes in the Oromia region were more severe as compared to the HSM crash severity proportion. To determine the nighttime crash proportion, crashes that occurred at night on unlit roadways were treated as nighttime crashes on unlighted roadways. *Figure 13(b) & Figure 13(c)* show the computed proportion of total nighttime crashes on unlighted roadways, as well as the severity proportion of unlighted roadway crashes, based on seven years of crash data in the region.

The Collision type proportion and percentages of driveway-related (*Run-Off-Road*, *Head-on Collision*, and *Sideswipe*) crashes were determined by omitting '*others*' and '*unknown*' collision types documented by traffic police officers. *Table 5* illustrates the aggregated percentage results of all collision types and the percentages of driveway-related crashes by summing the percentages of *Run-Off-Road*, *Head-on Collision*, and *Sideswipe Collision* based on seven years of crash data.



(a)

(b) (c)

Figure 13: (a) Total crash severity percentage (b) Nighttime crash proportion on unlighted roadway (c) Unlighted roadway crash severity percentage (Note: FI is Fatal plus all Injury crashes and PDO is property damage only)

5.3.2. CPM evaluation

The IHSDM software's Crash Prediction Module was used to validate and compare the crash prediction values of the default HSM CDD with the developed Oromia region's CDD. IHSDM is a tool developed by the Federal Roadway Administration (FHWA) that has been used to evaluate the safety and operational effects of highway geometric designs since 1993 (FWHA, 2019). The software was released to the public for the first time in 2004; since then, it has been made freely available to safety practitioners and can be downloaded from the www.ihsdm.org website. The IHSDM used in this study was a version of the 2020 release (*version of 16.0.0*).

Table 5: Collision type proportion and percentage of driveway related crashes

Collision Type	Percentage (%)		Percentage of Total (All Severity levels combined) (%)	The proportion of total crashes constituted by Run-off-the-road, Head-on collision, and Sideswipe (%)
	Fatal + Injury	PDO		
Collision with Animal	5.40	3.10	4.49	
Collision with Pedestrians	13.15	0.88	8.31	
Run-Off-Road	47.87	52.93	49.87	49.87
Overturned	4.76	10.01	6.83	
Other-single Vehicle Collision	2.72	2.82	2.76	
Total Single-Vehicle Crashes	73.91	69.74	72.27	
Angle Collision	5.96	5.08	5.61	
Head-on Collision	5.11	8.72	6.54	6.54
Rear-end Collision	6.67	8.08	7.22	
Sideswipe Collision	4.25	3.88	4.10	4.10
Other-multiple Collision	4.10	4.49	4.25	
Total Multiple-Vehicle Crashes	26.09	30.26	27.73	
Total Crashes	100.00	100.00	100.00	60.51*

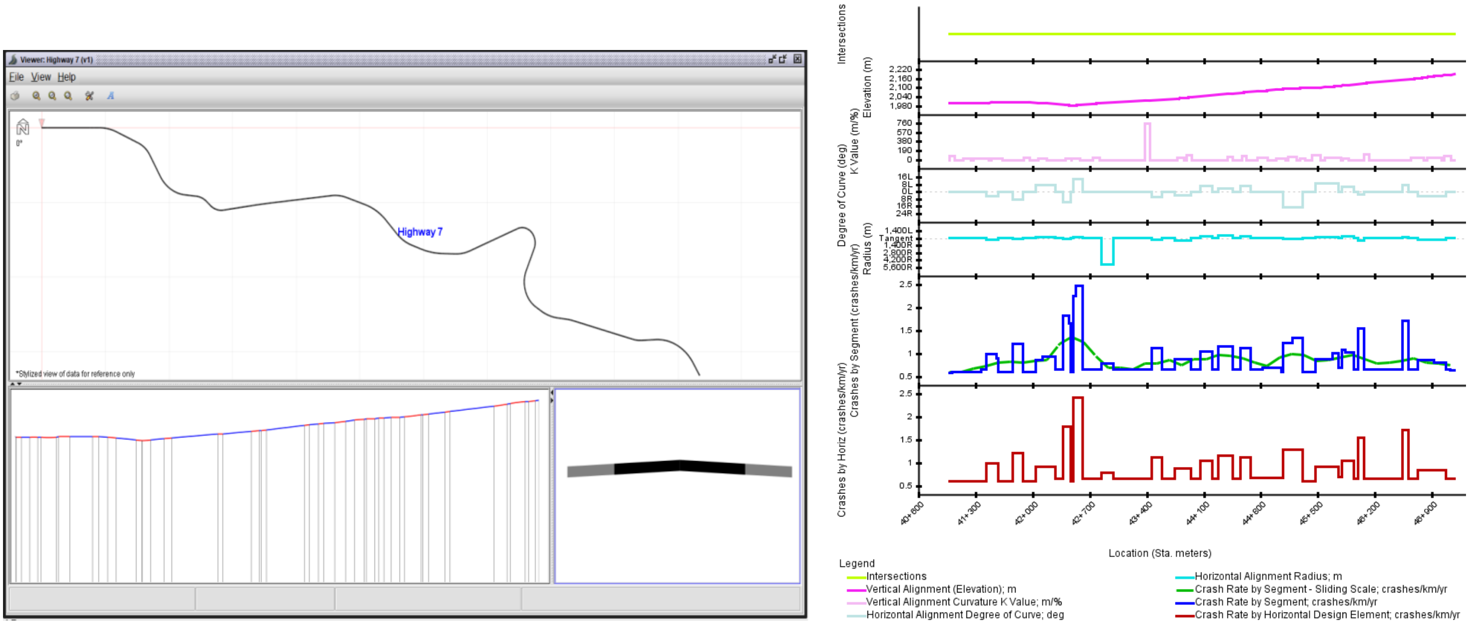
*total collisions constituted by three collision types (i.e., Run-off-the-road, Head-on Collision, and Sideswipe), not the overall collision type. This is computed based on the model developed in HSM as well as IHSDM's CPM.

The computed crash severity, nighttime crashes for the unlighted roadway, collision type, and total driveway-related crash proportions of the Oromia region were developed on the *Administration Tool* of IHSDM software as part of a calibration procedure. In addition, the AASHTO default policy was substituted by the ERA (Ethiopian Roads Authority), 2013 superelevation policy on the IHSDM *Administration Tool*. The comparison and validation of the developed CDD prediction and that of the default HSM's had been carried out by running CPM of IHSDM software. The rural two-way two-lane highway data from *'Addis Ababa'* to *'Chacha'* (which is 71.03km in length) was evaluated for the analysis period of two years (2017/18 to 2018/19) by using both the developed and default HSM's crash distribution dataset. Finally, their crash distribution predictions were compared and validated against the observed crash data.

5.4. Results and Discussions

5.4.1. CPM Evaluation

IHSDM's CPM evaluation was executed for all twelve rural roads imported into IHSDM software, and it was then segregated into 508 homogeneous roadway segments (roadway sites with similar characteristics) using the HSM's homogeneous roadway segregation. Out of the twelve highways evaluated, *Highway-7* is presented in this section as an illustration of CPM evaluation results for the developed CDDs. Crash prediction evaluation report of IHSDM for *Highway-7* on Addis Ababa to Chacha road is presented in *Apendix-A* for both HSM and Oromia configurations. The exported geometric data (i.e. the horizontal alignment, vertical alignment, and cross-section) and CPM summary of *Highway-7* are presented in *Figure 14*. For an evaluation period of two years (2017/18 to 2018/19), the IHSDM's CPM evaluation result of *Highway-7* (shown in *Figure 14(b)*) is interpreted as follows: A total of 10.64 crash frequencies are predicted over a 6.19km length. The highest crash rate, as evaluated by highway segment, is located between stations *42+531.139* and *42+613.424*, with a predicted crash rate of 2.4743 crashes/km/yr, also the highest crash rate, as measured by horizontal design element, is found at simple *curve #5* (*42+500.015* to *42+613.424*). This means that in the assessment of *Highway-7*, the station from *42+500.015* to *42+613.424* (or simple *curve # 5*) requires special treatment for crash reduction (a road segment with safety issues in design).



(a) (b)

Figure 14: Highway-7 (a) geometry (b) crash prediction summary

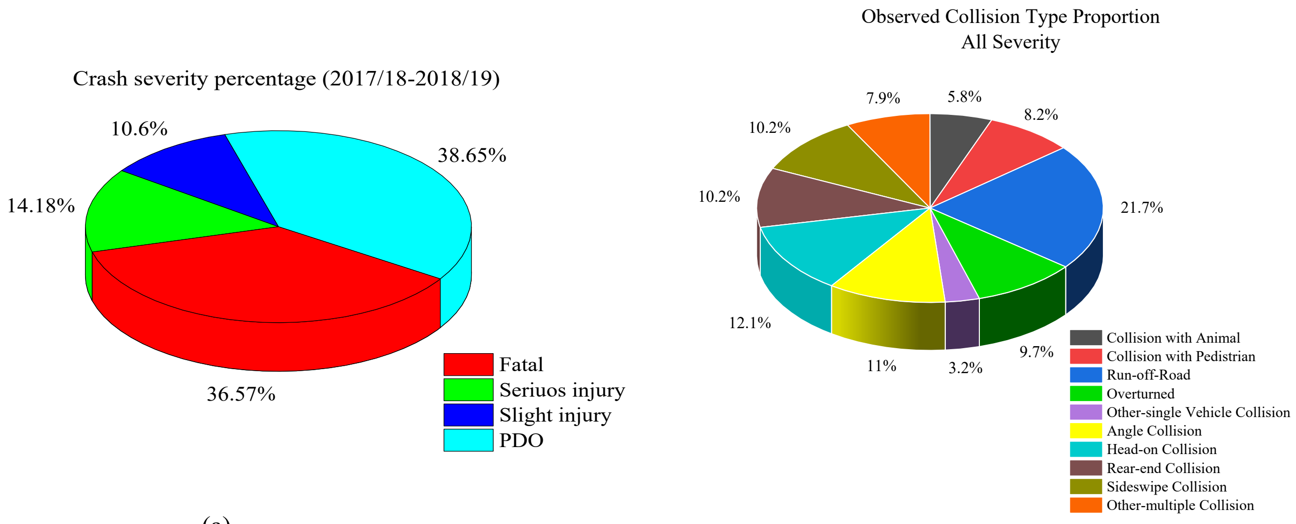
Table 6: Overall crash frequencies by collision type

Cumulative predicted crash frequency (All Severity)			
No.	Collision type	Oromia Configuration	HSM Configuration
1	Collision with Animal	4.54	12.23
2	Collision with Bicycle	None	0.21
3	Collision with Pedestrian	8.41	0.29
4	Head-on Collision	6.62	1.62
5	Other Multiple-vehicle Collision	4.29	2.74
6	Other Single-vehicle Collision	2.77	2.11
7	Overturned	6.89	2.54
8	Rear-end Collision	7.29	14.37
9	Angle Collision	5.67	8.6
10	Run-Off-Road	50.41	52.68
11	Sideswipe	4.16	3.74
12	Total Multiple Vehicle Crashes	28.03	31.04
13	Total Single-Vehicle Crashes	73.07	70.09
14	Total Highway Segment Crashes	101.08	101.13

The CPM evaluation of IHSDM was done individually for each of the twelve rural roads, using the same evaluation period and procedure as *Highway-7*. The developed CDD, as well as the default HSM configuration, were used to predict crash proportions, and the final summated crash frequency results for all highways are exhibited in *Table 6* and *Table 7*, in their respective CDDs. *Table 6* summarizes the predicted crash frequencies of all highways based on collision type, whereas *Table 7* shows the predicted crash frequencies of individual highways based on severity type. Run-off-Road collision types were more common in both states, such as Oromia and states used to develop HSM crash configuration.

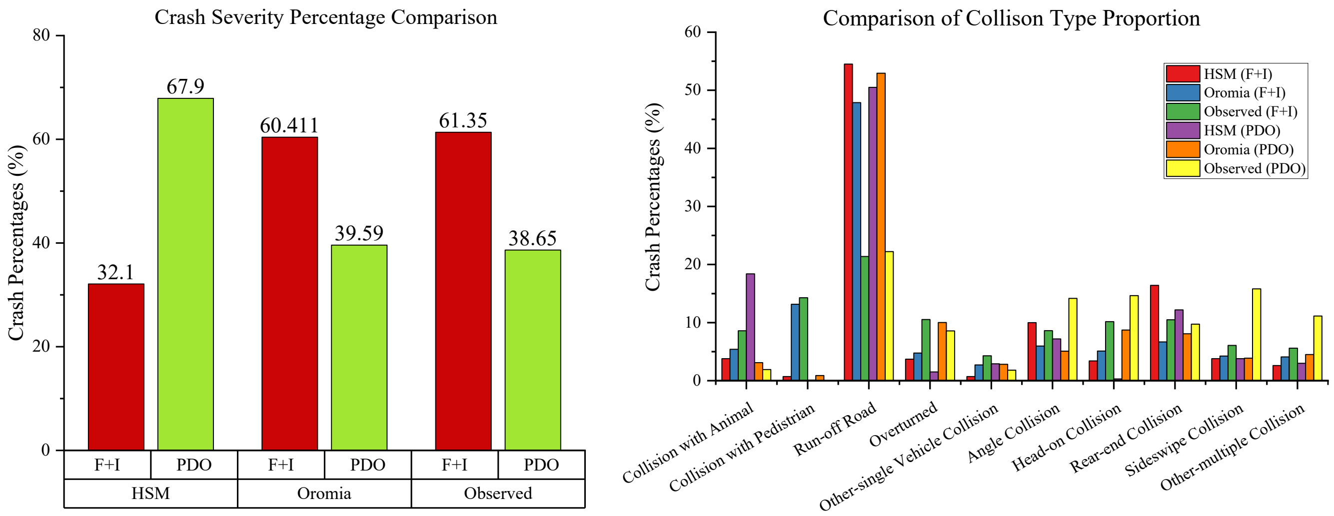
5.4.2. Comparison and Validation for the estimates of CDDs

The observed crash data from 2017/18 to 2018/19 have been documented on the Administration tool of IHSDM to compare and validate the developed crash distribution dataset prediction. Crash severity percentages and collision type proportions of the observed data are illustrated in *Figure 15*. *Figure 16* compares the developed, HSM, and observed crash distribution datasets in terms of crash severity percentage and collision type proportion. Based on this comparison, the developed and observed crash severity percentages are much closer, whereas the HSM crash severity percentage has significantly deviated from the observed.



(a) (b)

Figure 15: The (a) observed crash severity proportions (b) observed collision type proportion for all severity types



(a) (b)

Figure 16: The comparison of (a) crash severity percentage (b) collision type proportion

Goodness-of-fit statistics, such as Mean Absolute Difference, *MAD* and Symmetric Mean Absolute Percentage Error, *SMAPE*, as given in *Equation (18)* and *Equation (19)* were used to compare and validate crash distribution predictions from both the default HSM and the developed Fixed-Oromia's CDDs. The closer the MAD and SMAPE values are to zero, the more accurate the CDD prediction is in relation to the observed data. For both crash severity proportions and collision type distributions, the prediction accuracy of the default HSM configuration and that of the developed has been quantified. The results are exhibited and discussed as follows.

$$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|Y - \bar{Y}\right| \tag{18}$$

$$SMAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|Y - \bar{Y}\right|}{Y + \bar{Y}} * 100 \tag{19}$$

where Y is the observed value and $\bar{Y}$ is the predicted value

5.4.2.1. Crash severity percentage

Table 7 summarizes and presents the crash severity percentages of all highways predicted by the IHSDM crash prediction model for the developed and default HSM configurations. In addition, for comparison, the observed crash severity percentage data is included in the table. Whenever the observed crashes for a specific site are known, a calibration factor, C_x in *Equation (20)*, can be computed. The calibration factor for Fatal plus all Injury crashes (F+I) calculated using *Equation (20)* was *1.018* for the developed configuration and *1.915* for that of the HSM. Both configurations underpredict Fatal and Injury crashes (F+I), with the Oromia configuration underpredicting in 1.8% and the HSM configuration underpredicting in 91.5%. These calibration factor computations show that the developed configuration outperforms the HSM in terms of predicting crash severity percentage.

$$C_x = \frac{\sum N_{Observed}}{\sum N_{Predicted}} \tag{20}$$

Where C_x is a calibration factor, $N_{Observed}$ is the observed crash proportion and $N_{Predicted}$ is the predicted crash proportion.

Aside from calibration factor computations, goodness-of-fit statistics were used to compare and validate the developed crash distribution estimates in terms of severity type. As detailed in *Table 8*, the resulted *MAD* and *SMAPE* goodness-of-fit statistics show that the developed Oromia's crash distribution dataset predicts both FI and PDO crash severity proportions more accurately than the HSM. For FI crash estimates, the developed configuration yielded a *MAD* of 0.09, which is much closer to zero than the HSM configuration, which yielded a *MAD* of 2.4742. Similarly, the developed configuration had a *SMAPE* of 0.9199% for FI prediction, while the HSM configuration had a higher *SMAPE* of 31.4488%, which is too far from zero. The efficacy of the developed crash distribution dataset to predict severity percentages in the study area was proven by the goodness-of-fit statistics employed in this study.

Table 7: *Crash severity proportions summarized by highway number*

Highway No.	Length (Km)	Severity type	Observed	Oromia Configuration	HSM Configuration
1	3.7	All	5.09	5.08	5.08
		FI	3.12	3.07	1.63
2	2.275	All	4.1	4.09	4.09
		FI	2.52	2.47	1.31
3	0.95	All	1.17	1.16	1.16
		FI	0.72	0.7	0.37
4	6.06	All	7.84	7.82	7.83
		FI	4.81	4.72	2.51
5	2.35	All	3.57	3.56	3.56
		FI	2.19	2.15	1.14
6	10.6	All	15.78	15.74	15.75
		FI	9.68	9.51	5.06
7	6.195	All	10.66	10.64	10.64
		FI	6.54	6.43	3.42
8	8.35	All	10.7	10.67	10.68
		FI	6.56	6.45	3.43
9	4.25	All	5.45	5.44	5.44
		FI	3.34	3.29	1.75
10	10.65	All	15.17	15.14	15.15
		FI	9.31	9.15	4.86
11	6.3	All	8.88	8.86	8.87
		FI	5.45	5.35	2.85
12	9.35	All	12.9	12.88	12.88
		FI	7.91	7.78	4.13

'All' represents all crashes and 'FI' is for Fatal plus all Injury crashes

Table 8: *Performance measures of predicting crashes by severity proportions*

Severity type	A measure of prediction accuracy	Oromia Configuration	HSM Configuration
FI	MAD	0.0900	2.4742
	SMAPE (%)	0.9199	31.4488
PDO	MAD	0.0708	2.4592
	SMAPE (%)	1.0785	27.3722

5.4.2.2. *Collision type distribution*

Exclusive of *Other Single-vehicle Collisions* and *Other Multiple-vehicle Collisions*, *Collision with Animal*, *Collision with Bicycle*, *Collision with Pedestrian*, *Head-on Collision*, *Overturned*, *Rear-end Collision*, *Angle Collision*, *Run-Off-Road*, and *Sideswipe* are the nine collision types in HSM and IHSDM. Eight of the nine collision types have been recorded and classified in the Oromia crash recording system, except for the *Collision with Bicycle*, which has not been specifically recorded. Thus, *Collision with Bicycle* was omitted for model calibration, and in addition to the eight collision types, *Other Single-vehicle Collisions* and *Other Multiple-vehicle Collisions* were added, totaling ten collision types evaluated. The crash prediction results of the twelve rural roads were aggregated in terms of their respective collision type distribution, and the final summated values for both CDDs were statistically assessed for goodness-of-fit. *Table 9* and *Table 10* show the detailed goodness-of-fit statistics computed for the collision type prediction accuracy of both configurations.

From the ten collision type distribution datasets developed for Fatal and Injury (FI) crash predictions, the HSM's CDD predicted *Run-Off-Road* and *Rear-end Collision* relatively well, while the rest was predicted more accurately by the developed CDD closer to the observed data. Except for *Collisions with Pedestrians* and *Sideswipe Collisions*, the developed crash distribution dataset prediction consistently outperforms the HSM in the overall crash severity type evaluation. The developed CDD for predicting crash frequencies in terms of both severity and collision type proportions for the study's jurisdiction has been validated, and the results confirm its effectiveness. As a result, the systematic approach used in this study to develop a jurisdiction CDD is capable of fixing the prediction error caused by the use of the default HSM's dataset.

Table 9: Performance measures of collision type prediction categorized in FI severity

No.	Collision type	FI			
		Oromia Configuration		HSM Configuration	
		MAD	SMAPE	MAD	SMAPE
1	Collision with Animal	0.1692	0.2318	0.3425	0.6331
2	Collision with Pedestrian	0.0733	0.0522	0.7225	0.9548
3	Head-on Collision	0.2650	0.3312	0.4333	0.7031
4	Other Multiple-vehicle Collision	0.0800	0.1574	0.2192	0.6131
5	Other Single-vehicle Collision	0.0825	0.2253	0.2025	0.8564
6	Overturned	0.2633	0.3513	0.3883	0.6369
7	Rear-end Collision	0.2017	0.2243	0.0958	0.0947
8	Angle Collision	0.1425	0.1912	0.1717	0.2352
9	Run-Off-Road	1.3283	0.3756	0.3658	0.1417
10	Sideswipe	0.0983	0.1829	0.2108	0.5136

Table 10: Performance measures of collision type prediction categorized in All severity

No.	Collision type	All Severity			
		Oromia Configuration		HSM Configuration	
		MAD	SMAPE	MAD	SMAPE
1	Collision with Animal	0.1083	0.1294	0.5325	0.3515
2	Collision with Pedestrian	0.0050	0.0035	0.6717	0.9388
3	Head-on Collision	0.4642	0.2943	0.8808	0.7629
4	Other Multiple-vehicle Collision	0.3117	0.3023	0.4408	0.4903
5	Other Single-vehicle Collision	0.0417	0.0870	0.0967	0.2252
6	Overturned	0.2133	0.1600	0.5292	0.5380
7	Rear-end Collision	0.2500	0.1731	0.3400	0.1658
8	Angle Collision	0.4533	0.3229	0.2092	0.1279
9	Run Off-Road	2.3633	0.3916	2.5525	0.4098
10	Sideswipe	0.5150	0.4247	0.5500	0.4714

5.5. Conclusions

Examining the safety performance of roadways, such as CPM evaluation, for specific treatments is critical in improving highway safety. The FHWA developed the predictive HSM to quantify the expected average crash frequency that may result from a specific highway feature; however, the default HSM may be unreliable for use by local jurisdictions other than those used to develop HSM. The predictive HSM method predicts traffic crashes based on the proportions of severity and collision type. A jurisdiction-specific Crash Distribution Dataset (CDD) must be developed and used in the evaluation to incorporate crash severity and collision type proportions in the CPM. This study developed a fixed Oromia's CDD and evaluated its effectiveness by replacing the default HSM values on the *Administration tool* of IHSDM software. The crash dataset was developed using crash data that occurred on rural two-way two-lane roads in the Oromia region collected over seven years (from 2010/11 to 2016/17). The CDD development included both estimates of the crash severity percentages and the collision type proportions.

The study result shows that the developed CDD, when compared to the default HSM dataset, predicts crash severity proportions much closer to the observed values. For Fatal and Injury crashes (F+I), the calibration factors for the developed and HSM configurations are 1.018 and 1.915, respectively. Both configurations underpredict Fatal and Injury crashes, with the Oromia configuration underpredicting in 1.8% and the HSM configuration underpredicting in 91.5%. According to the calibration factors obtained above, crashes in the Oromia region are severe as compared to the states used to develop the HSM configuration. Therefore, at this point, the study highlights that transportation authorities, traffic police bureaus, safety practitioners, and other concerned parties still have a lot of work to do to reduce the severity of crashes across the region. In addition to the calibration factor results, the goodness-of-fit statistics used in this study confirmed the accuracy of the developed CDD in predicting crash severity percentages in the study area.

Furthermore, the study results in the collision type predictions part show that the developed CDD predicts much better than the default HSM, but not in all collision type proportions. The default HSM configuration, for example, predicts *Angle Collision* and *Sideswipe Collision* proportions more precisely from the ten collision type proportions developed and validated. Based on the availability of complete crash data (i.e. crash location), the result points to the need for developing collision type proportion as a function rather than a fixed configuration for a better result.

By adopting and following the procedures in the Highway Safety Manual, the target of highway safety improvement becomes more achievable for the predictive safety analysis based on the performance method. The predictive Highway Safety Manual and IHSDM software need to be adopted in Oromia for a better road safety study. However, to obtain accurate and locally feasible crash estimates in Oromia, the default HSM crash configuration must have to be substituted by the developed CDD in this chapter. As demonstrated in this study, unsubstituted default HSM configuration with the locally developed one may result in inaccurate and unrealistic crash distribution estimates and emasculate its liability.

In general, the current study assures practitioners that CDDs vary from jurisdiction to jurisdiction due to differences in geographic conditions, crash reporting systems, road users characteristics (i.e., pedestrians, animals, and drivers behavior), vehicle characteristics, climate conditions, and other undetected factors. A statement is made that, in order to better suit local conditions, safety practitioners should develop the jurisdiction's CDD using the methodologies demonstrated and validated as true in this study, rather than using the default HSM crash configuration. CPMs that are based on an accurate jurisdiction's crash distribution (i.e., by severity level and collision type) investigate the relationships between roadway geometric features and their associated crash types, thus, assisting policymakers, road safety engineers, and transport agencies in making effective improvements on the severer crashes.

CHAPTER 6

Safety Performance Evaluation of Rural Two-Lane Roads

6.1. Introduction

Current Ethiopian road design standards assume that the policy minimum values based on the selected design speed provide general safety performance on rural two-lane highways (ERA, 2013). The design speed is defined as "*the maximum safe speed that can be maintained over a specified section of road when conditions are so favorable that the design features of the road govern the speed*."(ERA, 2013). In terms of safety, road design procedures based on the design speed concept have numerous flaws (Fitzpatrick, Wooldridge, et al., 2000). Considering design speed as the index that primarily defines the geometric standards of road elements as the only surrogate measure of safety demonstrates the gap of performance-based road design and evaluations in Ethiopia. To bridge this gap, the current study used the HSM predictive approach in IHSDM software to assess the safety and operational effects of the existing roadway geometric conditions in Ethiopia. The predictive HSM can fill a gap in the road safety studies such as the lack of standardized and approved models, as well as substantive highway safety evaluation (Shin et al., 2014). The HSM or IHSDM technique, as a decision-making tool, is intended to assist transportation agencies in making better use of limited budgets by prioritizing safety planning and design alternatives based on the evaluation of road safety performance.

To benefit the full capacity of the CPM of IHSDM it is recommended to develop or calibrate the base SPF and Crash Distribution Dataset (CDD) on the *Administration tool* of the software. To do so, accurate and detailed crashes, roadway or intersection inventories, and traffic volume data are deemed necessary, and observed crashes must be assigned to their respective roadway segments or intersections (AASHTO, 2010). In this study, the CDD developed for the Oromia region in *Chapter 5* of this dissertation was used. However, due to a lack of crash location data (i.e. crashes related to each roadway segment or intersection) in Ethiopia (UNECE, 2021), the study was unable to calibrate the base SPF to local jurisdiction. It is recommended to evaluate the relative safety effects of different design alternatives in this case, such as when there is no local calibration data for SPF (Wemple et al., 2010). The predictive HSM has been effective for evaluating the relative safety effects of various design alternatives or the uncalibrated models can be used to compare the relative safety effects to the no-build environment (Wemple et al., 2010). The objective of the study is to identify geometrically hazardous segments of rural two-lane roads and evaluate the relative safety performance of alternative designs or mitigations in a Computer-Aided Design (CAD) environment using the most up-to-date analytical methods of the IHSDM's crash prediction module (CPM) incorporated with the locally developed CDD (in *Chapter 5*).

6.2. Methods and Materials

6.2.1. Data collection

This study was conducted on Ethiopian two-lane rural roads. Rural roads from *Addis Ababa* to *Chacha (AA-Ch)*, *Addis Ababa* to *Dillela (AA-D)*, and *Addis Ababa* to *Modjo (AA-M)* were considered for study based on the availability of As-built geometric design data. The general information on the roads evaluated is provided in *Table 11*.

Table 11: General roadway information

Roads	Functional Class	Road №	Length (Km)	Average Feature Road AADT (vpd)	Design Class	Surface Type
Addis Ababa-Chacha (AA-Ch)	Trunk Road	A2-1	95.05	3,128	DC7	Paved
Addis Ababa-Dillela (AA-D)	Trunk Road	A5-1	83.96	7,198	DC7	Paved
Addis Ababa-Modjo (AA-M)	Trunk Road	A1-1	57.80	19,540	DC8	Paved

Data was collected on all of the study roadways in compliance with the study's objective and the IHSDM data input requirements. When modeling highways, IHSDM offers various data fields that allow users to attain their preferred detailing. For each roadway, the CPM of IHSDM requires the following data inputs:

- Horizontal alignment
- Vertical alignment
- Road cross-section (i.e. lane, shoulder section, cross slope, and surface type)
- Traffic Data (i.e. Annual Average Daily Traffic, AADT)
- General highway information (i.e. Area type, Functional class, and Terrain)
- Roadside cross-section (i.e. Driveway density and Roadside hazard rating, RHR)
- Design speed

The As-built geometric design data were obtained from the Ethiopian Roads Authority (ERA) and imported as a *LandXML* file into IHSDM software. From the imported As-built geometric design, all roadway data, such as horizontal alignment, vertical alignment, design speed, and road cross-section data, have been documented on the software. For all the three roads studied, the Ethiopian Roads Authority also provided AADT data from *2010* to *2018*. The *SPF* model developed by HSM for the undivided rural two-way two-lane road is only applicable to roads with a maximum AADT of *17,800 vpd*. However, the obtained average AADT on *Addis Ababa* to *Modjo* road, (which is *19,540 vpd*) exceeded the specified maximum AADT, so it was excluded from the analysis, and only the segregated rural roads of *AA-Ch* and *AA-D* were evaluated. *Figure 17* depicts a map of the study area with the evaluated roads. There are twelve segregated rural roads for *AA-Ch* road and nine for *AA-D* road.

The functional classifications of the selected roads are obtained from *Appendix A* of ERA Geometric Design Manual, 2013 (ERA, 2013). Accordingly, both roads are documented as *Trunk Road* with the road numbers of *A2-1 and A5-1* for *Addis Ababa* to *Chacha (AA-Cha)* and *Addis Ababa* to *Dillela (AA-D)* roads respectively. The rural roads were segregated from urban roads based on their roadway characteristics (i.e. cross-section types), surrounding population, and land uses. The area type of both roads is '*Rural Road*'. For driveway density, terrain, and Roadside Hazard Rating (RHR) *Google Earth* and *Street Map* were used. Finally, all the necessary information of the collected data had been imported and documented into IHSDM software for CPM evaluation.

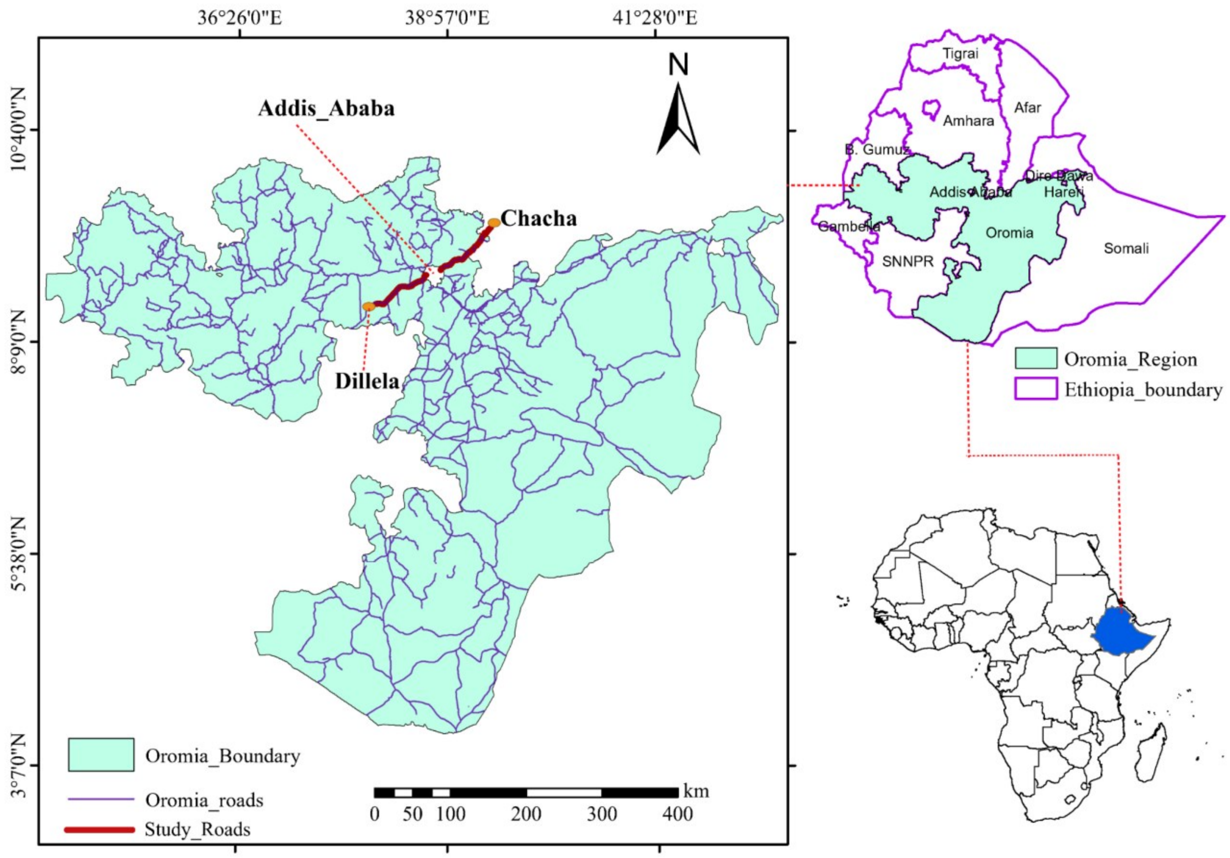


Figure 17: Map of the study area: For Safety Performance evaluation

6.2.2. CPM Evaluation

After importing and documenting all the necessary information of the analysis roads into IHSDM software, the *CPM* evaluation was executed and the predicted average crash frequency and crash rate resulted had been used to identify the hazardous road segments. The CPM incorporated in IHSDM is the predictive approach of the Highway Safety Manual (HSM). In this study, the predictive model in *Part C* of the HSM for the undivided rural two-lane two-way roadway facility type has been used. Although the predictive models differ depending on the facility and site type, they all share the same basic components, as illustrated in *Equation 21* (AASHTO, 2010).

$$N_{Predicted} = N_{SPFx} \times \left(CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx} \right) \times C_x \tag{21}$$

Where, $N_{predicted}$ is predicted average crash frequency for a specific year for site type x *(crashes/year)*; N_{SPFx} is predicted average crash frequency determined for *'base conditions'* of the SPF developed for site type x; CMF_{1x}, CMF_{2x}…, CMF_{yx} are crash modification factors specific to site type x and specific geometric design and traffic control features y; and C_x calibration factor to adjust SPF for local conditions for site type x.

Safety Performance Functions (SPFs) utilize known information about a roadway, such as geometry and Annual Average Daily Traffic *(*AADT*)*, to estimate the average crash frequency for a facility type with specified '*base conditions*'. SPFs are Mathematical Regression Models developed for roadway segments and intersections by assuming that crash frequencies follow a Negative Binomial distribution. The SPF for rural two-lane two-way roadway segments, such as the facility types preferred in the current study, that meet the HSM's *'base conditions'* is shown in *Equation 22* (AASHTO, 2010). The following are the HSM *'base conditions'* for rural two-lane two-way roadway segments (AASHTO, 2010):

- Lane width, *12 ft*;
- Shoulder width, *6 ft*;
- Shoulder type, *paved*;
- Roadside hazard rating, *3*;
- Driveway density, *5 driveways per mile*;
- Horizontal curvature, *none*;
- Vertical curvature, *none*;
- Centerline rumble strips, *none*;
- Passing lanes, *none*;
- Two-way left-turn lanes, *none*;
- Lighting, *none*;
- Automated speed enforcement, *none*; and
- Grade level of *0%*.

Whenever a base condition is not met, a crash modification factor (CMF) is applied to the model.

$$N_{SPFx} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312} \qquad 22$$

Where, *AADT* is the Annual Average Daily Traffic volume on a roadway segment *(vpd)* and $AADT_{max}=17{,}800$ *vpd*; *L* is the length of the roadway segment *(miles).*

CMFs are multiplied by a base model of *Equation 22* to account for the differences between *'base conditions' (condition 'a')* and the site conditions under consideration *(condition 'b')*. CMFs are used to address the effect of individual geometric design and traffic control features on the SPF estimate of predicted crash frequency, and their computation is shown in *Equation 3*. The IHSDM software incorporates all of the twelve CMFs available in HSM for rural two-lane two-way roadway segments, and the current study implemented them to address the effects of site-specific geometric design and traffic control characteristics.

A calibration factor *(C_x)* is also multiplied by the crash frequency predicted by the statistical base model to account for the differences between the general local conditions (site-specific condition) and HSM conditions (states used to develop HSM). The study was unable to calibrate the base SPF to local jurisdiction due to a lack of crash location data (i.e. crashes related to each roadway segment or intersection) in the study area (UNECE, 2021). In this case, such as when there is no local calibration data for SPF, it is recommended to evaluate the relative safety impacts of different design alternatives. As a result, the current study has been devoted to analyzing the safety implications of various design alternatives.

Whereas SPFs predict crash frequency as an aggregate, HSM provides a default Crash Distribution Dataset for rural two-lane two-way roadway segments based on HSIS (Highway Safety Information System) data to distinguish the predicted crash frequency into collision type and crash severity. Because these distributions differ from jurisdiction to jurisdiction, HSM believes that as part of the calibration procedure, this default CDD must be replaced with local crash distribution estimates. In this study, the CDD of the Oromia region, which was developed and validated using the IHSDM *Administration Tool* in *Chapter 5* of this report, has been used. Furthermore, the ERA Geometric Design Manual (2013) replaced the AASHTO superelevation policy as a calibration procedure to the local design standard in the IHSDM *Administration Tool*.

6.2.3. Identifying geometrically hazardous road segments and the possible design alternatives

The CPM evaluation of IHSDM necessitates the selection of a calibrated/uncalibrated SPF, a CMF, a superelevation policy, a crash distribution dataset, and an evaluation period. In this study, an evaluation period of twenty consecutive years, from *2010* to *2029*, has been preferred for analysis. Finally, the CPM evaluation was executed for both of the studied rural two-lane two-way roadway segments, with the uncalibrated SPF, HSM's CMFs, ERA superelevation policy, Oromia's CDD, and for 20 years of the evaluation period (i.e. *2010* as the first year of analysis and *2029* as the final year of analysis). The inconsistencies in roadway segments were identified based on the predicted crash frequency and crash rate report of the IHSDM CPM evaluations. To identify and prioritize the hazardous segments, the *Predicted Travel Crash Rate (crashes/million veh-km)* result of each homogeneous roadway segment has been used.

Though applying engineering mitigations to hazardous road segments can improve safety, these mitigation procedures are only small patches to the entire roadway facility (Qin et al., 2013a). With safety in mind, the identified hazardous road segments were redesigned using *AutoCAD Civil 3D-2019* software. Prior to redesigning, the IHSDM's Policy Review Module (PRM) was evaluated using the ERA, 2013 Geometric Design Manual (ERA, 2013) and AADT. The PRM evaluation report is useful for identifying issues with specific road geometric elements. The radius of a curve is primarily checked for its adequacy since the radius or degree of curvature has a significant impact on the occurrence of a crash (Aram, 2010). When the existing curvature does not meet the policy minimum, the curve radius is increased to meet the minimum requirement or to the maximum extent possible. The curve length is then checked against the policy minimum. If the result is inadequate, the curve radius is expanded as much as possible to meet the standard value.

To ensure safety, appropriate superelevation, as well as curve widening, were provided based on the policy minimum. In case of difficulty to modify or make good alternative designs, very sharp curves have been eliminated. Furthermore, based on the road functional classification and AADT, the minimum policy for lane width and shoulder width was checked and attempted to meet the standard as much as possible while considering the available right-of-way through site inspection and *Google Earth* and *Street View*. The procedure was repeated for all identified geometrically hazardous road segments. After implementing all engineering mitigations in *AutoCAD Civil 3D* software, the finally modified highway data was imported into IHSDM software for further CPM evaluation, such as substituting the hazardous segments. In order to assess the relative safety effects of design alternatives, the current CPM evaluation was also carried out using similar analysis parameters as the previous one, such as the uncalibrated SPF, HSM's CMFs, ERA superelevation policy, Oromia's CDD, and for *20* years of the evaluation period (i.e. *2010* as the first year of analysis and *2029* as the final year of analysis). Finally, the safety benefits of engineering mitigations made to the identified inconsistencies in the roadway segments were compared and quantified.

6.3. Results and Discussions

The safety of the road network can be improved by redesigning and fixing the hazardous segments in the roadway network; however, these mitigative tasks are only simple spots to the roadway network (Qin et al., 2013a). In recent times, it has become practical and accepted that a valuable number of crashes could have been prevented if the planning and design of highways had been done in a scientific, consistent, and proactive manner. The current study aimed to identify hazardous road segments (locations with higher predicted crashes) and apply engineering mitigations by redesigning them; the findings of this work are outlined in this section.

This study examined three rural two-lane roads in Ethiopia. These are; a) *Addis Ababa* to *Chacha* (*AA-Ch*), b) *Addis Ababa* to *Dillela* (*AA-D*) on the way to *Welkite* town and c) '*Addis Ababa*' to '*Modjo*' (*AA-M*) roads. The SPF model developed by HSM for the undivided rural two-way two-lane road is only applicable to roads with a maximum AADT of *17,800 vpd*. However, the obtained average AADT on *Addis Ababa* to *Modjo* road, *AA-M* (which is *19,540 vpd*) exceeded the specified maximum AADT, so it was excluded from the analysis, and only the segregated rural roads of *AA-Ch* and *AA-D* were evaluated.

6.3.1. Identifying hazardous road segments

The IHSDM CPM was carried out for all rural roads selected for evaluation, and the inconsistencies in road sections were identified and prioritized based on their safety performance evaluation. For each homogeneous segment, the CPM evaluation of IHSDM reports the *Predicted Total Crash Frequency (crashes/yr)*, *Predicted Crash Rate (crashes/km/yr)* and *Predicted Travel Crash Rate (crashes/million veh-km)*. For assessing the relative safety performance of highways, it is preferable to consider the length and AADT of roadway segments, *i.e.,* the *Predicted Travel Crash Rate (crashes/million veh-km)*. In this study, hazardous road segments are identified and prioritized based on the CPM reports of the *Predicted Travel Crash Rate* (*crashes/million veh-km*). Roadway segments that have a

Predicted Travel Crash Rate of more than *1.4 crashes/million veh-km* are identified as hazardous. Accordingly, fifteen roadway segments on both *AA-Ch* and *AA-D* roads have been detected as hazardous by horizontal design element diagnosis and the result is exhibited in *Table 12*. *Appendix-B* of this dissertation contains the entire crash prediction evaluation report of IHSDM on the *AA-D* road of *Section 4* (from station 4+510.000 to 7+730.000). This section (*Section 4* on the *AA-D* road) includes three hazardous road segments, including the first ranked (4+853.484 to 4+862.57), third ranked (7+017.218 to 7+104.199) and fifteenth ranked (6+831.965 to 6+922.933).

A total of *1.25km* roadway segments have been identified as hazardous, accounting for *0.89*% of the total *140.66-kilometer-long* rural roads evaluated. The total predicted crash frequency for the entire road network evaluated is *140.41 crashes/yr*, whereas the hazardous segment has a crash frequency of *5.00 crashes/yr*, accounting for *3.56%* of the total crash frequency despite being only *0.89%* of the total length. Overall, the average predicted crash rate for rural roads evaluated is *0.998 crashes/km/yr*, whereas the predicted crash rate for hazardous road segments is more than four times as hazardous, at *4.011 crashes/km/yr* and the details are illustrated in *Table 13*. As a result of the higher crash rates perceived on the identified hazardous road segments, implementing engineering mitigations on these segments has the potential to economically improve overall highway safety.

Table 12: Hazardous road segments based on the Predicted Travel Crash Rate (crashes/million veh-km) by horizontal design element

Rank	Highway	Title	Start Location (Station, m)	End Location (Station, m)	Predicted Travel Crash Rate (crashes/million veh-km)	Length (m)
1	AA-D	Spiral Curve	4+853.484	4+855.420	4.84	9.09
	AA-D	Simple Curve	4+855.420	4+860.634	4.84	
	AA-D	Spiral Curve	4+860.634	4+862.570	4.84	
2	AA-Ch	Simple Curve	9+933.489	9+971.900	2.79	38.41
3	AA-D	Spiral Curve	7+017.218	7+024.745	2.5	86.98
	AA-D	Simple Curve	7+024.745	7+096.671	2.5	
	AA-D	Spiral Curve	7+096.671	7+104.199	2.5	
4	AA-D	Spiral Curve	11+972.179	11+979.389	2.29	111.92
	AA-D	Simple Curve	11+979.389	12+076.889	2.33	
	AA-D	Spiral Curve	12+076.889	12+084.098	2.38	
5	AA-D	Spiral Curve	14+725.232	14+738.581	2.1	86.62
	AA-D	Simple Curve	14+738.581	14+798.507	2.1	
	AA-D	Spiral Curve	14+798.507	14+811.856	2.1	
6	AA-D	Simple Curve	9+650.000	9+650.380	2.01	14.21
	AA-D	Spiral Curve	9+650.380	9+664.208	2.01	
7	AA-Ch	Simple Curve	29+008.489	29+043.274	2	34.78
8	AA-D	Spiral Curve	11+346.228	11+356.950	1.91	99.26
	AA-D	Simple Curve	11+356.950	11+434.762	1.91	
	AA-D	Spiral Curve	11+434.762	11+445.484	1.91	
9	AA-Ch	Simple Curve	42+500.015	42+613.424	1.81	113.27
10	AA-D	Spiral Curve	12+124.150	12+137.565	1.73	87.24
	AA-D	Simple Curve	12+137.565	12+197.977	1.73	
	AA-D	Spiral Curve	12+197.977	12+211.392	1.73	
11	AA-D	Spiral Curve	10+108.127	10+119.643	1.62	132.70
	AA-D	Simple Curve	10+119.643	10+229.309	1.64	
	AA-D	Spiral Curve	10+229.309	10+240.825	1.64	
12	AA-Ch	Simple Curve	39+549.882	39+608.489	1.59	58.61
13	AA-D	Spiral Curve	15+643.704	15+658.617	1.55	94.85
	AA-D	Simple Curve	15+658.617	15+723.639	1.55	
	AA-D	Spiral Curve	15+723.639	15+738.552	1.64	
14	AA-Ch	Simple Curve	10+016.518	10+204.330	1.54	187.81
15	AA-D	Spiral Curve	6+831.965	6+850.095	1.54	90.97
	AA-D	Simple Curve	6+850.095	6+904.803	1.42	
	AA-D	Spiral Curve	6+904.803	6+922.933	1.4	

Table 13: Hazardous road segments versus overall rural roads evaluated

Title	$AADT_{avg}$	Length (km)	Length Proportion (%)	Total Predicted Crashes for Evaluation Period	Predicted Total Crash Frequency (crashes/yr)	Average Predicted Crash Rate (crashes/k m/yr)	Average Predicted Travel Crash Rate (crashes/million veh- km)
All Rural Roads Evaluated							
AA-Ch Road	3128	71.030	50.5	865.844	43.293	0.609	0.534
AA-D Road	7198	69.628	49.5	1942.450	97.122	1.395	0.531
Total	-	140.658		2808.29	140.41	Mean average per length proportion	
						0.998[1]	0.532[2]
Hazardous Road Segments							
AA-Ch Road	3128	0.433	34.75	17.469	0.874	2.017	1.767
AA-D Road	7198	0.813	65.25	82.511	4.126	5.073	1.931
Total	-	1.246		99.980	5.00	Mean average per length proportion	
						4.011[3]	1.874[4]
Total coverage		0.89%		3.56%	3.56%	Hazardousness compared to overall	
						401.80%	351.96%

[1] $\text{AA-Ch}_{(Crashes/km/yr)}$*$\text{AA-Ch}_{(Length\ Proportion)}$ + $\text{AA-D}_{(Crashes/km/yr)}$*$\text{AA-D}_{(Length\ Proportion)}$ = 0.609*50.5% + 1.395*49.5% = 0.998

[2] $\text{AA-Ch}_{(Crashes/million\ veh\text{-}km)}$*$\text{AA-Ch}_{(Length\ Proportion)}$ + $\text{AA-D}_{(Crashes/million\ veh\text{-}km)}$*$\text{AA-D}_{(Length\ Proportion)}$=0.534*50.5% + 0.531*49.5% = 0.532

[3] $\text{AA-Ch}_{(Crashes/km/yr)}$*$\text{AA-Ch}_{(Length\ Proportion)}$ + $\text{AA-D}_{(Crashes/km/yr)}$*$\text{AA-D}_{(Length\ Proportion)}$ = 2.017*34.75% + 5.073*65.25% = 4.011

[4] $\text{AA-Ch}_{(Crashes/million\ veh\text{-}km)}$*$\text{AA-Ch}_{(Length\ Proportion)}$ + $\text{AA-}_{(Crashes/million\ veh\text{-}km)}$*$\text{AA-D}_{(Length\ Proportion)}$ = 1.767*34.75% + 1.931*65.25% = 1.874

6.3.2. Engineering mitigations

The current study applied engineering mitigations or provided an alternative design for the identified hazardous road segments to improve safety, and finally, the relative safety effects of the design alternatives were quantified. Hazardous road segments have been inspected on the site as well as on *Google Streetview/Google Earth*, and their design features are also being checked against ERA standards by running the PRM of IHSDM and the findings of related studies before re-designing them. For illustration the policy review evaluation report of IHSDM on the *AA-D* road of *Section 4* (from station 4+510.000 to 7+730.000) is presented in *Appendix-C*. The design vehicle selected to run the PRM of IHSDM was *WB-19/WB-62* which best fits the ERA design vehicle dimensions. The prefix *WB* refers to a truck's wheelbase, and the number (suffix) is a code assigned depending on the vehicle's dimensions (i.e., *WB-19* for Metric, meter and *WB-62* for US customary, feet). The *WB-19* is a two-unit Interstate Semitrailer with a width of 2.6 m and a minimum design turning radius of 13.7 m (Harwood et al., 2003). The dimensions of the two units wheelbases are *WB1*=6.1 m and *WB2*=12.3 m (Harwood et al., 2003). Based on the examination of safety concerns, the hazardous road segments were redesigned to improve safety using the *AutoCAD Civil 3D-2019* software. Since vertical alignment design necessitates detailed surface modeling via surveying or data collection and contour generation, the current study is dedicated to redesigning horizontal alignments in conjunction with cross-sections. For each identified hazardous road segment, the following design alternatives are provided.

6.3.2.1. First-ranked hazardous segment

This segment is on the road from *Addis Ababa* to *Dillela*, at a station from *4+853.48 to 4+862.57*. There is a circular curve with spiral curves on both sides having a radius of *100m* at this segment, and two curves with radiuses of *80m* and *120m* precede it, with a *30m* tangent length between them. At this segment, the following deficiencies are observed, and also, the PRM evaluation confirms (*see Appendix-C*): the curve radius is less than the ERA-2013 policy minimum, such as the existing curve radius is *100m*, whereas the policy minimum is *229m*; the minimum controlling criteria for lane width is *7.3m* while the existing is *7.0m* and for shoulder width, it is *3.0m* while the existing is *1.5m*; and the provided superelevation is inadequate (i.e. 4% while the policy recommends 8% superelevation for a 100m radius with 80km/hr design speed). There is no Stopping Sight Distance (SSD) issue. The design modifications made at this segment are:

- The preceding two curves with a small tangent in between has been changed to one circular curve and designed with adequate spiral curve length. Which also, helps to increase the radius of the next curve (the first hazardous segment) by providing an appropriate deflection angle within the existing road.
- Increasing radius from *100m* to *394m* and moving the PI to get the existing road.
- Lane width increased to *7.3m* from *7.0m*.
- Shoulder width increased to *2.0m* from *1.5m.*

Figure 18 shows a more thorough depiction.

6.3.2.2. Second-ranked hazardous segment

These segments are found on *Addis Ababa* to *Chacha* road. At this location, there are the 2nd and 14th ranked hazardous road segments with stations of *9+933.489 to 9+971.900* and *10+016.518 to 10+204.330* respectively. The curve radiuses that are found at the 2nd and 14th ranked hazardous segments are *190m* and *98m* respectively. PRM evaluation result and the observed deficiencies at these segments are: for station *10+016.518* to *10+204.330 Superelevation required, no superelevation identified* and the policy superelevation is *6.9%*;

for station *9+969.489* to *9+971.489* on the right side of the road, the provided SSD is *67m* while policy SSD is *70m* (*Road value varies from recommended values; check obstructions beyond shoulder; source of SSD limitation is horizontal alignment*); and the minimum controlling criteria for lane width is *7.3m* while the existing is *7.0m* and for shoulder width, it is *3.0m* while the existing varies from *2.0* to *2.5m*. The design modifications made at this segment are:

- As illustrated in *Figure 19*, providing the policy minimum within the existing road alignment is difficult due to the short tangent between curves and their small curve length. Thus, engineering mitigation or design changes made here include removing a curve at the second hazardous segment and increasing the 14th hazardous's curve radius from *98m* to *200m*. Since there is a bridge on the 14th hazardous segment, the centerline is carefully passed on the bridge by adjusting the PI's and curve radius.
- Also, the succeeding curve radius is increased from 1*50m* to *200m.*
- Adequate superelevation and SSD are provided.

6.3.2.3. Third-ranked hazardous segment

At this location, there are the 3rd and 15th ranked hazardous segments on *Addis Ababa* to *Dillela* road with the stations of *7+017.218 to 7+104.199* and *6+831.965 to 6+922.933* respectively. These curves are a reverse curve with a *94.28m* tangent length between them. PRM evaluation result and the observed deficiencies at this location are: both radiuses are less than the ERA-2013 policy minimum, such as the existing curve radiuses are *67.5m* and *163.2m* for the 3rd and 15th, whereas the policy minimum is *229m*; the minimum controlling criteria for lane width is *7.3m* while the existing is *7.0m* and for shoulder width, it is *2.0m* while the existing is *1.5m*. The design modifications made at this location are:

- The radius of a curve found at the 3rd hazardous road segment has been increased to 1*50m* (from *67.5m*) and the preceding curve radius is increased to *200m* (from *163.2m*). Their PI's are also adjusted to align on the existing road.
- Even if the radius of both curves is increased to the maximum by keeping in mind not to shift from the existing road, the minimum ERA policy for curve radius is not provided. However, the recommended superelevation based on the selected design speed and curve radius have been provided for both curves.
- Lane width increased to *7.3m* from *7.0m*
- Shoulder width increased to *2.0m* from *1.5m*

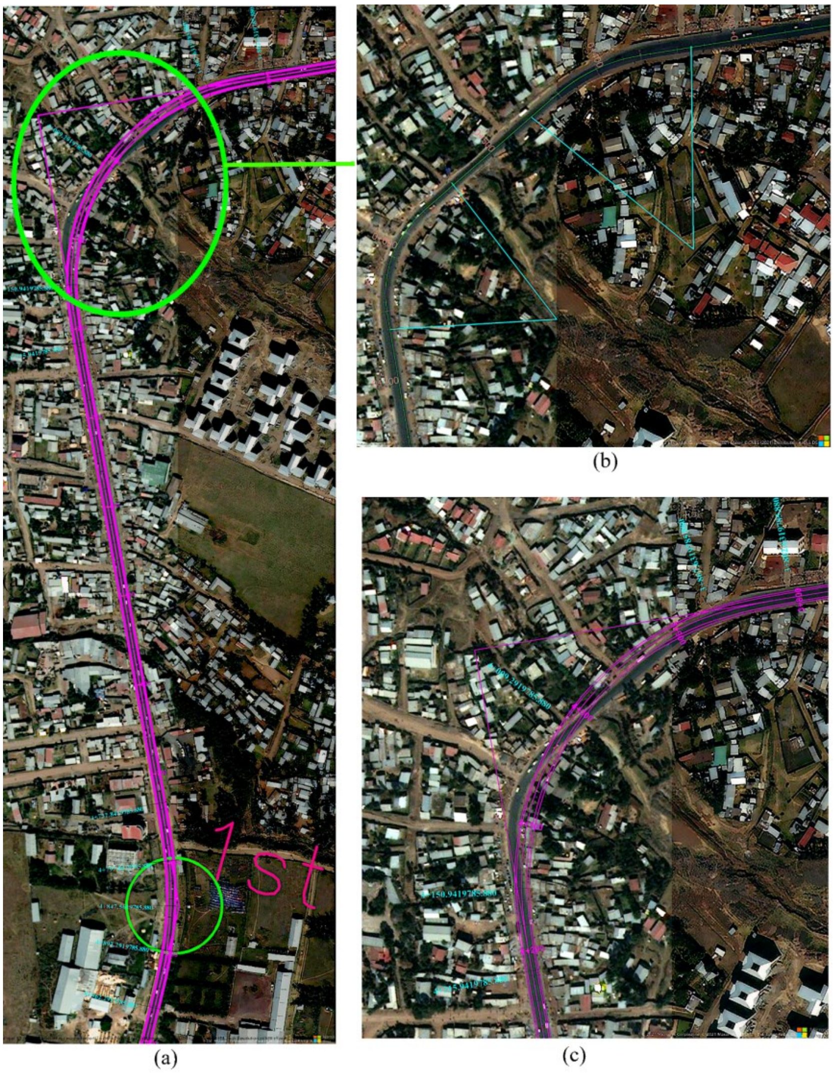
Figure 20 shows a more thorough depiction.

6.3.2.4. The fourth-ranked hazardous segment

The 4th hazardous segment at station *11+972.179 to 12+084.098* and 10th hazardous segment at *12+124.150 to 12+211.392* are found at this location on *Addis Ababa* to *Dillela* road with curve radiuses of *64.5m* and *120.0m* respectively. At these segments, the following deficiencies are observed, and also, the PRM evaluation confirms: a sharp curve with a *64.5m* radius, the 4th ranked hazardous segment, is followed by another curve (the 10th hazardous segment) with a *40m* tangent length in between them; the minimum controlling criteria for lane width is *7.3m* while the existing is *7.0m* and for shoulder width, it is *3.0m* while the existing is *1.75m* for the first curve and *1.5m* for the preceding; and *road value varies from controlling criteria; check obstructions beyond shoulder; source of SSD limitation is horizontal alignment*: SSD of the road at *11+852.00 to 12+172.00* in Right direction is *64m, 12+196.00* to *12+396.00* in the Right is *80m* and *12+004.00 to 12+314.00* in the Left is *58m* while policy SSD is *155m*. The design modifications made at these segments are:

- Modifying the alignment as shown in *Figure 21* may be challenging owing to the short tangent between curves and their small curve length. The mitigation used in this study was to eliminate the next curve found at the 10th hazardous section in order to modify the sharp curve with a high crash rate. The radius of this sharp curve (the curve at the 4th hazardous segment) is increased to *120m* from *64.5m* as a result of this action.
- Furthermore, adequate superelevation and curve widening is provided.
- Indeed, the new alignment is somewhat shifted from that of the existing road so that, the *benefit-cost ratio* analysis needs to be executed to assess the feasibility of this mitigation or alternative design. But there is no agreed-upon or standardized crash cost in Ethiopia which needs a detailed study. It is recommended in this paper that the feasibility of all the design alternatives or mitigations must have to be carried out in the future framework.
- Lane width increased to *7.3m* from *7.0m*
- Shoulder width increased to *2.0m* from *1.75m*

Figure 21 shows a more thorough depiction.



(a) (b) (c)

Figure 18: (a) the first-ranked hazardous road segment; (b) the preceding two curves with a small tangent in between them of the existing road; and (c) the redesigned circular curve

Figure 19: The second-ranked hazardous road segment

(a) (b)

Figure 20: (a) the existing road at the third-ranked hazardous road segment; (b) re-designed

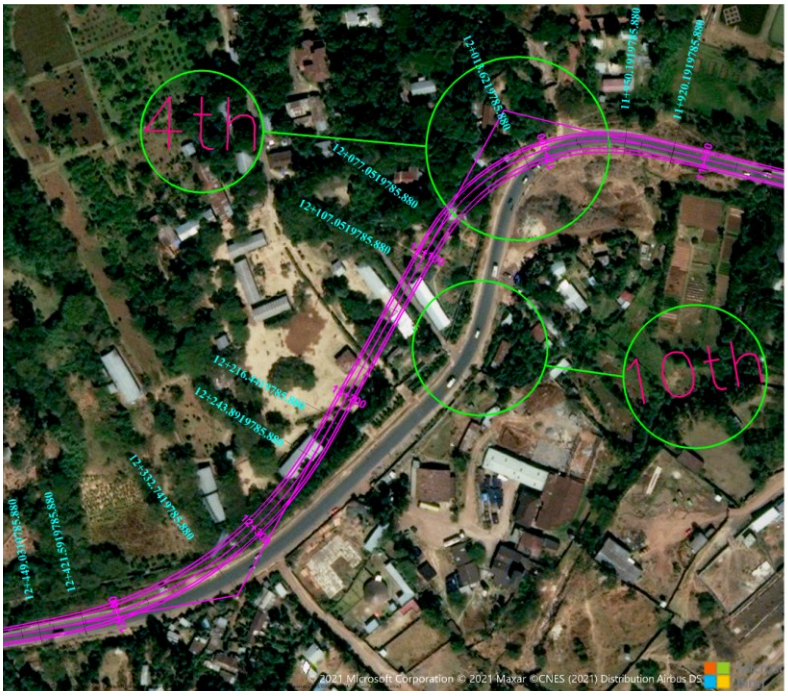


Figure 21: The fourth-ranked hazardous road segment

6.3.2.5. *The rest identified hazardous road segments*

Table 14 shows the alternative designs or engineering mitigations applied to the remaining hazardous road segments following a thorough examination of their geometric design characteristics in conjunction with the Policy Review Module (PRM) evaluation result of IHSDM.

Table 14: Engineering mitigations made to the hazardous road segments

Rank	Road	Station	Measures	Remark
5th	AA-D	14+725.23 to 14+811.86	Radius increased to 394m from 120m; Lane width increased to 7.3m from 7.0m; Shoulder width increased to 2.0m from 1.5m.	A minimum radius is provided
6th	AA-D	9+650 to 9+664.21	Radius increased to 250m from 120m; Lane width increased to 7.3m from 7.0m; Shoulder width increased to 2.0m from 1.5m.	
7th	AA-Ch	29+008.49 to 29+043.27	Radius increased to 370m from 300m; Curve length increased as a result of the increased radius; Increasing curve widening.	The existing curve radius is sufficient but increasing curve length by changing the radius from 300m to 370m makes the road comfortable.
8th	AA-D	11+346.23 to 11+445.48	Radius increased to 100m from 96.5m; Lane width increased to 7.3m from 7.0m; Shoulder width increased to 2.0m from 1.5m.	
9th	AA-Ch	42+500.02 to 42+613.42	The tangent length between curves is increased to 98m from 22m by moving the PI's apart keeping the bridge untouched.	There are two circular curves with a short tangent (22m) between them. Also, there is a bridge between these curves which is difficult to modify the alignment due to the cost of bridges.
11th	AA-D	10+108.13 to 10+240.83	Radius increased to 140m from 103m; Lane width increased to 7.3m from 7.0m; Shoulder width increased to 2.0m from 1.5m.	
12th	AA-Ch	39+549.88 to 39+608.49	The tangent length between curves is increased to 84m from 41.5m by moving the PI's apart keeping the bridge untouched.	There are two circular curves with a short tangent (41.5m) between them. Also, there is a bridge between these curves which is difficult to modify the alignment due to the cost of bridges.
13th	AA-D	15+643.7 to 15+738.55	Radius increased to 250m from 134m; Increasing curve widening; Lane width increased to 7.3m from 7.0m; Shoulder width increased to 2.0m from 1.5m.	

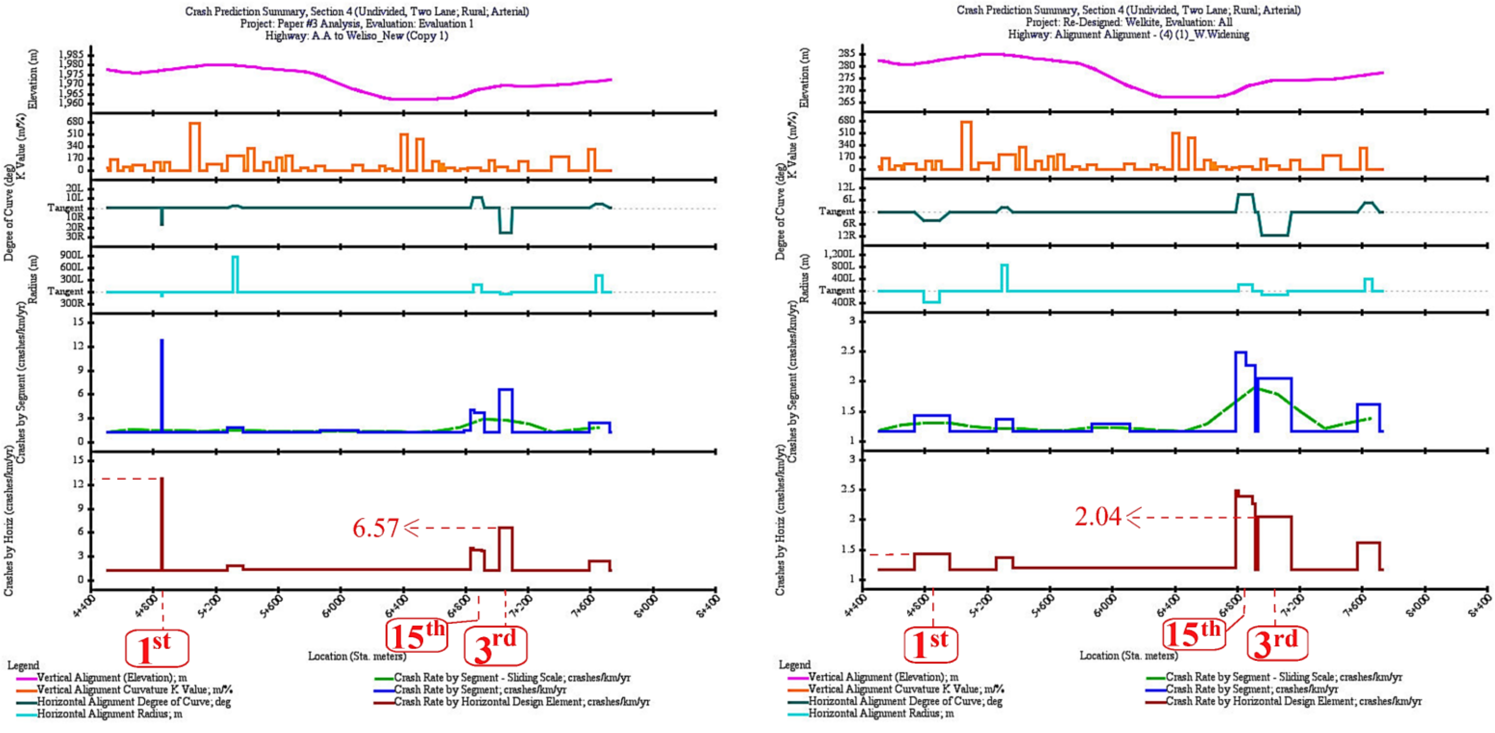
6.3.3. Relative Safety Performance evaluation of design alternatives

All of the prescribed modifications for the hazardous road segments were completed using the *AutoCAD-Civil 3D* software, and the ERA standard was imported into the software to be incorporated into the design of superelevation, curve widening, and adequate SSD provision. All geometric design changes made were imported into IHSDM software for further CPM analysis. For the sake of assessing relative safety performance, the CPM evaluation used a similar analysis period, crash distribution dataset, superelevation policy, and AADT. The *Predicted Travel Crash Rate* of the modified highways has been summarized and presented in *Table 15* after running the CPM of IHSDM.

Table 15 shows that there is a significant reduction in crash rate, particularly on the first top five hazardous segments, where astonishing improvements are noticed. For example, reducing the *Predicted Travel Crash Rate (crashes/million veh-km)* from *4.84 to 0.55, 2.79 to 0.5, 2.5 to 0.78, 2.29 to 0.92*, and *2.1 to 0.54*, in ascending order of the first top-five inconsistencies modified, resulted in a safety benefit. *Figure 22* depicts a graph of CPM results for the existing and redesigned hazardous segments of the 1st, 3rd, and 15th ranked to demonstrate the relative safety impacts of geometric changes. As exhibited in *Figure 22*, the predicted crash rate at the 1st hazardous segment for the existing road was *12.72 crashes/km/year*, however, after improving the curve, shoulder, and lane width, the estimated crash rate was remarkably reduced to *1.43 crashes/km/year*. Similarly, by modifying the horizontal curves at the 3rd and 15th hazardous segments, the predicted crash rates were reduced from *6.57* to *2.04* and *3.67* to *2.38 crashes/km/year*, respectively.

Table 15: CPM result of the alternative design

Ranking	Title	Start Location (Station)	End Location (Station)	Predicted Travel Crash Rate (crashes/million veh-km)	Length (m)
1(AA-D)	Spiral Curve	4+732.84	4+797.84	0.55	229.45
	Simple Curve	4+797.84	4+897.29	0.55	
	Spiral Curve	4+897.29	4+962.29	0.55	
2(AA-Ch)	Tangent	9+831.72	9+989.26	0.5	157.54
3(AA-D)	Spiral Curve	6+937.56	6+957.56	0.78	209.04
	Simple Curve	6+957.56	7+126.60	0.78	
	Spiral Curve	7+126.60	7+146.60	0.78	
4(AA-D)	Spiral Curve	11+920.19	11+950.19	0.92	186.86
	Simple Curve	11+950.19	12+077.05	0.92	
	Spiral Curve	12+077.05	12+107.05	0.92	
5(AA-D)	Spiral Curve	14+596.86	14+610.21	0.54	256.42
	Simple Curve	14+610.21	14+839.93	0.54	
	Spiral Curve	14+839.93	14+853.28	0.54	
6(AA-D)	Spiral Curve	9+650.00	9+705.70	1.1	55.70
	Simple Curve	9+650.00	9+650.38	2.01	
7(AA-Ch)	Simple Curve	29+416.37	29+547.49	0.74	131.12
8(AA-D)	Spiral Curve	11+287.18	11+352.18	1.13	156.35
	Simple Curve	11+352.18	11+378.53	1.13	
	Spiral Curve	11+378.53	11+443.53	1.13	
9(AA-Ch)	Simple Curve	43+003.35	43+120.09	1.32	116.75
10(AA-D)	Tangent	12+107.05	12+216.44	0.45	109.39
	None	None	None	None	
	None	None	None	None	
11(AA-D)	Spiral Curve	10+037.63	10+102.63	0.77	229.61
	Simple Curve	10+102.63	10+202.24	0.84	
	Spiral Curve	10+202.24	10+267.24	0.85	
12(AA-Ch)	Simple Curve	40+011.39	40+085.37	1.14	73.98
13(AA-D)	Spiral Curve	15+561.25	15+576.16	0.69	165.11
	Simple Curve	15+576.16	15+711.45	0.69	
	Spiral Curve	15+711.448	15+726.361	0.69	
14(AA-Ch)	Simple Curve	9+989.261	10+303.527	0.75	314.27
15(AA-D)	Spiral Curve	6+793.198	6+811.328	0.95	122.37
	Simple Curve	6+811.328	6+897.435	0.91	
	Spiral Curve	6+897.435	6+915.565	0.86	



(a) (b)

Figure 22: The comparison of the CPM graph (a) existing; (b) re-designed

A comparison with the existing segments was conducted by totaling the predicted crash frequencies, crash rates, and travel crash rates in million vehicles for all fifteen modified segments, and the results are shown in *Table 16*. The geometric design changes made on these segments resulted in a reduction of *17.18%* in total crash frequency *(crashes/yr)*, *58.94%* in crash rate *(crashes/km/yr)*, and *58.86%* in travel crash rate *(crashes/million veh-km)*. Because the crash rate was used as the primary safety threshold in the study, a solid crash percentage reduction was obtained. Modifying *0.89%* of the total length of the roadways evaluated, such as the hazardous road segments, resulting in a *58.86%* improvement in the travel crash rates. Even with a more than *100%* increase in overall segment length, the total predicted crash frequency was reduced by *17.18%*. The overall length of the hazardous road segments modified increased due to increased curve radiuses and curve lengths.

According to the comparison based on the developed CDD, which is included in the current crash prediction evaluation, FI crashes could be reduced by 10.38 crashes during the evaluation period. Furthermore, if the crash severity has been split again, the engineering mitigations made on these shorter roadway lengths would prevent more than 4 fatalities (4.3 fatal crashes) during the evaluation period.

Table 16: The relative safety performance

	Length (km)	Total Predicted Crashes for Evaluation Period	Predicted Total Crash Frequency (crashes/yr)	Predicted Crash Rate (crashes/k m/yr)	Predicted Travel Crash Rate (crashes/million veh- km)
Existing $\text{TOTAL}_{\text{IRS}}$	1.246	99.980	5.00	4.011	1.874
Re-Designed $\text{TOTAL}_{\text{IRS}}$	2.514	82.808	4.141	1.647	0.771
(Existing) - (Re-Designed)	-1.268	17.172	0.859	2.364	1.103
Percentage reduction	-101.72%	17.18%	17.18%	58.94%	58.86%

6.4. Conclusions and Recommendations

Safety evaluations based on road safety performance estimates (i.e. CPM evaluation) are an effective technique for identifying inconsistencies in a roadway network as well as quantifying the relative safety performance of design alternatives. In Ethiopia, however, road design standards based on the selection of design speed are regarded as the only surrogate measure of safety. This study aimed to fill the gap in using the predictive approach of road safety performance evaluation in Ethiopia by applying the most up-to-date analytical methods of the HSM predictive approach in IHSDM software to evaluate the safety and operational effects of existing road geometric features and quantify the relative safety effects of design alternatives. From the selected roads for evaluation, the roads from *Addis Ababa* to *Chacha* and *Addis Ababa* to *Dillela* have met the HSM model specification, and a study was conducted based on these roads.

The As-built geometric design and AADT data were collected from the Ethiopian Roads Authority (ERA), and all necessary information was imported and documented into IHSDM software for CPM evaluation. The hazardous road segments were identified and prioritized based on the *Predicted Travel Crash Rate (crashes/million veh-km)* resulted from the CPM evaluation of each homogeneous roadway segment. Following the Policy Review Module (PRM) evaluation results, engineering mitigations were made for all identified hazardous road segments by redesigning them on *AutoCAD Civil 3D* software. The modified roadway segments were imported into IHSDM software for further CPM evaluation by substituting the existing hazardous segments. The relative safety effects of the design changes made in this study were compared to the existing roadway segments, and the benefits of the design changes were finally quantified.

The study discovered fifteen hazardous road segments on both the *Addis Ababa* to *Chacha* and *Addis Ababa* to *Dillela* roads based on the results of *Predicted Travel Crash Rate (crashes/million veh-km)* by horizontal design element. A total of *1.25km* length of roadway segments were identified as hazardous, accounting for *0.89%* of the total *140.66km* of rural roads evaluated. As a whole, the average predicted crash rate for rural roads evaluated *is 0.998 (crashes/km/yr)*, whereas the predicted crash rate for hazardous road segments is *4.011 (crashes/km/yr)*, demonstrating that the identified hazardous segments are more than four times as hazardous and clearly have safety issues. Thus, applying engineering mitigations to these segments have the potential to economically improve overall road safety. The design modifications made on the hazardous road segments have resulted in an impressive reduction in crash rate, particularly on the first top-five hazardous segments, where astounding improvements have been witnessed. For instance, design changes made in this study to the first top-five geometrically hazardous segments have yielded the reduction in *Predicted Travel Crash Rate (crashes/million veh-km)* to *0.55* from *4.84*, *0.5* from *2.79, 0.78* from *2.5, 0.92* from *2.29, and 0.54* from *2.1* in ascending order. The following are the aggregated safety benefits obtained by applying engineering mitigations to the fifteen identified hazardous segments: Total crash frequency *(crashes/yr)* reduced by *17.18%*, crash rate *(crashes/km/yr)* reduced by *58.94%*, and travel crash rate *(crashes/million veh-km)* reduced by *58.86%*. Crash frequency indeed increases with road length, which is also true in HSM's SPF model; however, with a more than *100%* increase observed in the total length of hazardous road segments modified, the total predicted crash frequency was reduced by *17.18%*.

The current study revealed the effectiveness of safety performance-based road evaluation or design in providing safer roadway infrastructure. IHSDM results, aid decision-making in the roadway design process by providing a quantitative evaluation of the safety impact of different design features. Furthermore, when properly implemented, IHSDM is a tool capable of saving time for Road Safety Audit (RSA) teams and detecting road segments with safety issues. This study encourages transportation agencies to practice IHSDM as a decision-support tool during the RSA process to assess and estimate the safety and operation effects of different geometric design parameters for new and existing roads. A jurisdiction-specific SPFs for Ethiopian roads must be developed, or HSM's SPFs must be calibrated, in order to achieve an accurate roadway performance prediction analysis. To do so, the observed crash locations must be precisely recorded so that they can be assigned to their proper roadway segments or intersections. In Ethiopia, there is no computerized crash recording database; instead, crash recording is manual and paper-based, with no georeferenced crash locations (UNECE, 2021). As a result, it is recommended that the Ethiopian Ministry of Transport work on developing crash database recording that is capable of documenting all crash characteristics, including crash locations using high-precision GPS technology, for the prospective road safety study.

CHAPTER 7

Conclusions, Recommendations and Prospective Research Direction

The reduction of traffic crashes, as well as their socio-economic consequences, has become the world's most pressing problem. In Ethiopia, road traffic crashes result in enormous losses of lives and economic wealth. Given the gravity of the traffic crash problem, the necessity of road transportation in Ethiopia, and the pace at which the road infrastructure is developing, traffic safety is an urgent topic that must be addressed. While having a small number of road infrastructure and vehicle ownership, the country has a rather substantial crash rate, which has been mentioned as the worst case by many researchers. Scientific research and technological advancements are improving the efficacy of safety measures or traffic interventions; nevertheless, little is known in Ethiopia about the safety performance of roadway geometric features and the relative safety impact of design alternatives. Hence, detailed and engineered research efforts in the field of road traffic safety are essential to improve the safety of the country's road infrastructure.

The preceding chapters provided an introduction and review of the study's theoretical framework, a road safety overview of the study region (Ethiopia), and three scientific investigations that addressed the dissertation's primary objectives. This last chapter concludes with a review of the major findings and an explanation of how they contribute to Ethiopia's traffic crash prevention and traffic management research program. The aspects of the findings, as well as their limitations, are discussed, and recommendations for prospective research work are stated.

7.1. Conclusions and Overview of the Scientific Investigations

This section summarizes the scientific analysis complied with the dissertation's concrete objectives.

I. Crash Severity and Spatial Pattern Mapping

For effective road safety interventions, the transport agencies and safety researchers need to utilize or adapt the most up-to-date safety tools and analysis techniques. For decades, safety experts and transportation authorities in developed countries have used advanced GIS-based hotspot analysis to examine historical Road Traffic Crash (RTC) information. Considering the gap in applying GIS in the field of road safety to map crash spatial patterns in Ethiopia, the first objective of the study, as reported in *Chapter 4*, was to demonstrate a GIS application to identify and quantify statistically significant crash hotspots based on crash spatial dependency, frequency, and severity. This analysis identified crash hotspots based on the severity of the crashes and by integrating spatial autocorrelation of crashes and Getis Ord *Gi**. Spatial autocorrelation provides the added benefit of allowing statistical analysis of crash spatial patterns. *Gi** statistics' ability to distinguish high crash clusters from low crash clusters makes them a superior technique for detecting crash hotspots than Moran's I index. Following an examination of crash spatial autocorrelation, *Gi** statistics were utilized to identify high and low crash severity clusters.

The first crash hotspot identification result for all Ethiopian regions and administrative cities revealed Addis Ababa and Oromia region as high crash severity clusters, with confidence intervals of 99% and 95%, respectively. Second, by combining spatial autocorrelation with *Gi** statistics, six statistically significant crash hotspots in Oromia were identified. The quantitative findings of Z-Scores prioritized East 'Shewa' zone and 'Burayu' town as the most crash hotspots with a confidence level of 99%. The six identified crash hotspot zones and towns are all located around the entrance to Addis Ababa, Ethiopia's capital city. Five main highways interconnect Addis Ababa to other towns, zones, and regions in Ethiopia, and all of these linking roads pass through the identified crash hotspots of Oromia. As a result of these findings, the study concluded that the detected crash hotspots are Addis Ababa and its entry and departure. Furthermore, the study's findings confirmed that the used approach of identifying crash hot spots has the ability to evaluate spatial patterns of crashes and identify densely clustered incidents in frequency and severity with statistical significance. The study found that employing GIS in Ethiopia has a substantial advantage when it comes to identifying prospective sites for safety improvements.

II. Applications of CPM for road safety performance evaluation

Safety evaluations based on road safety performance estimates (*i.e.,* CPM evaluation) are an efficient method for finding inconsistencies in a roadway network and measuring the relative safety performance of design alternatives. Predicting the number of crashes that may occur as a result of certain roadway characteristics is essential in assessing various remedies or design changes. However, in Ethiopia, road design guidelines based on design speed selection are recognized as the sole proxy measure of safety. The other two objectives of this dissertation, as stated in *Chapters 5* and *6*, were to fill a gap in the application of the predictive approach for road safety performance evaluation in Ethiopia by utilizing the most up-to-date analytical methods of the HSM predictive approach in IHSDM software to evaluate the safety and operational effects of existing road geometric features and quantify the relative safety effects design alternatives. The summaries of their findings are presented as follows.

A. Jurisdiction-Specific Crash Distribution Dataset

Chapter 5 presented the development and validation of a jurisdiction-specific Crash Distribution Dataset (CDD) for the undivided rural roads in the Oromia region, Ethiopia. Because various roadway geometric characteristics might impact CDDs, the Highway Safety Manual's (HSM's) prediction approach encourages users to predict crashes based on the proportions of severity and collision type. Seven years of collision data from rural two-way two-lane roads in the Oromia region were used to develop a CDD utilizing Interactive Highway Safety Design Model (IHSDM) software. The CDD is divided into two parts: crash severity proportions and collision type percentages. Using goodness-of-fit statistics and calibration factors, the developed Oromia's fixed CDD was tested and validated against the default HSM crash configuration.

As the first part of the CDD, the validation findings for the developed crash severity percentage indicated that the developed crash severity configuration estimations are more accurate and closer to the observed values. For example, the calibration factors for Fatal and Injury crashes (F+I) for the developed and HSM configurations are 1.018 and 1.915, respectively. Both configurations underestimate Fatal and Injury crashes, however, the developed configuration only does so in 1.8% of instances, whereas the HSM configuration does so in 91.5%. The findings also reveal that crashes in the Oromia region are more severe than those in the states where the HSM crash configuration was established. As the second part of the CDD (collision type proportion) validation, the developed fixed CDD outperforms the default HSM configuration in most collision type proportions, but not in all. For instance, of the ten collision type proportions developed, *Right-Angle* and *Sideswipe* collision proportions are predicted more precisely by the default HSM configuration. Based on the availability of complete crash data (i.e. crash locations), the second part of the CDD finding indicates the necessity for developing collision type proportion as a function rather than a fixed configuration for better estimates.

In general, the study acknowledges the international academic communities that CDDs vary from jurisdiction to jurisdiction due to differences in geographic conditions, crash reporting systems, road user characteristics (i.e., pedestrians, animals, and driver behavior), vehicle characteristics, climate conditions, and other undetected factors. To fully realize the capability of HSM’s predictive approach, researchers need to develop a jurisdiction CDD based on local crash data. The method employed in this study to develop the jurisdiction’s CDD has been confirmed as appropriate, so safety practitioners are encouraged to use it, and local agencies and safety experts in Ethiopia can incorporate the developed dataset into the crash prediction model analysis.

B. Safety performance evaluation

Finally, as the dissertation's final objective, the safety performance of existing rural two-way two-lane roads in Ethiopia was evaluated in *Chapter 6* using the local CDD developed in *Chapter 5*. The last objective of the dissertation is twofold: first, to close a gap in the integration of the predictive approach to road safety performance evaluation in Ethiopia by using the most recent analytical methods and technologies in the evaluation of the safety and operational effects of the existing roadway geometric design, and second, to quantify the relative safety effects of design changes made to the hazardous road segments. In the analysis, the recently formed and well-accepted safety tools of the HSM predictive method in the IHSDM software were used.

The study identified fifteen hazardous road segments on existing rural two-lane roads from *Addis Ababa to Chacha (AA-Ch)* and *Addis Ababa to Dillela (AA-D)* based on the Crash Prediction Module (CPM) evaluation of IHSDM software (i.e., the report of *Predicted Travel Crash Rate*, *crashes/million veh-km*). The geometric design modifications applied to the hazardous road segments have resulted in a considerable reduction in crash rates, notably on the top five most dangerous segments, where incredible reductions have been observed. The following are the overall safety advantages obtained by applying engineering mitigations to the fifteen identified hazardous segments: *Total Crash Frequency (crashes/yr)* decreased by 17.18%, *Crash Rate (crashes/km/yr)* decreased by 58.94%, and *Travel Crash Rate (crashes/million veh-km)* decreased by 58.86%. This demonstrates the significant effects of road geometric design features on the level of traffic safety.

In conclusion, the study's findings highlighted the efficacy of performance-based road safety evaluation and design in providing safe, efficient, and economically viable roadway infrastructure. The IHSDM reports and graphical outputs aid decision-making in the road design process by offering a quantitative assessment of the safety impact of various design characteristics and flagging roadway segments with safety problems. For example, based on the *Average Predicted Crash Rates* of all roads assessed and the identified hazardous segments, the result reveals that the identified hazardous segments are more than four times riskier and clearly they have safety issues in design. Furthermore, IHSDM is a time-saving tool for Road Safety Audit (RSA) teams.

7.2. Limitations of the Study

The availability of crash data recorded with precise incident locations in coordinates (using the Global Positioning System, GPS) or mileposts that can be linked to roadway geometric characteristics allows for a well-organized crash spatial pattern analysis that is specific to roadway segments and intersections, as well as the development of jurisdiction-specific Safety Performance Functions (SPFs) or calibration of the default SPFs for Ethiopia. The Ethiopian ministry of transport, regional transport authorities, and federal police commission-traffic police departments are in charge of collecting and reporting crash characteristics to safety researchers who require them. However, crash locations along a road alignment (milepost) are not available (have not been recorded) in Ethiopia. Due to this problem, such as the inaccessibility of crash locations (crashes assigned to specific roadway segments or intersections) in the study area (UNECE, 2021), the study was unable to investigate the spatial dependence of crashes on roadway parameters (such as road length, degree of curvature, AADT, sight distances, and others) as a contributing factor to crash occurrences, and it was also impossible to develop jurisdiction-specific SPFs or calibrate the *'base SPFs'* to local conditions.

7.3. Recommendations and Prospective Research Directions

Emphasizing the conclusions of the scientific studies and study limitations discussed earlier, the following recommendations and future research directions have been settled.

The identified crash hotspot locations are Addis Ababa and along the city's entrance and exit; therefore, the concerned bodies and traffic management agencies should give these areas top priority by intervening in traffic operations and conducting a thorough study to reduce the socio-economic impact of traffic collisions. It is suggested that the Oromia region's traffic management, transportation authority, and traffic police bureau intervene and monitor traffic flows based on the results of this study's crash analysis by day of week and time of day, such as during peak crash days and times when a higher number of crashes are most likely to occur. Moreover, the study concluded that using GIS in Ethiopia has a significant benefit when it comes to identifying potential sites for safety improvements. As a result, the use of GIS in crash hotspot analysis and mapping should be investigated and used as a tool for future road safety research initiatives in Ethiopia.

While statistical crash analysis is important in determining the road safety impact, it should be supplemented with spatial and temporal pattern analysis of crashes and traffic crash trends determined using a scientific approach. As a result, research on the spatial dependence, trend, distribution, causes, and magnitudes of traffic crashes must be conducted on a regular basis. The study's recommendations for future road safety improvements include the development of a national crash hotspot (blackspot) identification manual, the exploration of a catalog of crash modification factors and their benefits (using before and after analysis), the frequent spatial and temporal mapping of crash patterns, and the provision of training for safety engineers on the aforementioned factors as well as the integrity of advanced technology like GIS.

The predictive Highway Safety Manual and IHSDM software need to be adopted in Ethiopia for a better road safety performance assessment. As demonstrated in this study, unsubstituted default HSM configuration with the locally developed one may result in inaccurate and unrealistic crash distribution estimates and emasculate its liability. Therefore, to obtain accurate and locally feasible crash estimates in Ethiopia, the default HSM crash distribution must have to be substituted by the developed CDD in this study (for roads in Oromia) or developing regional CDDs using the procedures outlined in this study (in the case of roads apart from Oromia). Based on an accurate jurisdiction's crash distribution (i.e., by severity level and collision type), crash prediction models investigate the associations between roadway geometric characteristics and their related crash types. As a result, ERA and the Ethiopian MoT are recommended to incorporate the locally developed CDD in this study into the CPM evaluation to make effective improvements to the most severe crashes.

The findings of the CDD development and validation show that crashes in the Oromia region are more severe than in the states utilized to build the default HSM configuration. Therefore, a recommendation is made to the Oromia transportation authorities, traffic police bureaus, safety practitioners, and other concerned parties to cooperate and work in the reduction of crash severity levels across the region.

This study encourages transportation agencies and safety teams to implement IHSDM software as a decision-support tool during the RSA process to assess and quantify the safety and operation effects of different geometric design parameters for new and existing roads. To obtain reliable crash frequency prediction, jurisdiction-specific SPFs for Ethiopian roads must be developed, or the default HSM's SPFs must be calibrated. However, developing jurisdiction SPFs or calibrating the default SPFs requires assigning crash events to specific road segments (in mileposts) or intersections, which the country's crash recording systems are incapable of doing. As a result, it is recommended that the country's leading traffic safety councils and ministries address the data gaps and strive to develop local SPFs as prospective research work.

The actual extent of the country's traffic crash burden is far bigger than the police reported. The reason for the large disparities among police reported and WHO projections of crash fatalities in Ethiopia are attributable to underreporting and the country's poor quality of vital registry data. Whereas the country-reported data may be underreporting the issue, the WHO forecast might be regarded as an overestimate, and it should be answered properly by the WHO and the country’s traffic police department.

In Ethiopia, there is no computerized crash recording database; instead, crash recording is manual and paper-based, with no georeferenced crash locations (UNECE, 2021). Advanced technologies must support the crash recording and data-sharing platform, such as the application of a computerized crash database system and centralized mobile applications that enable GPS, which makes it easier to identify crash characteristics and locations at a crash event. To identify and evaluate the crash spatial pattern to apply effective safety measures, a trustworthy crash recording database is essential. Unfortunately, due to a lack of computerized crash databases and skilled experts, the crash recording systems of the country faces underreporting and errors in coding or injury severity estimation. Crash data collection, crash inspection, and reconstruction, and also traffic violation data recording need to be strengthened in the country. This data should be gathered and included in the national road safety database so that data-driven traffic monitoring and engineering mitigations can be implemented across the country. Finally, it is recommended that the Ethiopian Ministry of Transport work on developing crash database recording that is capable of documenting all crash characteristics, including crash locations using high-precision GPS technology, for the prospective road safety study.

Furthermore, a traffic crash costing platform for specific crash severity levels and the cost of various mitigations must be established in order to select the most economically feasible alternative mitigations and ensure that resource is distributed correctly. For the proposed engineering mitigations in *Chapter 6*, a benefit-cost ratio analysis must be performed to determine the viability of these mitigations or alternative designs. However, there is no agreed-upon or defined crash costs in Ethiopia, necessitating a thorough investigation. As a result, the study recommends that the viability of all design alternatives or mitigations must be examined in the future framework for implementation.

Road design standards based on design speed selection (ERA Geometric Design Manual) are recognized as the sole surrogate measure of safety in Ethiopia. Some Regional Authorities adhere to the ERA instructions and manual, whereas others design and operate with little safety concern. There has been minimal attention devoted to implementing best practices in road safety auditing during the design, construction, and operational stages. To mitigate the impact of road traffic crashes in Ethiopia, the following general recommendations are made to the relevant governments, non-governmental organizations, and individuals:

- Using the predictive technique outlined in this dissertation, the safety performance of new and existing roads of Ethiopia should be investigated regularly. The most modern analytical methods and technology should be maintained and calibrated for Ethiopia.
- Legislation should make RSAs (Road Safety Audits) and inspections mandatory, and RSA manuals should be drafted with the local circumstances of vehicles, road users, and traffic operations in mind. Policies and guidelines for the accreditation of traffic safety auditors and inspectors must be developed by the ministry of transport.
- To assure that road design and construction standards can meet the demands of road safety, they should be revised. Provide the implementation of safety performance-based road design and assessment.
- The government must invest in road safety research and innovations. Scientific analysis and research are essential for transferring proven and promising road safety approaches and technologies, as well as exploring crash modification factors and effective safety mitigations. Therefore, the responsible ministries and councils should hire experts and provide the necessary tools and resources for effective safety mitigation; collaborate with research institutions and universities; provide training for practitioners in road safety audits and inspections; and establish a national level road safety assessment framework using the most up-to-date analytical techniques and applicable technologies, such as HSM and IHSDM, which have been shown in this dissertation to be effective in assessing the relative safety performance of rural roads.

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Appendices

<u>Appendix-A</u>: Crash Prediction Evaluation Report, Highway #7 on Addis Ababa to Chacha Road

A.1. Evaluation Title-1: HSM Configuration (Crash Distribution Dataset)

Table A.1.1: Predicted Highway Crash Rates and Frequencies Summary (Highway 7)

First Year of Analysis	2017
Last Year of Analysis	2018
Evaluated Length (km)	6.1950
Average Future Road AADT (vpd)	3,653
Predicted Crashes	
Total Crashes	10.64
Fatal and Injury Crashes	3.42
Property-Damage-Only Crashes	7.23
Percent of Total Predicted Crashes	
Percent Fatal and Injury Crashes (%)	32
Percent Property-Damage-Only Crashes (%)	68
Predicted Crash Rate	
Crash Rate (crashes/km/yr)	0.8591
FI Crash Rate (crashes/km/yr)	0.2758
PDO Crash Rate (crashes/km/yr)	0.5833
Predicted Travel Crash Rate	
Total Travel (million veh-km)	16.52
Travel Crash Rate (crashes/million veh-km)	0.64
Travel FI Crash Rate (crashes/million veh-km)	0.21
Travel PDO Crash Rate (crashes/million veh-km)	0.44

NB: Total Travel (million veh-km) = (years of evaluation)(Length)*($AADT_{avg}$)*(365_{days})*10^{-6}*

Table A.1.2: Predicted Crash Frequencies and Rates by Horizontal Design Element (Highway 7)

Title	Start Location (Sta. m)	End Location (Sta. m)	Length (km)	Total Predicted Crashes for Evaluation Period	Predicted Total Crash Frequency (crashes/yr)	Predicted FI Crash Frequency (crashes/yr)	Predicted PDO Crash Frequency (crashes/yr)	Predicted Crash Rate (crashes/km/yr)	Predicted Travel Crash Rate (crashes/million veh-km)
Tangent	40+978.489	41+430.695	0.4522	0.550	0.2751	0.0883	0.1868	0.6083	0.46
Simple Curve 1	41+430.695	41+575.007	0.1443	0.285	0.1424	0.0457	0.0967	0.9869	0.74
Tangent	41+575.007	41+755.988	0.1810	0.218	0.1091	0.0350	0.0740	0.6026	0.45
Simple Curve 2	41+755.988	41+882.598	0.1266	0.306	0.1530	0.0491	0.1039	1.2083	0.91
Tangent	41+882.598	42+042.653	0.1601	0.193	0.0964	0.0310	0.0655	0.6026	0.45
Simple Curve 3	42+042.653	42+282.846	0.2402	0.438	0.2188	0.0702	0.1486	0.9110	0.68
Tangent	42+282.846	42+371.358	0.0885	0.117	0.0587	0.0188	0.0398	0.6628	0.50
Simple Curve 4	42+371.358	42+467.211	0.0959	0.343	0.1715	0.0551	0.1165	1.7895	1.34
Tangent	42+467.211	42+500.015	0.0328	0.040	0.0198	0.0063	0.0134	0.6026	0.45
Simple Curve 5	42+500.015	42+613.424	0.1134	0.547	0.2737	0.0879	0.1858	2.4135	1.81

Tangent	42+613.424	42+843.504	0.2301	0.305	0.1525	0.0490	0.1035	0.6628	0.50
Simple Curve 6	42+843.504	42+994.897	0.1514	0.236	0.1180	0.0379	0.0801	0.7796	0.58
Tangent	42+994.897	43+465.968	0.4711	0.625	0.3122	0.1002	0.2120	0.6628	0.50
Simple Curve 7	43+465.968	43+591.333	0.1254	0.279	0.1394	0.0448	0.0947	1.1121	0.83
Tangent	43+591.333	43+739.964	0.1486	0.197	0.0985	0.0316	0.0669	0.6628	0.50
Simple Curve 8	43+739.964	43+939.633	0.1997	0.349	0.1745	0.0560	0.1185	0.8738	0.66
Tangent	43+939.633	44+061.625	0.1220	0.162	0.0809	0.0260	0.0549	0.6628	0.50
Simple Curve 9	44+061.625	44+205.082	0.1435	0.303	0.1513	0.0486	0.1027	1.0547	0.79
Tangent	44+205.082	44+279.748	0.0747	0.099	0.0495	0.0159	0.0336	0.6628	0.50
Simple Curve 10	44+279.748	44+451.148	0.1714	0.396	0.1979	0.0635	0.1344	1.1546	0.87
Tangent	44+451.148	44+551.527	0.1004	0.133	0.0665	0.0214	0.0452	0.6628	0.50
Simple Curve 11	44+551.527	44+672.723	0.1212	0.273	0.1364	0.0438	0.0926	1.1255	0.84
Tangent	44+672.723	45+072.562	0.3998	0.544	0.2720	0.0873	0.1847	0.6802	0.51
Simple Curve 12	45+072.562	45+312.168	0.2396	0.620	0.3098	0.0994	0.2103	1.2929	0.97
Tangent	45+312.168	45+469.230	0.1571	0.189	0.0947	0.0304	0.0643	0.6030	0.45
Simple Curve 13	45+469.230	45+749.816	0.2806	0.509	0.2548	0.0818	0.1730	0.9080	0.68
Tangent	45+749.816	45+795.479	0.0457	0.064	0.0319	0.0102	0.0217	0.6990	0.52
Simple Curve 14	45+795.479	45+939.616	0.1441	0.301	0.1506	0.0483	0.1023	1.0448	0.78
Tangent	45+939.616	45+994.562	0.0549	0.073	0.0364	0.0117	0.0247	0.6628	0.50
Simple Curve 15	45+994.562	46+065.704	0.0711	0.219	0.1094	0.0351	0.0743	1.5379	1.15
Tangent	46+065.704	46+542.798	0.4771	0.632	0.3162	0.1015	0.2147	0.6628	0.50
Simple Curve 16	46+542.798	46+612.781	0.0700	0.239	0.1195	0.0384	0.0812	1.7079	1.28
Tangent	46+612.781	46+723.041	0.1103	0.146	0.0731	0.0235	0.0496	0.6628	0.50
Simple Curve 17	46+723.041	47+073.246	0.3502	0.584	0.2921	0.0938	0.1984	0.8342	0.63
Tangent	47+073.246	47+173.489	0.1002	0.131	0.0654	0.0210	0.0444	0.6525	0.49

Table A.1.3: Predicted Crash Type Distribution (Highway 7)

Element Type	**Crash Type**	**Fatal and Injury**		**Property Damage Only**		**Total**	
		Crashes	**Crashes (%)**	**Crashes**	**Crashes (%)**	**Crashes**	**Crashes (%)**
Highway Segment	Collision with Animal	0.13	1.2	1.33	12.5	1.29	12.1
Highway Segment	Collision with Bicycle	0.01	0.1	0.01	0.1	0.02	0.2
Highway Segment	Other Single-vehicle Collision	0.02	0.2	0.21	2.0	0.22	2.1
Highway Segment	Overturned	0.13	1.2	0.11	1.0	0.27	2.5
Highway Segment	Collision with Pedestrian	0.02	0.2	0.01	0.1	0.03	0.3
Highway Segment	Run Off Road	1.86	17.5	3.65	34.3	5.55	52.1
Highway Segment	Total Single Vehicle Crashes	2.18	20.5	5.31	49.9	7.38	69.3
Highway Segment	Right-Angle Collision	0.34	3.2	0.52	4.9	0.91	8.5
Highway Segment	Head-on Collision	0.12	1.1	0.02	0.2	0.17	1.6
Highway Segment	Other Multi-vehicle Collision	0.09	0.8	0.22	2.0	0.29	2.7
Highway Segment	Rear-end Collision	0.56	5.3	0.88	8.3	1.51	14.2
Highway Segment	Sideswipe	0.13	1.2	0.28	2.6	0.39	3.7
Highway Segment	Total Multiple Vehicle Crashes	1.24	11.7	1.92	18.0	3.27	30.7
Highway Segment	Total Highway Segment Crashes	3.42	32.2	7.23	67.9	10.64	100.0
	Total Crashes	3.42	32.2	7.23	67.9	10.64	100.0

Note: *Fatal and Injury Crashes* and *Property Damage Only Crashes* do not necessarily sum up to *Total Crashes* because the distribution of these three crashes had been derived independently.

A.2. Evaluation Title-2: Oromia Configuration (Crash Distribution Dataset)

Table A.2.1: Predicted Highway Crash Rates and Frequencies Summary (Highway 7)

First Year of Analysis	2017
Last Year of Analysis	2018
Evaluated Length (km)	6.1950
Average Future Road AADT (vpd)	3,653
Predicted Crashes	
Total Crashes	10.64
Fatal and Injury Crashes	6.43
Property-Damage-Only Crashes	4.21
Percent of Total Predicted Crashes	
Percent Fatal and Injury Crashes (%)	60
Percent Property-Damage-Only Crashes (%)	40
Predicted Crash Rate	
Crash Rate (crashes/km/yr)	0.8587
FI Crash Rate (crashes/km/yr)	0.5188
PDO Crash Rate (crashes/km/yr)	0.3400
Predicted Travel Crash Rate	
Total Travel (million veh-km)	16.52
Travel Crash Rate (crashes/million veh-km)	0.64
Travel FI Crash Rate (crashes/million veh-km)	0.39
Travel PDO Crash Rate (crashes/million veh-km)	0.26

Table A.2.2: Predicted Crash Frequencies and Rates by Horizontal Design Element (Highway 7)

Title	Start Location (Sta. m)	End Location (Sta. m)	Length (km)	Total Predicted Crashes for Evaluation Period	Predicted Total Crash Frequency (crashes/yr)	Predicted FI Crash Frequency (crashes/yr)	Predicted PDO Crash Frequency (crashes/yr)	Predicted Crash Rate (crashes/km/ yr)	Predicted Travel Crash Rate (crashes/million veh-km)
Tangent	40+978.489	41+430.695	0.4522	0.550	0.2749	0.1661	0.1088	0.6080	0.46
Simple Curve 1	41+430.695	41+575.007	0.1443	0.285	0.1424	0.0860	0.0564	0.9865	0.74
Tangent	41+575.007	41+755.988	0.1810	0.218	0.1090	0.0659	0.0432	0.6023	0.45
Simple Curve 2	41+755.988	41+882.598	0.1266	0.306	0.1529	0.0924	0.0605	1.2078	0.91
Tangent	41+882.598	42+042.653	0.1601	0.193	0.0964	0.0582	0.0382	0.6023	0.45
Simple Curve 3	42+042.653	42+282.846	0.2402	0.438	0.2187	0.1321	0.0866	0.9106	0.68
Tangent	42+282.846	42+371.358	0.0885	0.117	0.0586	0.0354	0.0232	0.6626	0.50
Simple Curve 4	42+371.358	42+467.211	0.0959	0.343	0.1715	0.1036	0.0679	1.7889	1.34
Tangent	42+467.211	42+500.015	0.0328	0.040	0.0198	0.0119	0.0078	0.6023	0.45
Simple Curve 5	42+500.015	42+613.424	0.1134	0.547	0.2736	0.1653	0.1083	2.4126	1.81
Tangent	42+613.424	42+843.504	0.2301	0.305	0.1524	0.0921	0.0604	0.6626	0.50
Simple Curve 6	42+843.504	42+994.897	0.1514	0.236	0.1180	0.0713	0.0467	0.7793	0.58
Tangent	42+994.897	43+465.968	0.4711	0.624	0.3121	0.1885	0.1236	0.6626	0.50
Simple Curve 7	43+465.968	43+591.333	0.1254	0.279	0.1394	0.0842	0.0552	1.1117	0.83
Tangent	43+591.333	43+739.964	0.1486	0.197	0.0985	0.0595	0.0390	0.6626	0.50
Simple Curve 8	43+739.964	43+939.633	0.1997	0.349	0.1744	0.1054	0.0691	0.8735	0.66
Tangent	43+939.633	44+061.625	0.1220	0.162	0.0808	0.0488	0.0320	0.6626	0.50
Simple Curve 9	44+061.625	44+205.082	0.1435	0.302	0.1512	0.0914	0.0599	1.0543	0.79
Tangent	44+205.082	44+279.748	0.0747	0.099	0.0495	0.0299	0.0196	0.6626	0.50
Simple Curve 10	44+279.748	44+451.148	0.1714	0.396	0.1978	0.1195	0.0783	1.1541	0.87
Tangent	44+451.148	44+551.527	0.1004	0.133	0.0665	0.0402	0.0263	0.6626	0.50
Simple Curve 11	44+551.527	44+672.723	0.1212	0.273	0.1364	0.0824	0.0540	1.1251	0.84

Tangent	44+672.723	45+072.562	0.3998	0.544	0.2719	0.1642	0.1076	0.6799	0.51
Simple Curve 12	45+072.562	45+312.168	0.2396	0.619	0.3097	0.1871	0.1226	1.2924	0.97
Tangent	45+312.168	45+469.230	0.1571	0.189	0.0947	0.0572	0.0375	0.6028	0.45
Simple Curve 13	45+469.230	45+749.816	0.2806	0.509	0.2547	0.1538	0.1008	0.9076	0.68
Tangent	45+749.816	45+795.479	0.0457	0.064	0.0319	0.0193	0.0126	0.6987	0.52
Simple Curve 14	45+795.479	45+939.616	0.1441	0.301	0.1505	0.0909	0.0596	1.0445	0.78
Tangent	45+939.616	45+994.562	0.0549	0.073	0.0364	0.0220	0.0144	0.6626	0.50
Simple Curve 15	45+994.562	46+065.704	0.0711	0.219	0.1094	0.0661	0.0433	1.5373	1.15
Tangent	46+065.704	46+542.798	0.4771	0.632	0.3161	0.1910	0.1251	0.6626	0.50
Simple Curve 16	46+542.798	46+612.781	0.0700	0.239	0.1195	0.0722	0.0473	1.7073	1.28
Tangent	46+612.781	46+723.041	0.1103	0.146	0.0731	0.0441	0.0289	0.6626	0.50
Simple Curve 17	46+723.041	47+073.246	0.3502	0.584	0.2920	0.1764	0.1156	0.8339	0.62
Tangent	47+073.246	47+173.489	0.1002	0.131	0.0653	0.0395	0.0259	0.6517	0.49

Table A.2.3: Predicted Crash Type Distribution (Highway 7)

Element Type	**Crash Type**	**Fatal and Injury**		**Property Damage Only**		**Total**	
		Crashes	**Crashes (%)**	**Crashes**	**Crashes (%)**	**Crashes**	**Crashes (%)**
Highway Segment	Collision with Animal	0.35	3.3	0.13	1.2	0.48	4.5
Highway Segment	Collision with Bicycle	0.00	0.0	0.00	0.0	0.00	0.0
Highway Segment	Other Single-vehicle Collision	0.17	1.6	0.12	1.1	0.29	2.8
Highway Segment	Overturned	0.31	2.9	0.42	4.0	0.73	6.8
Highway Segment	Collision with Pedestrian	0.84	7.9	0.04	0.3	0.88	8.3
Highway Segment	Run Off Road	3.08	28.9	2.23	21.0	5.31	49.9
Highway Segment	Total Single Vehicle Crashes	4.75	44.6	2.94	27.6	7.69	72.3
Highway Segment	Right-Angle Collision	0.38	3.6	0.21	2.0	0.60	5.6
Highway Segment	Head-on Collision	0.33	3.1	0.37	3.5	0.70	6.5
Highway Segment	Other Multi-vehicle Collision	0.26	2.5	0.19	1.8	0.45	4.2
Highway Segment	Rear-end Collision	0.43	4.0	0.34	3.2	0.77	7.2
Highway Segment	Sideswipe	0.27	2.6	0.16	1.5	0.44	4.1
Highway Segment	Total Multiple Vehicle Crashes	1.68	15.8	1.27	12.0	2.95	27.7
Highway Segment	Total Highway Segment Crashes	6.43	60.4	4.21	39.6	10.64	100.0
	Total Crashes	6.43	60.4	4.21	39.6	10.64	100.0

Note: *Fatal and Injury Crashes* and *Property Damage Only Crashes* do not necessarily sum up to *Total Crashes* because the distribution of these three crashes had been derived independently.

Appendix-B: CPM Evaluation Report on Addis Ababa to Dilella Road, Section-4 (4+510.000 – 7+730.000)

Interactive Highway Safety Design Model

Crash Prediction Evaluation Report

Prepared by

Alamirew Mulugeta Tola

April 20, 2021

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Report Overview

Report Generated: Apr 20, 2021 9:22 PM
Report Template: System: Single Page [System] (mlcpm3, Mar 21, 2021 9:10 AM)

Evaluation Date: Mon Apr 19 03:02:25 EAT 2021
IHSDM Version: v16.0.0 (Sep 30, 2020)

Crash Prediction Module: v11.0.0 (Sep 30, 2020)
Project Title: Paper #3 Analysis
Project Comment: Created Fri Apr 02 03:52:20 EAT 2021
Project Unit System: Metric

Highway Title: Addis Ababa to Dilella Road
Highway Comment: Addis Ababa to Dilella Road (v1)
Highway Version: 1

Evaluation Title: Evaluation 1
Evaluation Comment: Created Mon Apr 20 02:58:40 EAT 2021

Minimum Location: 4+510.000
Maximum Location: 7+730.000
Policy for Superelevation: ERA 2013 Metric
Calibration: HSM Configuration
Crash Distribution: Oromia Configuration
Model/CMF: HSM Configuration
First Year of Analysis: 2010
Last Year of Analysis: 2029
Empirical-Bayes Analysis: None
First Year of Observed Crashes:
Last Year of Observed Crashes:

Disclaimer Regarding Crash Prediction Method

IMPORTANT NOTICE ABOUT COMPARING RESULTS FROM HIGHWAY SAFETY MANUAL FIRST EDITION (2010) MODELS TO RESULTS FROM NEW MODELS DEVELOPED UNDER NCHRP PROJECTS 17-70 AND 17-58

Since the publication of the Highway Safety Manual - First Edition (HSM-1), in 2010 by the American Association of State Highway and Transportation Officials (AASHTO), multiple research efforts have been undertaken through the National Cooperative Highway Research Program (NCHRP) to develop safety performance models for road segment and intersection facility types that were not initially reflected in the HSM-1, in order to expand the breadth and depth of the HSM in the future.

The IHSDM Crash Prediction Module (CPM) is intended as a faithful implementation of HSM Part C predictive methods. As NCHRP projects to develop new predictive methods for the HSM are completed, FHWA works to incorporate the new methods into IHSDM, sometimes in advance of publication in the HSM. The following new crash predictive methods have been accepted by NCHRP project panels and incorporated into IHSDM, while pending AASHTO's approval for incorporation into a future edition of the HSM:

- Roundabouts: completed in 2018 under NCHRP Project 17-70, the new methods will provide improved outcomes for the safety analysis of roundabouts.
- 6+ lane and one-way urban/suburban arterials (including models for segments and intersections): completed under NCHRP Project 17-58.

However, in the absence of local calibration factors (see HSM-1 Part C, Appendix A for guidance on calibration of the predictive models), it is neither appropriate nor advisable to directly compare the results from new models (from NCHRP Projects 17-58 and 17-70) to results from HSM-1 models, as the models were not calibrated to the same base state data sets, and consequently can produce unexpected results. If local calibration factors are available and applied to both new models and HSM-1 models, then it may be appropriate to directly compare the results.*[Note: Work being performed under NCHRP Project 17-72 (Update of Crash Modification Factors for the Highway Safety Manual) is expected to re-calibrate many of the old (HSM-1) and new (e.g., NCHRP 17-70) models to data from a single (or small number of) states, that would allow results from all models to be directly compared.]*

The models produced for NCHRP Project 17-70 have independent value in terms of informing the design of a roundabout and assessing the effects of different design characteristics on the expected safety performance of a roundabout.

The HSM-1 interim method previously included in IHSDM for evaluating roundabouts on urban/suburban arterials (i.e., evaluating an existing intersection and then applying a Crash Modification Factor for replacing the existing intersection with a roundabout) has been deactivated in IHSDM, to minimize any confusion with the new roundabout methodology.

Section Types

Section 4 Evaluation

Section: Section 4
Evaluation Start Location: 4+510.000
Evaluation End Location: 7+730.000
Area Type: Rural
Functional Class: Arterial
Type of Alignment: Undivided, Two Lane
Model Category: Rural, Two Lane
Calibration Factor: 2U=1.0;

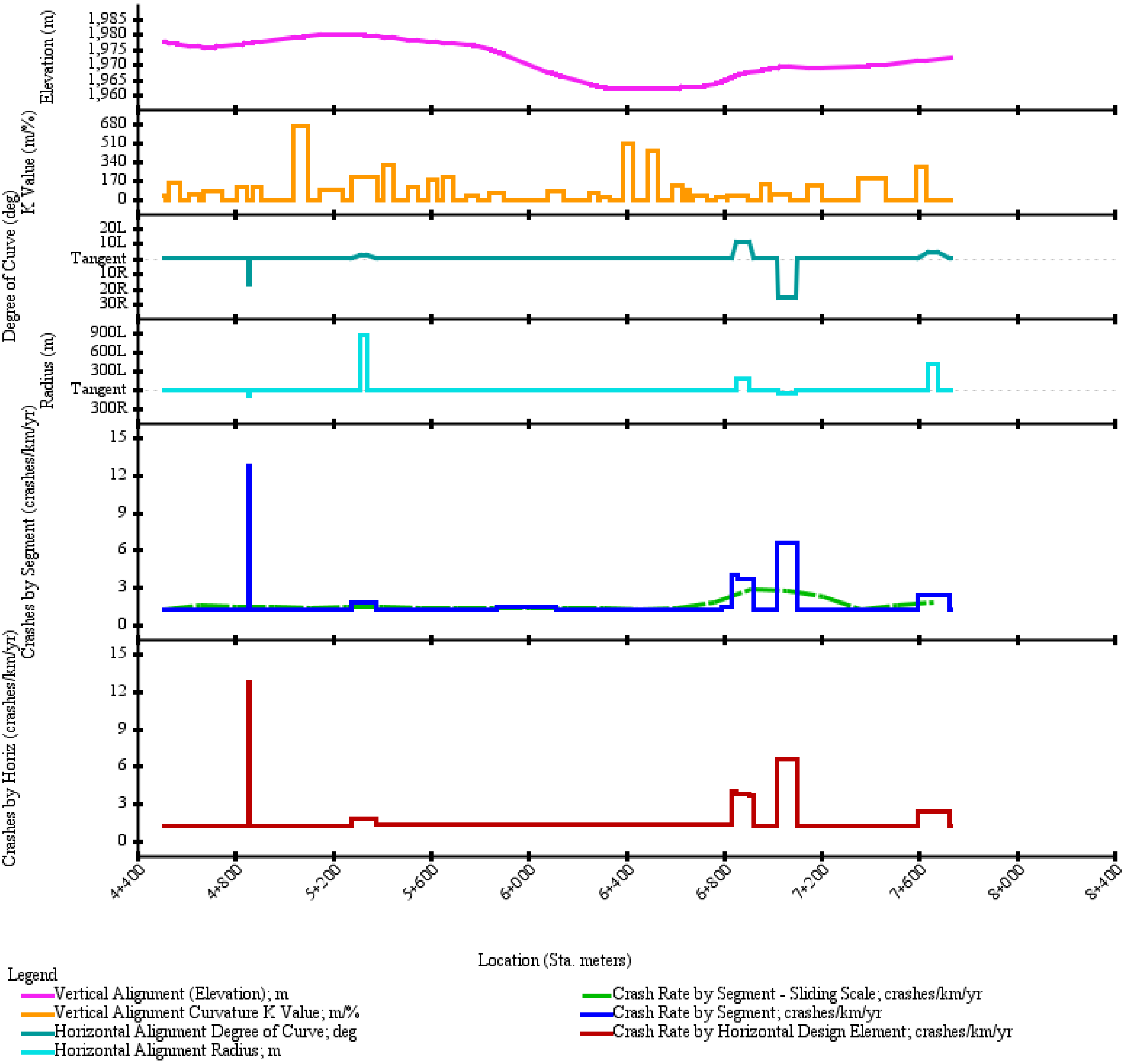

Figure B.1. Crash Prediction Summary (Section 4)

Table B.1. Evaluation Highway - Homogeneous Segments (Section 4)

Seg. No.	Type	Start Location (Sta. m)	End Location (Sta. m)	Length (m)	Left Lane Width (m)	Right Lane Width (m)	Left Shoulder Width (m)	Right Shoulder Width (m)	Grade (%)	Driveway Density (driveways/km)	RHR	Centerline Rumble Strip	Passing Lanes	TWLT Lane	Lighting	Automated Speed Enforcement	Radius (m)	Superelevation (%)	Design Speed (km/h)
1	UR-TL-TW	4+510.000	4+550.000	40.00	3.50	3.50	1.50	1.50	- 1.00	1.6	3	false	0	false	false	false			
2	UR-TL-TW	4+550.000	4+630.000	80.00	3.50	3.50	1.50	1.50	- 1.34	1.6	3	false	0	false	false	false			
3	UR-TL-TW	4+630.000	4+710.000	80.00	3.50	3.50	1.50	1.50	- 0.33	1.6	3	false	0	false	false	false			
4	UR-TL-TW	4+710.000	4+830.000	120.00	3.50	3.50	1.50	1.50	0.89	1.6	3	false	0	false	false	false			
5	UR-TL-TW	4+830.000	4+853.484	23.48	3.50	3.50	1.50	1.50	1.25	1.6	3	false	0	false	false	false			
6	UR-TL-TW	4+853.484	4+855.420	1.94	3.50	3.50	1.50	1.50	1.25	1.6	3	false	0	false	false	false	100.00	4.0	80
7	UR-TL-TW	4+855.420	4+860.634	5.21	3.50	3.50	1.50	1.50	1.25	1.6	3	false	0	false	false	false	100.00	4.0	80
8	UR-TL-TW	4+860.634	4+862.570	1.94	3.50	3.50	1.50	1.50	1.25	1.6	3	false	0	false	false	false	100.00	4.0	80
9	UR-TL-TW	4+862.570	4+890.000	27.43	3.50	3.50	1.50	1.50	1.25	1.6	3	false	0	false	false	false			
10	UR-TL-TW	4+890.000	5+070.087	180.09	3.50	3.50	1.50	1.50	0.90	1.6	3	false	0	false	false	false			
11	UR-TL-TW	5+070.087	5+194.080	123.99	3.50	3.50	1.50	1.50	0.81	1.6	3	false	0	false	false	false			
12	UR-TL-TW	5+194.080	5+275.757	81.68	3.50	3.50	1.50	1.50	- 0.26	1.6	3	false	0	false	false	false			
13	UR-TL-TW	5+275.757	5+310.040	34.28	3.50	3.50	1.50	1.50	- 0.26	1.6	3	false	0	false	false	false	857.08	2.5	80
14	UR-TL-TW	5+310.040	5+330.000	19.96	3.50	3.50	1.50	1.50	- 0.26	1.6	3	false	0	false	false	false	857.08	2.5	80
15	UR-TL-TW	5+330.000	5+342.317	12.32	3.50	3.50	1.50	1.50	- 0.82	1.6	3	false	0	false	false	false	857.08	2.5	80
16	UR-TL-TW	5+342.317	5+376.600	34.28	3.50	3.50	1.50	1.50	- 0.82	1.6	3	false	0	false	false	false	857.08	2.5	80
17	UR-TL-TW	5+376.600	5+430.000	53.40	3.50	3.50	1.50	1.50	- 0.82	1.6	3	false	0	false	false	false			
18	UR-TL-TW	5+430.000	5+530.000	100.00	3.50	3.50	1.50	1.50	- 0.95	1.6	3	false	0	false	false	false			
19	UR-TL-TW	5+530.000	5+610.000	80.00	3.50	3.50	1.50	1.50	- 0.56	1.6	3	false	0	false	false	false			
20	UR-TL-TW	5+610.000	5+671.968	1.97	3.50	3.50	1.50	1.50	- 0.78	1.6	3	false	0	false	false	false			
21	UR-TL-TW	5+671.968	5+770.000	98.03	3.50	3.50	1.50	1.50	- 0.58	1.6	3	false	0	false	false	false			
22	UR-TL-TW	5+770.000	5+870.000	100.00	3.50	3.50	1.50	1.50	- 2.11	1.6	3	false	0	false	false	false			
23	UR-TL-TW	5+870.000	6+111.969	241.97	3.50	3.50	1.50	1.50	- 3.20	1.6	3	false	0	false	false	false			
24	UR-TL-TW	6+111.969	6+270.000	158.03	3.50	3.50	1.50	1.50	- 2.30	1.6	3	false	0	false	false	false			

25	UR-TL-TW	6+270.000	6+311.969	41.97	3.50	3.50	1.50	1.50	- 1.63	1.6	3	false	0	false	false	false			
26	UR-TL-TW	6+311.969	6+410.000	98.03	3.50	3.50	1.50	1.50	- 0.02	1.6	3	false	0	false	false	false			
27	UR-TL-TW	6+410.000	6+510.000	100.00	3.50	3.50	1.50	1.50	0.06	1.6	3	false	0	false	false	false			
28	UR-TL-TW	6+510.000	6+610.000	100.00	3.50	3.50	1.50	1.50	- 0.03	1.6	3	false	0	false	false	false			
29	UR-TL-TW	6+610.000	6+651.970	41.97	3.50	3.50	1.50	1.50	0.29	1.6	3	false	0	false	false	false			
30	UR-TL-TW	6+651.970	6+703.245	51.27	3.50	3.50	1.50	1.50	0.04	1.6	3	false	0	false	false	false			
31	UR-TL-TW	6+703.245	6+793.156	89.91	3.50	3.50	1.50	1.50	1.98	1.6	3	false	0	false	false	false			
32	UR-TL-TW	6+793.156	6+831.965	38.81	3.50	3.50	1.50	1.50	3.92	1.6	3	false	0	false	false	false			
33	UR-TL-TW	6+831.965	6+850.095	18.13	3.50	3.50	1.50	1.50	3.92	1.6	3	false	0	false	false	false	163.17	4.0	80
34	UR-TL-TW	6+850.095	6+860.000	9.90	3.50	3.50	1.50	1.50	3.92	1.6	3	false	0	false	false	false	163.17	4.0	80
35	UR-TL-TW	6+860.000	6+904.803	44.80	3.50	3.50	1.50	1.50	1.31	1.6	3	false	0	false	false	false	163.17	4.0	80
36	UR-TL-TW	6+904.803	6+922.933	18.13	3.50	3.50	1.50	1.50	1.31	1.6	3	false	0	false	false	false	163.17	4.0	80
37	UR-TL-TW	6+922.933	6+970.000	47.07	3.50	3.50	1.50	1.50	1.31	1.6	3	false	0	false	false	false			
38	UR-TL-TW	6+970.000	7+017.218	47.22	3.50	3.50	1.50	1.50	1.60	1.6	3	false	0	false	false	false			
39	UR-TL-TW	7+017.218	7+024.745	7.53	3.50	3.50	1.50	1.50	1.60	1.6	3	false	0	false	false	false	67.75	7.0	80
40	UR-TL-TW	7+024.745	7+033.000	8.26	3.50	3.50	1.50	1.50	1.60	1.6	3	false	0	false	false	false	67.75	7.0	80
41	UR-TL-TW	7+033.000	7+096.671	63.67	3.50	3.50	1.50	1.50	- 0.22	1.6	3	false	0	false	false	false	67.75	7.0	80
42	UR-TL-TW	7+096.671	7+104.199	7.53	3.50	3.50	1.50	1.50	- 0.22	1.6	3	false	0	false	false	false	67.75	7.0	80
43	UR-TL-TW	7+104.199	7+175.000	70.80	3.50	3.50	1.50	1.50	- 0.22	1.6	3	false	0	false	false	false			
44	UR-TL-TW	7+175.000	7+406.534	231.53	3.50	3.50	1.50	1.50	0.24	1.6	3	false	0	false	false	false			
45	UR-TL-TW	7+406.534	7+592.480	185.95	3.50	3.50	1.50	1.50	0.84	1.6	3	false	0	false	false	false			
46	UR-TL-TW	7+592.480	7+610.000	17.52	3.50	3.50	1.50	1.50	0.84	1.6	3	false	0	false	false	false	392.76	2.5	80
47	UR-TL-TW	7+610.000	7+636.119	26.12	3.50	3.50	1.50	1.50	0.69	1.6	3	false	0	false	false	false	392.76	2.5	80
48	UR-TL-TW	7+636.119	7+680.443	44.32	3.50	3.50	1.50	1.50	0.69	1.6	3	false	0	false	false	false	392.76	2.5	80
49	UR-TL-TW	7+680.443	7+724.083	43.64	3.50	3.50	1.50	1.50	0.69	1.6	3	false	0	false	false	false	392.76	2.5	80
50	UR-TL-TW	7+724.083	7+730.000	5.92	3.50	3.50	1.50	1.50	0.69	1.6	3	false	0	false	false	false			

Table B.2. Predicted Highway Crash Rates and Frequencies Summary (Section 4)

First Year of Analysis	2010
Last Year of Analysis	2029
Evaluated Length (km)	3.2200
Average Future Road AADT (vpd)	7,198
Predicted Crashes	
Total Crashes	102.54
Fatal and Injury Crashes	61.95
Property-Damage-Only Crashes	40.60
Percent of Total Predicted Crashes	
Percent Fatal and Injury Crashes (%)	60
Percent Property-Damage-Only Crashes (%)	40
Predicted Crash Rate	
Crash Rate (crashes/km/yr)	1.5923
FI Crash Rate (crashes/km/yr)	0.9619
PDO Crash Rate (crashes/km/yr)	0.6304
Predicted Travel Crash Rate	
Total Travel (million veh-km)	169.20
Travel Crash Rate (crashes/million veh-km)	0.61
Travel FI Crash Rate (crashes/million veh-km)	0.37
Travel PDO Crash Rate (crashes/million veh-km)	0.24

Table B.3. Predicted Crash Frequencies and Rates by Highway Segment/Intersection (Section 4)

Segment Number/Intersection Name/Cross Road	Start Location (Sta. m)	End Location (Sta. m)	Length (km)	Total Predicted Crashes for Evaluation Period	Predicted Total Crash Frequency (crashes/yr)	Predicted FI Crash Frequency (crashes/yr)	Predicted PDO Crash Frequency (crashes/yr)	Predicted Crash Rate (crashes/km/yr)	Predicted Travel Crash Rate (crashes/million veh-km)
1	4+510.000	4+550.000	0.0400	1.018	0.0509	0.0308	0.0202	1.2731	0.48
2	4+550.000	4+630.000	0.0800	2.037	0.1018	0.0615	0.0403	1.2731	0.48
3	4+630.000	4+710.000	0.0800	2.037	0.1018	0.0615	0.0403	1.2731	0.48
4	4+710.000	4+830.000	0.1200	3.055	0.1528	0.0923	0.0605	1.2731	0.48
5	4+830.000	4+853.484	0.0235	0.598	0.0299	0.0181	0.0118	1.2731	0.48
6	4+853.484	4+855.420	0.0019	0.492	0.0246	0.0149	0.0097	12.7161	4.84
7	4+855.420	4+860.634	0.0052	1.326	0.0663	0.0401	0.0262	12.7161	4.84
8	4+860.634	4+862.570	0.0019	0.492	0.0246	0.0149	0.0097	12.7161	4.84
9	4+862.570	4+890.000	0.0274	0.698	0.0349	0.0211	0.0138	1.2731	0.48
10	4+890.000	5+070.087	0.1801	4.585	0.2293	0.1385	0.0908	1.2731	0.48
11	5+070.087	5+194.080	0.1240	3.157	0.1579	0.0954	0.0625	1.2731	0.48
12	5+194.080	5+275.757	0.0817	2.080	0.1040	0.0628	0.0412	1.2731	0.48
13	5+275.757	5+310.040	0.0343	1.273	0.0636	0.0384	0.0252	1.8561	0.71
14	5+310.040	5+330.000	0.0200	0.741	0.0370	0.0224	0.0147	1.8561	0.71
15	5+330.000	5+342.317	0.0123	0.457	0.0229	0.0138	0.0091	1.8561	0.71
16	5+342.317	5+376.600	0.0343	1.273	0.0636	0.0384	0.0252	1.8561	0.71

17	5+376.600	5+430.000	0.0534	1.360	0.0680	0.0411	0.0269	1.2731	0.48
18	5+430.000	5+530.000	0.1000	2.546	0.1273	0.0769	0.0504	1.2731	0.48
19	5+530.000	5+610.000	0.0800	2.037	0.1018	0.0615	0.0403	1.2731	0.48
20	5+610.000	5+671.968	0.0620	1.578	0.0789	0.0477	0.0312	1.2731	0.48
21	5+671.968	5+770.000	0.0980	2.496	0.1248	0.0754	0.0494	1.2731	0.48
22	5+770.000	5+870.000	0.1000	2.546	0.1273	0.0769	0.0504	1.2731	0.48
23	5+870.000	6+111.969	0.2420	6.777	0.3388	0.2047	0.1342	1.4004	0.53
24	6+111.969	6+270.000	0.1580	4.024	0.2012	0.1215	0.0796	1.2731	0.48
25	6+270.000	6+311.969	0.0420	1.069	0.0534	0.0323	0.0212	1.2731	0.48
26	6+311.969	6+410.000	0.0980	2.496	0.1248	0.0754	0.0494	1.2731	0.48
27	6+410.000	6+510.000	0.1000	2.546	0.1273	0.0769	0.0504	1.2731	0.48
28	6+510.000	6+610.000	0.1000	2.546	0.1273	0.0769	0.0504	1.2731	0.48
29	6+610.000	6+651.970	0.0420	1.069	0.0534	0.0323	0.0212	1.2731	0.48
30	6+651.970	6+703.245	0.0513	1.306	0.0653	0.0394	0.0258	1.2731	0.48
31	6+703.245	6+793.156	0.0899	2.289	0.1145	0.0691	0.0453	1.2731	0.48
32	6+793.156	6+831.965	0.0388	1.087	0.0543	0.0328	0.0215	1.4004	0.53
33	6+831.965	6+850.095	0.0181	1.463	0.0732	0.0442	0.0290	4.0355	1.54
34	6+850.095	6+860.000	0.0099	0.799	0.0400	0.0241	0.0158	4.0355	1.54
35	6+860.000	6+904.803	0.0448	3.287	0.1644	0.0993	0.0651	3.6686	1.40
36	6+904.803	6+922.933	0.0181	1.330	0.0665	0.0402	0.0263	3.6686	1.40
37	6+922.933	6+970.000	0.0471	1.198	0.0599	0.0362	0.0237	1.2731	0.48
38	6+970.000	7+017.218	0.0472	1.202	0.0601	0.0363	0.0238	1.2731	0.48
39	7+017.218	7+024.745	0.0075	0.990	0.0495	0.0299	0.0196	6.5738	2.50
40	7+024.745	7+033.000	0.0083	1.085	0.0543	0.0328	0.0215	6.5738	2.50
41	7+033.000	7+096.671	0.0637	8.371	0.4186	0.2529	0.1657	6.5738	2.50
42	7+096.671	7+104.199	0.0075	0.990	0.0495	0.0299	0.0196	6.5738	2.50
43	7+104.199	7+175.000	0.0708	1.803	0.0901	0.0545	0.0357	1.2731	0.48
44	7+175.000	7+406.534	0.2315	5.895	0.2948	0.1781	0.1167	1.2731	0.48
45	7+406.534	7+592.480	0.1859	4.734	0.2367	0.1430	0.0937	1.2731	0.48
46	7+592.480	7+610.000	0.0175	0.819	0.0410	0.0247	0.0162	2.3376	0.89
47	7+610.000	7+636.119	0.0261	1.221	0.0611	0.0369	0.0242	2.3376	0.89
48	7+636.119	7+680.443	0.0443	2.072	0.1036	0.0626	0.0410	2.3376	0.89
49	7+680.443	7+724.083	0.0436	2.040	0.1020	0.0616	0.0404	2.3376	0.89
50	7+724.083	7+730.000	0.0059	0.151	0.0075	0.0046	0.0030	1.2731	0.48
Total			3.2200	102.544	5.1272	3.0973	2.0299	1.5923	

Table B.4. Predicted Crash Frequencies and Rates by Horizontal Design Element (Section 4)

Title	Start Location (Sta. m)	End Location (Sta. m)	Length (km)	Total Predicted Crashes for Evaluation Period	Predicted Total Crash Frequency (crashes/yr)	Predicted FI Crash Frequency (crashes/yr)	Predicted PDO Crash Frequency (crashes/yr)	Predicted Crash Rate (crashes/km/yr)	Predicted Travel Crash Rate (crashes/mi llion veh- km)
Tangent	4+510.000	4+853.484	0.3435	8.746	0.4373	0.2642	0.1731	1.2731	0.48
Spiral Curve 1	4+853.484	4+855.420	0.0019	0.492	0.0246	0.0149	0.0097	12.7161	4.84
Simple Curve 2	4+855.420	4+860.634	0.0052	1.326	0.0663	0.0401	0.0262	12.7161	4.84
Spiral Curve 3	4+860.634	4+862.570	0.0019	0.492	0.0246	0.0149	0.0097	12.7161	4.84
Tangent	4+862.570	5+275.757	0.4132	10.520	0.5260	0.3178	0.2083	1.2731	0.48
Spiral Curve 4	5+275.757	5+310.040	0.0343	1.273	0.0636	0.0384	0.0252	1.8561	0.71
Simple Curve 5	5+310.040	5+342.317	0.0323	1.198	0.0599	0.0362	0.0237	1.8561	0.71
Spiral Curve 6	5+342.317	5+376.600	0.0343	1.273	0.0636	0.0384	0.0252	1.8561	0.71
Tangent	5+376.600	6+831.965	1.4554	37.771	1.8885	1.1409	0.7477	1.2976	0.49
Spiral Curve 7	6+831.965	6+850.095	0.0181	1.463	0.0732	0.0442	0.0290	4.0355	1.54

Simple Curve 8	6+850.095	6+904.803	0.0547	4.087	0.2043	0.1234	0.0809	3.7351	1.42
Spiral Curve 9	6+904.803	6+922.933	0.0181	1.330	0.0665	0.0402	0.0263	3.6686	1.40
Tangent	6+922.933	7+017.218	0.0943	2.401	0.1200	0.0725	0.0475	1.2731	0.48
Spiral Curve 10	7+017.218	7+024.745	0.0075	0.990	0.0495	0.0299	0.0196	6.5738	2.50
Simple Curve 11	7+024.745	7+096.671	0.0719	9.457	0.4728	0.2856	0.1872	6.5738	2.50
Spiral Curve 12	7+096.671	7+104.199	0.0075	0.990	0.0495	0.0299	0.0196	6.5738	2.50
Tangent	7+104.199	7+592.480	0.4883	12.432	0.6216	0.3755	0.2461	1.2731	0.48
Spiral Curve 13	7+592.480	7+636.119	0.0436	2.040	0.1020	0.0616	0.0404	2.3376	0.89
Simple Curve 14	7+636.119	7+680.443	0.0443	2.072	0.1036	0.0626	0.0410	2.3376	0.89
Spiral Curve 15	7+680.443	7+724.083	0.0436	2.040	0.1020	0.0616	0.0404	2.3376	0.89
Tangent	7+724.083	7+730.000	0.0059	0.151	0.0075	0.0046	0.0030	1.2731	0.48

Table B.5. Predicted Crash Frequencies by Year (Section 4)

Year	Total Crashes	FI Crashes	Percent FI (%)	PDO Crashes	Percent PDO (%)
2010	2.09	1.26	60.410	0.83	39.590
2011	2.82	1.70	60.410	1.12	39.590
2012	2.10	1.27	60.410	0.83	39.590
2013	2.97	1.79	60.410	1.17	39.590
2014	3.66	2.21	60.410	1.45	39.590
2015	4.83	2.92	60.410	1.91	39.590
2016	5.16	3.12	60.410	2.04	39.590
2017	5.93	3.58	60.410	2.35	39.590
2018	6.08	3.67	60.410	2.41	39.590
2019	6.08	3.67	60.410	2.41	39.590
2020	6.08	3.67	60.410	2.41	39.590
2021	6.08	3.67	60.410	2.41	39.590
2022	6.08	3.67	60.410	2.41	39.590
2023	6.08	3.67	60.410	2.41	39.590
2024	6.08	3.67	60.410	2.41	39.590
2025	6.08	3.67	60.410	2.41	39.590
2026	6.08	3.67	60.410	2.41	39.590
2027	6.08	3.67	60.410	2.41	39.590
2028	6.08	3.67	60.410	2.41	39.590
2029	6.08	3.67	60.410	2.41	39.590
Total	102.54	61.95	60.410	40.60	39.590
Average	5.13	3.10	60.410	2.03	39.590

Note: *Fatal and Injury Crashes* and *Property Damage Only Crashes* do not necessarily sum up to *Total Crashes* because the distribution of these three crashes had been derived independently.

Table B.6. Predicted Crash Type Distribution (Section 4)

Element Type	Crash Type	Fatal and Injury		Property Damage Only		Total	
		Crashes	Crashes (%)	Crashes	Crashes (%)	Crashes	Crashes (%)
Highway Segment	Collision with Animal	3.35	3.3	1.26	1.2	4.60	4.5
Highway Segment	Collision with Bicycle	0.00	0.0	0.00	0.0	0.00	0.0
Highway Segment	Other Single-vehicle Collision	1.69	1.6	1.15	1.1	2.83	2.8
Highway Segment	Overturned	2.95	2.9	4.06	4.0	7.00	6.8
Highway Segment	Collision with Pedestrian	8.15	7.9	0.36	0.3	8.52	8.3
Highway Segment	Run Off Road	29.65	28.9	21.49	21.0	51.14	49.9
Highway Segment	Total Single Vehicle Crashes	45.78	44.7	28.31	27.6	74.10	72.3
Highway Segment	Angle Collision	3.69	3.6	2.06	2.0	5.75	5.6
Highway Segment	Head-on Collision	3.17	3.1	3.54	3.5	6.71	6.5
Highway Segment	Other Multiple-vehicle Collision	2.54	2.5	1.82	1.8	4.36	4.3
Highway Segment	Rear-end Collision	4.13	4.0	3.28	3.2	7.40	7.2
Highway Segment	Sideswipe	2.63	2.6	1.57	1.5	4.20	4.1
Highway Segment	Total Multiple Vehicle Crashes	16.16	15.8	12.28	12.0	28.43	27.7
Highway Segment	Total Highway Segment Crashes	61.94	60.4	40.59	39.6	102.52	100.0
	Total Crashes	61.94	60.4	40.59	39.6	102.52	100.0

Note: *Fatal and Injury Crashes* and *Property Damage Only Crashes* do not necessarily sum up to *Total Crashes* because the distribution of these three crashes had been derived independently.

Appendix-C: PRM Evaluation Report on Addis Ababa to Dilella Road, Section-4 (4+510.000 – 7+730.000)

Interactive Highway Safety Design Model

Policy Review Evaluation Report

Prepared by

Alamirew Mulugeta Tola

July 13, 2021

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Report Overview

Report Generated: Jul 13, 2021 11:16 AM
Report Template: System: Single Page [System] (prm3, Mar 21, 2021 9:10 AM)

Evaluation Date: Mon Jul 12 15:55:24 EAT 2021
IHSDM Version: v16.0.0 (Sep 30, 2020)
Policy Review Module: v5.0.0 (Sep 30, 2020)

Project Title: Paper #3 Analysis
Project Comment: Created Fri Apr 02 03:52:20 EAT 2021
Project Unit System: Metric

Highway Title: Addis Ababa to Dilella Road
Highway Comment: Addis Ababa to Dilella Road (v1)

Highway Version: 1

Evaluation Title: Evaluation 1

Evaluation Comment: Created Mon Jul 12 15:54:58 EAT 2021

Minimum Location: 4+510.000

Maximum Location: 7+730.000

Design Vehicle: WB-19(WB-62) - null

Evaluation Year: 2018

Type of Project/Study: Reconstruction

Operations Design Vehicle: Typical Heavy Truck

Policy: ERA 2013 Metric

Traveled Way Width

[Traveled Way Width Check in the Engineer's Manual]

Evaluation Start Location: 4+510.000

Evaluation End Location: 7+730.000

Evaluation Year: 2018

Design Vehicle: WB-19(WB-62) - null

Type of Project/Study: Reconstruction

Table C.1. Traveled Width and Widening

Start Location (Sta. m)	End Location (Sta. m)	Policy TWW (m)	Side of Road	Road TWW (m)	Number of Lanes	Curve Radius (m)	Speed (km/h)	Terrain	Functional Class	AA DT (vpd)	Comment
4+510.000	4+853.484	7.30	Both	7.00	2		80	Rolling	Arterial	8,540	Road value varies from controlling criteria
4+853.484	4+862.570	7.30	Both	7.00	2	100.00	80	Rolling	Arterial	8,540	For policy ERA 2013 Metric, no minimum curve widening
4+862.570	5+275.757	7.30	Both	7.00	2		80	Rolling	Arterial	8,540	Road value varies from controlling criteria
5+275.757	5+376.600	7.30	Both	7.00	2	857.08	80	Rolling	Arterial	8,540	For policy ERA 2013 Metric, no minimum curve widening
5+376.600	6+831.965	7.30	Both	7.00	2		80	Rolling	Arterial	8,540	Road value varies from controlling criteria
6+831.965	6+922.933	7.30	Both	7.00	2	163.17	80	Rolling	Arterial	8,540	For policy ERA 2013 Metric, no minimum curve widening
6+922.933	7+017.218	7.30	Both	7.00	2		80	Rolling	Arterial	8,540	Road value varies from controlling criteria
7+017.218	7+104.199	7.30	Both	7.00	2	67.75	80	Rolling	Arterial	8,540	For policy ERA 2013 Metric, no minimum curve widening
7+104.199	7+592.480	7.30	Both	7.00	2		80	Rolling	Arterial	8,540	Road value varies from controlling criteria
7+592.480	7+724.083	7.30	Both	7.00	2	392.76	80	Rolling	Arterial	8,540	For policy ERA 2013 Metric, no minimum curve widening
7+724.083	7+730.000	7.30	Both	7.00	2		80	Rolling	Arterial	8,540	Road value varies from controlling criteria

Shoulder Width

[Shoulder Width Check in the Engineer's Manual]

Evaluation Start Location: 4+510.000

Evaluation End Location: 7+730.000

Evaluation Year: 2018

Table C.2. Shoulder Width

Start Location (Sta. m)	End Location (Sta. m)	Side of Road	Inside or Outside of Road	Shoulder Width (m)	Policy Width (m)	Shoulder Material	Bicycle Facility	Functional Class	Speed (km/h)	AADT (vpd)	Terrain	Comment
4+510.0	7+730.0	Left	Outside	1.50	3.00 [1]	Paved	No	Arterial	80	8,540	Rolling	Road value may vary from recommended values. Where volumes are low or a narrow section is needed to reduce construction impacts, the paved shoulder may be reduced to 0.60 m provided that bicycle use is not intended to be accommodated on the shoulder.
4+510.0	7+730.0	Right	Outside	1.50	3.00 [1]	Paved	No	Arterial	80	8,540	Rolling	Road value may vary from recommended values. Where volumes are low or a narrow section is needed to reduce construction impacts, the paved shoulder may be reduced to 0.60 m provided that bicycle use is not intended to be accommodated on the shoulder.

Footnotes

[1] Where volumes are low or a narrow section is needed to reduce construction impacts, the paved shoulder may be reduced to 2 feet provided that bicycle use is not intended to be accommodated on the shoulder.

Radius of Curve

[Radius of Curve Check in the Engineer's Manual]

Evaluation Start Location: 4+510.000

Evaluation End Location: 7+730.000

e_{max}: 8

Min Policy Speed: 15

Max Policy Speed: 130

Table C.3. Radius of Curve

Start Location (Sta. m)	End Location (Sta. m)	Road Radius (m)	Policy Radius (m)	Effective Design Speed (km/h)	Speed (km/h)	Functional Class	Surface Type	Comment
4+853.484	4+862.570	100.00	229.00	55	80	Arterial		Road value varies from controlling criteria
5+275.757	5+376.600	857.08	229.00	> 120	80	Arterial		Road value is within controlling criteria
6+831.965	6+922.933	163.17	229.00	68	80	Arterial		Road value varies from controlling criteria
7+017.218	7+104.199	67.75	229.00	46	80	Arterial		Road value varies from controlling criteria
7+592.480	7+724.083	392.76	229.00	97	80	Arterial		Road value is within controlling criteria

Table C.4. e_{max} Bounds

Start Location (Sta. m)	End Location (Sta. m)	e_{max} (%)	Policy (%)	Functional Class	Surface Type	Comment
4+510.000	7+730.000	8	4 to 8	Arterial	Paved	Road value is within recommended values

Superelevation

[Superelevation Check in the Engineer's Manual]

Evaluation Start Location: 4+510.000

Evaluation End Location: 7+730.000

Min Policy Speed: 30

Max Policy Speed: 120

Table C.5. Superelevation

Start Location (Sta. m)	End Location (Sta. m)	Side of Road	Road Superelevation (%)	Policy Superelevation (%)	Curve Radius (m)	Speed (km/h)	Evaluation Speed (km/h)	e_{max} (%)	Comment
4+855.420	4+860.634	Both	4.00	8.00	100.00	80		8	For policy ERA 2013 Metric, road value varies from controlling criteria, curve radius below policy minimum

5+310.040	5+342.317		None	4.60	857.08	80		8	Superelevation required, no superelevation identified
6+850.095	6+904.803				163.17	80		8	For policy ERA 2013 Metric, no superelevation, curve radius below policy minimum
7+024.745	7+096.671				67.75	80		8	For policy ERA 2013 Metric, no superelevation, curve radius below policy minimum
7+636.119	7+680.443		None	8.00	392.76	80		8	Superelevation required, no superelevation identified

Table C.6. e_{max} Bounds

Start Location (Sta. m)	End Location (Sta. m)	e_{max} (%)	Policy (%)	Functional Class	Surface Type	Comment
4+510.000	7+730.000	8	4 to 8	Arterial	Paved	Road value is within recommended values

Tangent Grade

[Tangent Grade Check in the Engineer's Manual]

Evaluation Start Location: 4+510.000

Evaluation End Location: 7+730.000

Evaluation Year: 2018

Table C.7. Tangent Grade

Start Location (Sta. m)	End Location (Sta. m)	Road Grade (%)	Policy (%)	Policy Allowance (%)	Tangent Length (m)	Terrain	Speed (km/h)	AADT (vpd)	Functional Class	Comment
4+515.311	4+525.000	1.00	0.50 to 6.00	1.00	9.69	Rolling	80	8,540	Arterial	Road value is within controlling criteria
4+575.000	4+610.000	1.34	0.50 to 6.00	1.00	35.00	Rolling	80	8,540	Arterial	Road value is within controlling criteria
4+650.000	4+670.000	0.33	0.50 to 6.00	1.00	20.00	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
4+750.000	4+810.000	0.89	0.50 to 6.00	1.00	60.00	Rolling	80	8,540	Arterial	Road value is within controlling criteria
4+850.000	4+870.000	1.25	0.50 to 6.00	1.00	20.00	Rolling	80	8,540	Arterial	Road value is within controlling criteria
4+910.000	5+040.087	0.90	0.50 to 6.00	1.00	130.09	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+100.087	5+147.380	0.81	0.50 to 6.00	1.00	47.29	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+240.780	5+274.300	0.26	0.50 to 6.00	1.00	33.52	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
5+385.700	5+410.000	0.82	0.50 to 6.00	1.00	24.30	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+450.000	5+507.500	0.95	0.50 to 6.00	1.00	57.50	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+552.500	5+590.000	0.56	0.50 to 6.00	1.00	37.50	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+630.000	5+651.968	0.78	0.50 to 6.00	1.00	21.97	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+691.968	5+745.000	0.58	0.50 to 6.00	1.00	53.03	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+795.000	5+840.000	2.11	0.50 to 6.00	1.00	45.00	Rolling	80	8,540	Arterial	Road value is within controlling criteria
5+900.000	6+081.969	3.20	0.50 to 5.00		181.97	Rolling	80	8,540	Arterial	Road value is within controlling criteria
6+141.969	6+250.000	2.30	0.50 to 6.00	1.00	108.03	Rolling	80	8,540	Arterial	Road value is within controlling criteria
6+290.000	6+291.969	1.63	0.50 to 6.00	1.00	1.97	Rolling	80	8,540	Arterial	Road value is within controlling criteria
6+331.969	6+390.000	0.02	0.50 to 6.00	1.00	58.03	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
6+430.000	6+490.000	0.06	0.50 to 6.00	1.00	60.00	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
6+530.000	6+590.000	0.03	0.50 to 6.00	1.00	60.00	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
6+630.000	6+641.970	0.29	0.50 to 6.00	1.00	11.97	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
6+661.970	6+673.245	0.04	0.50 to 6.00	1.00	11.28	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
6+733.245	6+768.156	1.98	0.50 to 6.00	1.00	34.91	Rolling	80	8,540	Arterial	Road value is within controlling criteria
6+818.156	6+818.500	3.92	0.50 to 6.00	1.00	0.34	Rolling	80	8,540	Arterial	Road value is within controlling criteria
6+901.500	6+950.000	1.31	0.50 to 6.00	1.00	48.50	Rolling	80	8,540	Arterial	Road value is within controlling criteria
6+990.000	6+993.000	1.60	0.50 to 6.00	1.00	3.00	Rolling	80	8,540	Arterial	Road value is within controlling criteria
7+073.000	7+145.410	0.22	0.50 to 6.00	1.00	72.41	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage
7+204.590	7+351.534	0.24	0.50 to 6.00	1.00	146.94	Rolling	80	8,540	Arterial	Road value may vary from recommended values, check drainage

Stopping Sight Distance

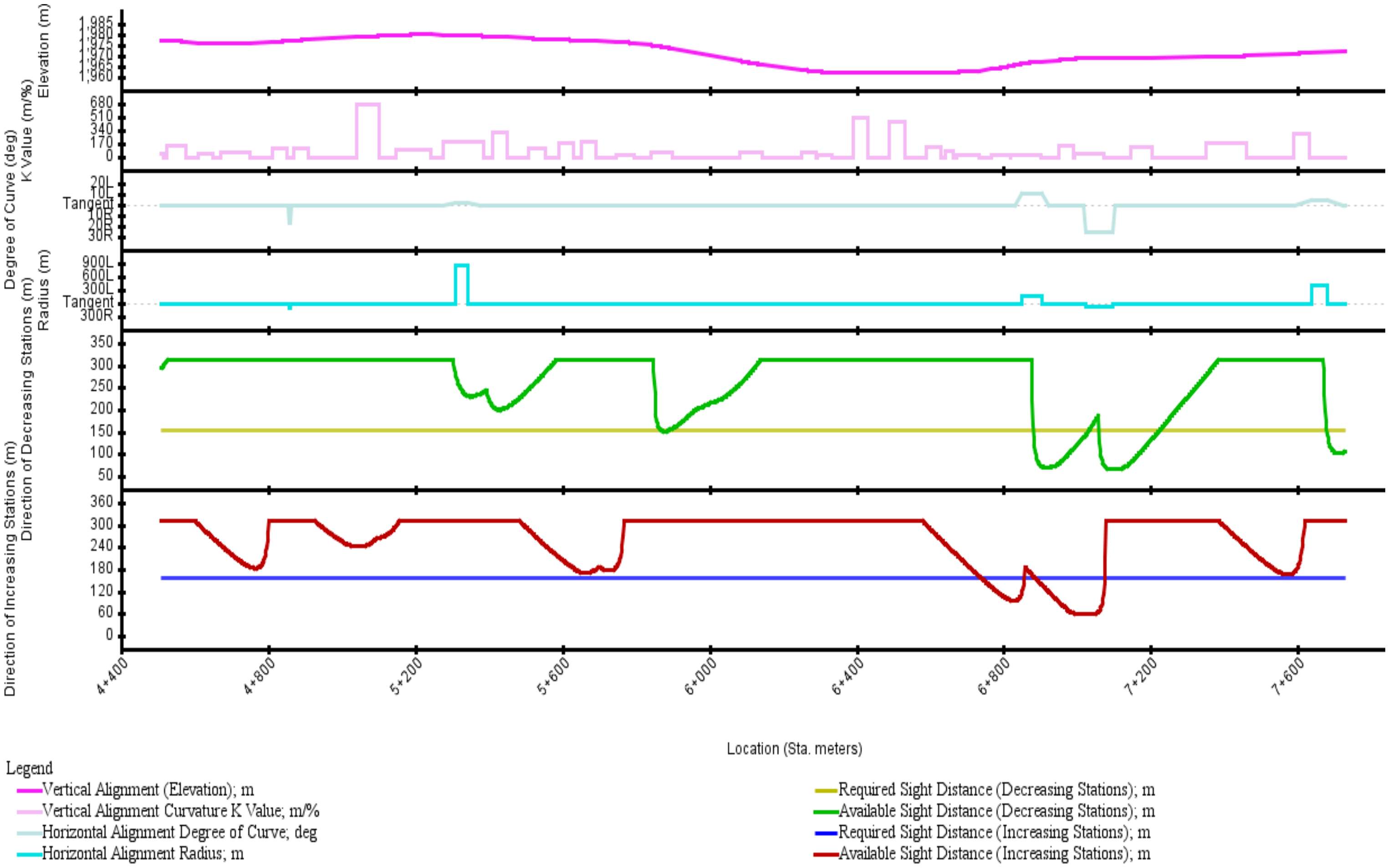

Figure C.1. Stopping Sight Distance

List of Publications

Publications included in this dissertation:

Tola, A. M., Demissie, T. A., Saathoff, F., & Gebissa, A. (2022). A Predictive Approach to Identify Geometrically Hazardous Road Segments and Evaluate the Relative Safety Effects of Design Alternatives. *Sustainability*, 14(5), 3026. https://doi.org/10.3390/su14053026

Tola, A. M., Demissie, T. A., Saathoff, F., & Gebissa, A. (2022). Crash Distribution Dataset: Development and Validation for the Undivided Rural Roads in Oromia, Ethiopia. *Transport and Telecommunication*, 23(1), 11-24. https://doi.org/10.2478/ttj-2022-0002

Tola, A. M., Demissie, T. A., Saathoff, F., & Gebissa, A. (2021). Severity, Spatial Pattern and Statistical Analysis of Road Traffic Crash Hot Spots in Ethiopia. *Applied Sciences*, 11(19), 8828. https://doi.org/10.3390/app11198828

Others:

Tola, A. M., & Gebissa, A. (2019). Assessment on the Impacts of Road Geometry and Route Selection on Road Safety: A Case of Mettu-Gore Road, Ethiopia. *American Journal of Civil Engineering and Architecture*, 7(1), 13–19. https://doi.org/10.12691/ajcea-7-1-2

Tola, A. M., & Gebissa, A. (2019). Identifying Black Spot Accident Zones using a Geographical Information System on Kombolcha-Dessie Road in Ethiopia. *International Journal of Sciences: Basic and Applied Research (IJSBAR)*, 48(1), 1–12. https://www.gssrr.org/index.php/JournalOfBasicAndApplied/article/view/10199

Tola, A. M., & Gebissa, A. (2018). Assessment on the Impacts of Geometric Design on Road Safety. KS Omniscriptum Publishing. https://www.lap-publishing.com/catalog/details/store/gb/book/978-3-330-04814-0/assessment-on-the-impacts-of-geometric-design-on-road-safety

Tola, A. M. (2018). Assessment on the Impacts of Geometric Design on Road Safety: A Case of Mettu-Gore Road. The 2nd Annual Ethiopian Road Safety Conference (RSC2018).

Curriculum Vitae

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STATEMENT

Proficient Civil Engineer specializing in Highway Engineering with experience in research, teaching, design, and consulting. Acquires hands-on experience in Highway Engineering design and construction, as well as road safety studies, with the goal of "safer roads through better design."

RESEARCH AND TEACHING AREA

Road Safety, GIS-based Crash Spatial and Temporal Analysis, Crash Prediction Modelling, Crash Distribution Dataset, Crash Modification Factors, Application of Artificial Intelligence, Sensor Fusion and Algorithms for Proactive Safety Management System, Road Geometric Design Consistency Modelling, Transportation Planning, Traffic Simulation.

EDUCATION

Ph.D.	Faculty of Agricultural and Environmental Sciences, Rostock University, Germany	Ongoing
M.Sc.	Faculty of Civil & Environmental Engineering, Jimma University, Ethiopia	November 2016
B.Sc.	Faculty of Civil & Environmental Engineering, Jimma University, Ethiopia	July 2013

ACADEMIC EXPERIENCE

Dec 2016 – Oct 2018	Lecturer, School of Civil, Water Resource Engineering and Architecture, Wollo University, Ethiopia
Aug 2013 – Aug 2015	Assistant Lecturer, School of Civil, Water Resource Engineering and Architecture, Wollo University, Ethiopia

TEACHING EXPERIENCE

School of Civil, Water Resource Engineering and Architecture, Wollo University, Ethiopia

Highway Engineering-I
Surveying-II
Highway Engineering-II
Integrated Highway Design
Highway Maintenance
Transportation Engineering

PROFESSIONAL SOCIETIES

- Membership: American Society of Civil Engineers (ASCE), Transportation and Development Institute of ASCE
- Served as a reviewer for Wiley: International Social Science Journal and Abyssinia Journal of Engineering and Computing.

DESIGN AND CONSULTING EXPERIENCE

Nov 2016 – Sept 2018 Highway Engineer, Lacomenza Consulting Architects and Engineers, Wollo University, Ethiopia

- Designed 'Tsehaymewcha-Tikeshign-Tima' and 'Jatu-Matikos-Washet' roads for Amhara Roads and Transport Bureau.

TECHNICAL SKILLS

Anadelta Tessera, ArcGIS, AutoCAD, AutoCAD Civil 3D, Eagle Point, ETABS, IHSDM, Global Mapper, Microsoft Office, MicroStation, SAP 2000, and ArchiCAD.

PUBLICATIONS

Tola, A. M., Demissie, T. A., Saathoff, F., & Gebissa, A. (2022). A Predictive Approach to Identify Geometrically Hazardous Road Segments and Evaluate the Relative Safety Effects of Design Alternatives. *Sustainability*, 14(5), 3026. https://doi.org/10.3390/su14053026

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Tola, A. M., & Gebissa, A. (2018). Assessment on the Impacts of Geometric Design on Road Safety. KS Omniscriptum Publishing. https://www.lap-publishing.com/catalog/details/store/gb/book/978-3-330-04814-0/assessment-on-the-impacts-of-geometric-design-on-road-safety

Tola, A. M. (2018). Assessment on the Impacts of Geometric Design on Road Safety: A Case of Mettu-Gore Road. The 2nd Annual Ethiopian Road Safety Conference (RSC2018).