MAKERERE UNIVERSITY

COLLEGE OF ENGINEERING, DESIGN, ART AND TECHNOLOGY (CEDAT)

SCHOOL OF ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

CIV 4200: CIVIL ENGINEERING PROJECT II

ASSESSMENT OF THE INFLUENCE OF ROAD GEOMETRIC DESIGN PARAMETERS ON CRASH FREQUENCY AND SEVERITY AT BWAISE INTERCHANGE

BY

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Submitted in Partial Fulfilment of the Requirements for the Award of a Degree of Bachelor of Science in Civil Engineering of Makerere University

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ACKNOWLEDGEMENT

We extend our sincere gratitude to the research coordinators for introducing and guiding us through the research protocols. In the same way, we are equally grateful to our supervisors, Prof. Umaru Bagampadde and Dr. Andrew Bwambale, for their continued guidance, constructive feedback, and encouragement throughout the research project.

We extend our sincere appreciation to the Ministry of Works and Transport for providing us with the as-built drawing of the Bwaise interchange, which was our case study.

We acknowledge the Uganda Police Force's Directorate of Traffic and Road Safety and the Bloomberg Philanthropies-funded KCCA Road Safety for their assistance in providing us access to the traffic accident records.

Our parents, family, and friends, who continually encouraged and supported us emotionally, spiritually, and financially, ensured that we continued putting in effort until the very end of this research study.

ABSTRACT

Road geometric design parameters are fundamental determinants of road safety, governing vehicle operating speeds, driver workload, braking performance, and the margin available for collision avoidance. Deficiencies in horizontal curvature, longitudinal gradient, lane width, and intersection configuration systematically elevate both crash frequency and severity, yet localized quantitative analyses linking such deficiencies to crash occurrence at urban hotspots in Uganda remain scarce. This study assessed the influence of road geometric design parameters on crash frequency and severity at Bwaise interchange, Kawempe Division, Kampala, over the period 2020-2024. Twenty segments, ten circulatory arcs, and ten approach/exit arm segments produced a panel of 100 segment-year observations from 74 spatially confirmed crash events sourced from Kawempe Police Station and the KCCA Bloomberg Road Safety Database. Geometric parameters were extracted from Ministry of Works and Transport as-built drawings and Google Earth Pro profiles, with spatial allocation in ArcGIS Pro 3.4.2. Poisson, Negative Binomial, and Zero-Inflated Negative Binomial regression were employed for crash frequency, ordered logistic regression for severity, and Crash Modification Factors derived from model Incidence Rate Ratios using the AASHTO Highway Safety Manual framework.

The study recorded a mean crash rate of 21.01 crashes per kilometer per year across 20 segments, with four primary hotspots identified. Damage-only crashes dominated at 65.92%, while 18.1% involved injury or fatality; all recorded fatalities occurred on approach arm segments with steep gradients, three of which exceeded the recommended maximum of 4%, the worst recording 7.01%. The Negative Binomial model was confirmed as the most appropriate crash frequency estimator. Each one percentage point increase in longitudinal gradient was associated with a 17.8 -19.5% increase in expected annual crash count. Horizontal curve radius was the strongest geometric predictor, with each one-meter increase reducing expected crashes by 2.9-5.0% (r = -0.675). Crash Modification Factor analysis indicated that gradient reduction from 7.01% to the recommended 4.0% was associated with a 39-41% crash reduction, the single highest-impact intervention at the junction. Ordered logistic regression confirmed gradient and curve radius as significant predictors of crash severity. These findings confirm that geometric design non-compliance is systematically associated with elevated crash frequency and severity at Bwaise interchange

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASTO	American Association of State Highways and Transportation officials
AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
BZINB	Bivariate Zero Inflated Negative Binomial
CMF	Crash Modification Factors
CSI	Crash Severity Index
DSL	Different Speed Limits
GIS	Geographic Information System
GKMA	Greater Kampala Metropolitant Area
GPS	Global Positioning System
IRR	Incident Rate Ratios
KCCA	Kampala Capital City Authority
LMICs	Low and Middle-Income Countries
LC	Local Council
MoWT	Ministry of Works and Transport
NB	Negative Binomial
NCHRP	National Coperative Highway Research Program
OLS	Ordinary Least Squares
Q-Q plot	Quartile-Quartile plot
RD	Rutting Depth
RTI	Road Traffic Injury
SD	Standard deviation
UN	United Nations
VMR	Variance to Mean Ratio
VRUs	Vulnerable Road Users
WHO	World Health Organization
ZINB	Zero Inflated Negative Binomial

Chapter 1 : INTRODUCTION

1.1 Background

Road traffic injuries (RTIs) are a leading cause of death for people age 5-29 globally, it claims approximately 1.19 million lives annually. More than 90% of these deaths occur in low and middle-income countries (LMICs) where vulnerable road users (VRUs) such as pedestrians, cyclists and motorcyclists account for over 50% of all fatalities(WHO, 2023). In Uganda, RTIs result in over 5,000 deaths each year. This represents a daily average number of 14 people and a mortality rate of 29 deaths per 100,000 people, which far exceeds the global average of 18 (Whinstone, 2025). GKMA, the country's most populous area, accounts for nearly half of all national crashes. This high incidence is attributed to a rapid increase in motorization, high traffic density, inadequate infrastructure (e.g. poor road conditions and limited pedestrian facilities), and behavioral risks like speeding, which is a factor in 44.5% of crashes. VRUs are disproportionately affected, with pedestrians accounting for 40% of fatalities and boda-boda riders accounting for 30%. Collectively, these vulnerable groups represent 94% of reported traffic fatalities. The economic impact is significant, costing the country close to 5% of its Gross Domestic Product and hindering sustainable development (Whinstone, 2025). Despite initiatives and policies such as the United Nation Decade of action for road safety (2011-2020) and Ongoing UN Decade of action for road safety (2021-2030), National Road Safety Strategy (2020-2026) and the KCCA Road Safety Strategy (2021-2030).

There are several factors that contribute to rad crashes, they can be categorized as Human factors (relates to the actions, behaviors, and physical / mental states of road users (drivers, pedestrians, cyclist, and passengers), road factors (including design, physical characteristics, and maintenance condition of the road infrastructure itself), vehicle factor i.e., vehicle design, condition, and type of vehicles involved in the traffic and Environmental factors which is the external natural condition at the time of crash. Previously, several studies and traffic safety interventions in Uganda and other LMICs have focused on behavioral factors (speeding, alcohol use, enforcement), vehicle conditions, and general traffic flow; less attention has been paid to infrastructure design and geometric road features. While such factors are undeniably important, the growing evidence globally suggests that road geometry such as lane widths, shoulder design, alignment, intersection layout, sight distance, cross-section, curvature plays a fundamental role in crash risk and severity. By neglecting geometric variables, local research may be missing critical, high-impact opportunities for intervention. Given these gaps, this study seeks to examine the contribution of road geometric parameters to the crash rates observed in Bwaise interchange, Kawempe-Division highlighted to have the highest fatalities following the KCCA road safety report of the analysis of crashes using 2022-2024 crash data (Report, 2024). This study employs the use of regression models to quantify the relationships between geometric design parameters and crash rates, identifying which design parameter has significantly high influence, the findings are expected to provide evidence-based guidance for engineering interventions and contribute to more effective road safety design in Bwaise interchange and other roads in Uganda.

1.2 Problem statement

Road traffic crashes continue to pose a severe public health and economic burden in Uganda, with Kampala experiencing a disproportionately high number of crashes and fatalities (Balikuddembe et al., 2020). Existing literature broadly acknowledges the influence of road infrastructure and geometric design parameters on crash rates (Abebe, 2019; Jima & Sipos, 2022). In Kampala, studies have been done to identify these high-risk zones across the city (Vaca et al., 2020; Zziwa et al., 2022) but localized investigations that specifically link road geometry parameters to crash occurrences at such hotspots are scanty. This lack of in-depth analysis creates a significant challenge, without a clear understanding of how geometric elements contribute to the elevated crash rates in these hotspots, road safety interventions often remain generalized. Such broad approaches may not effectively address the unique and localized design deficiencies that may exist, leading to inefficient resource allocation and limited improvements in safety outcomes. This therefore, calls for the need to systematically analyze the statistical relationship between road geometry parameters and crash rates in Bwaise interchange in Kawempe-Kampala, providing actionable, evidence-based insights necessary for designing targeted and effective engineering interventions to mitigate road traffic crashes and enhance overall road safety in the region.

1.3 Objectives

1.3.1 General objective

The main objective of this study is to assess the influence of road geometric design parameters on crash frequency and severity at Bwaise interchange, Kawempe Division.

1.3.2 Specific objectives

1. To quantify the crash frequencies, severity, and crash rates for the pre-identified hotspot segments based on available crash and traffic exposure data.
2. To characterize the key geometric design parameters of the hotspot segments.
3. To determine the relationships between geometric design parameters and crash occurrence using appropriate crash rate models.

1.4 Research question

1. What are the crash frequencies, severity distributions, and exposure-based crash rates at the pre-identified hotspots in Kawempe Division?
2. What are the geometric characteristics of the identified crash hotspots road segment?
3. Which geometric design parameters are significantly associated with high frequency and severity?

1.5 Justification

The high incidence of road traffic crashes in Kampala, with Bwaise interchange identified in the KCCA Road Safety Report (2024) as one of the highest-fatality locations in the network, underscores the urgent need for this study, justified on two grounds.

Road safety interventions in Kampala have predominantly relied on behavioral measures, enforcement, speed cameras, and road user education, without a systematic understanding of how road geometry contributes to crash occurrence. This study addresses that gap by producing segment-level crash rates, design standard compliance assessments, and Crash Modification Factor estimates attributable to specific geometric parameters, thereby equipping KCCA, UNRA, and the Ministry of Works and Transport with a quantitative basis for prioritizing geometric improvement investments and providing a replicable framework applicable to other Ugandan roundabouts lacking geometric safety assessment.

The overwhelming majority of geometry-crash studies have been conducted on rural highways in developed countries under conditions not directly transferable to Sub-Saharan African urban environments (Peden et al., 2018; WHO, 2023). By applying Safety Performance Functions and CMF analysis to an urban Kampala roundabout using a panel data framework, 20 segments over five years producing 100 segment-year observations, alongside formal spatial autocorrelation assessment, the study generates locally calibrated parameter estimates and establishes a methodological benchmark for geometry-crash research in low- and middle-income country urban road safety contexts.

1.6 Scope of the Study

This study focuses on Bwaise interchange in Kawempe Division, Kampala (approximately 0.353° N, 32.561° E), and a five-leg urban junction connecting Bombo Road, Sir Apollo Kaggwa Road, and the Northern Bypass. It was selected for its documented status as one of the highest-fatality road locations in the Greater Kampala Metropolitan Area (KCCA, 2024). The junction was delineated into twenty homogeneous segments, ten circulatory arc segments forming the rotary carriageway between consecutive entry and exit points and ten approach and exit arm segments connecting the roundabout to the surrounding road network, serving as the spatial unit of analysis. This study examines four road geometric design parameters; horizontal curve radius, absolute longitudinal gradient, lane width, and segment length, selected because they directly govern vehicle speed, lateral stability, and braking performance at the junction and are measurable from available engineering drawings. These parameters are evaluated against the ERA Uganda Road Design Manual (2016) and NCHRP 672 design thresholds within the Safety Performance Function and Crash Modification Factor framework of the AASHTO Highway Safety Manual (2010), employing Negative Binomial and Zero-Inflated Negative Binomial regression for crash frequency and ordered logistic regression for severity. The study does not extend to behavioral, vehicular, or environmental crash contributory factors, nor does it incorporate Annual Average Daily Traffic as an independent variable, owing to the absence of systematic traffic counts at the study site, with segment length serving as the exposure proxy instead the five years from January 2020 to December 2024, a window deliberately chosen to capture sufficient crash events across all twenty segments for statistical reliability, utilizing crash records from the Uganda Police Force and the KCCA BIRGS database, and producing a balanced panel of 100 segment-year observations.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

This literature review synthesizes current research on the influence of road geometric design parameters on crash frequency and severity, with particular emphasis on roundabout safety, crash modification factors, methodological approaches, and the unique challenges posed by mixed traffic conditions in developing countries. The review draws upon recent empirical studies, meta-analyses, and methodological advances to provide a comprehensive foundation for understanding the state of knowledge in this critical domain of road safety research.

2.2 Road Geometric Design Parameters and Crash Frequency

2.2.1 Fundamental Relationships

The relationship between road geometric design and crash frequency has been extensively studied across various road types and traffic conditions. Research consistently demonstrates that geometric design elements significantly influence crash occurrence through their effects on vehicle speeds, driver decision-making, and conflict opportunities (Wang et al., 2020). Key geometric parameters identified in the literature include horizontal curvature, vertical alignment, lane width, shoulder width, median characteristics, sight distance, and intersection design features (Sameen & Pradhan, 2016).

A comprehensive study examining expressway geometric design features using high-resolution laser scanning data and GIS found that several geometric parameters significantly determine accident occurrence at the 5% significance level (Sameen & Pradhan, 2016). Specifically, the length of road segments (elasticity = 0.122), the number of vertical curves in a road section (elasticity = 0.999), and the presence of a horizontal curve in a road segment (elasticity = 0.877) were all positively associated with crash frequency (Sameen & Pradhan, 2016). These findings highlight the importance of geometric complexity in creating hazardous conditions that increase crash risk.

2.2.2 Horizontal and Vertical Alignment

Horizontal curvature represents one of the most studied geometric design elements in crash analysis. Research indicates that the presence of horizontal curves significantly increases crash risk, with elasticity values of 0.877 reported in expressway studies (Sameen & Pradhan, 2016). However, the relationship between curve radius and crash frequency has shown inconsistent results across different studies, attributed to the combined effects of road curvature and limited variation in degree of curvature (Sameen & Pradhan, 2016). Some studies have found that both narrow and wide lanes (less than 2.8 m and over 3.2 m, respectively) increase crash risks with equal magnitude, suggesting an optimal range for lane width that balances safety and operational efficiency (AlKheder et al., 2021).

Vertical alignment elements, including vertical curves and grades, also play crucial roles in crash causation. The number of vertical curves in a road section has been shown to have a very high elasticity (0.999) in determining accident occurrence (Sameen & Pradhan, 2016). The K value, a design parameter related to vertical curves representing the horizontal distance along which a 1% change in grade occurs, has been identified as another important factor in crash prediction (Sameen & Pradhan, 2016). These findings underscore the importance of considering three-dimensional road design rather than treating horizontal and vertical alignment as independent elements.

2.2.3 Cross-Sectional Elements

Cross-sectional design elements, including lane width, shoulder width, median width, and number of lanes, have demonstrated significant relationships with crash frequency. A study examining highway design impacts on casualty and non-casualty traffic accidents found that the number of lanes had the highest sensitivity index followed by median width, and then lane width (AlKheder et al., 2021). This suggests that modifying the number of lanes on a highway is anticipated to have the highest impact on accident frequency and road safety compared to other geometric parameters (AlKheder et al., 2021).Research has shown that as the number of lanes in one direction increases on multilane roads, accident rates decrease (AlKheder et al., 2021). This finding may be attributed to improved lane discipline, reduced lane-changing maneuvers, and better separation of traffic streams. However, the relationship between lane width and crash risk appears non-linear, with both excessively narrow and excessively wide lanes associated with increased crash risk (AlKheder et al., 2021). This U-shaped relationship suggests the importance of finding optimal lane width ranges that balance safety, capacity, and driver comfort.

2.2.4 Access Management and Intersection Spacing

The management of access points and intersection spacing represents another critical geometric design consideration affecting crash frequency. Studies have shown that the average distance to the nearest access point has a negative elasticity (-0.035) in determining accident occurrence, suggesting that greater distances between access points reduce crash risk (Sameen & Pradhan, 2016). This finding aligns with access management principles that seek to control the frequency and location of driveway and intersection connections to main roadways.

Research has also examined the relationship between intersection spacing and crash risk. One study found that fatal injuries are 1.7 times more likely to occur at locations where intersections are separated by a distance of more than 500 m compared to locations where intersections are separated by a distance shorter than 500 m (Awadalla & Albuquerque, 2021). This counterintuitive finding may reflect the complex interactions between geometric design, traffic operations, and driver behavior that characterize different urban and suburban environments.

2.3. Roundabout as a Safe alternative intersection

2.3.1 Overall Safety Benefits

Roundabouts have emerged as a preferred intersection treatment in many countries due to their demonstrated safety advantages over traditional signalized and stop-controlled intersections. A comprehensive meta-analysis of 44 studies containing 154 estimates of effect found that converting junctions to roundabouts is associated with a reduction of fatal accidents of about 65% and a reduction of injury accidents of about 40% (Elvik, 2017). These summary estimates of effect were found to be robust for fatal and injury accidents, though the mean effect on property-damage-only accidents was ambiguous (Elvik, 2017).

The safety benefits of roundabouts have been consistently documented across multiple countries and study designs. Elvik's earlier meta-analysis of 28 studies containing 113 estimates of effect reported similar findings, with roundabouts showing particularly strong effectiveness in reducing traffic fatalities (Elvik, 2017). More recent research has confirmed these findings, with studies showing that roundabouts can reduce fatal crashes by up to 65% and injury crashes by 40% (Aziz et al., 2025). These substantial safety improvements have led many transportation agencies to adopt roundabouts as the preferred choice over other types of traffic control such as stop signs and traffic signals (Al-Marafi et al., 2019).

2.3.2 Mechanisms of Safety Improvement

The safety advantages of roundabouts can be attributed to several geometric and operational characteristics. Roundabouts have a low number of potential conflict points compared to traditional intersections, with a conventional intersection exhibiting 32 vehicle conflict points whereas a single-lane roundabout has only 8 (Aziz et al., 2025). This dramatic reduction in conflict points significantly decreases opportunities for crashes to occur. Additionally, roundabout geometry motivates reduced vehicle speeds, which helps reduce delay and decreases the number of decision points for road users (Al-Marafi et al., 2019).

The geometric configuration of roundabouts promotes slower vehicle speeds and facilitates continuous traffic flow, minimizing the severity of crashes (Ashqar et al., 2024). The lane curvature generally results in lower speeds, reducing collision angles and eliminating intersection conflict points (Aziz et al., 2025). These characteristics make roundabouts particularly effective at reducing severe crash types such as right-angle, head-on, and left-turn collisions that are common at traditional intersections.

2.3.3 Geometric Design Elements and Roundabout Safety

Specific geometric design elements within roundabouts have been identified as critical factors influencing safety performance. Entry radius, entry width, central island diameter, angle to the next leg, and entry path radius are the geometric parameters that influence entering-circulating crashes (Vinayaraj & Vedagiri, 2022). Research has shown that geometric design accounts for 36% of accidents at roundabouts, followed by traffic operation at 22% (Suleiman et al., 2024). This highlights the substantial influence that geometric design choices have on roundabout safety outcomes.

A study using the Median Ranked Set Sample and Analytic Hierarchy Process found that for single-lane roundabouts, about 54% of investigated crashes occurred at the entry and about 20% at the exit (Suleiman et al., 2024). This distribution indicates the importance of geometric design factors like excessive radius of deflection of the entering approach or small deviation angle in crash causation. Conflicts at roundabouts remain a significant cause of accidents due to roundabout geometric design elements such as radius, small deviation angle, and large roundabout roadway width (Suleiman et al., 2024).

2.3.4 Roundabout Types and Safety Performance

Different types of roundabouts exhibit varying safety performance characteristics. Single-lane roundabouts are widely favored for their simplicity and perceived safety benefits (Aziz et al., 2025). Research has shown that single-lane roundabouts significantly reduce collision rates compared to conventional intersections due to streamlined geometric design that minimizes conflict points and promotes safer traffic movements (Aziz et al., 2025). For high-traffic volumes, turbo roundabouts-an advancement of conventional multi-lane roundabouts-have been found to be particularly effective as they minimize conflict points and increase capacity (Aziz et al., 2025). However, multi-lane roundabouts introduce different safety challenges compared to single-lane roundabouts, with one major issue being the difficulty drivers face when merging into multi-lane roundabouts due to higher circulating speeds (Aziz et al., 2025). Mini roundabouts, which are much less expensive and can usually be installed with relatively minor changes to intersection geometry, can be useful in low-speed urban environments where conventional roundabout design is not possible due to right-of-way constraints (Aziz et al., 2025).

2.4. Crash Modification Factors and Cross-Sectional Methods

2.4.1 Crash Modification Factors with Concept and Application

Crash Modification Factors represent a fundamental tool in road safety engineering for quantifying the expected change in crash frequency resulting from specific geometric design or operational changes. CMFs are multiplicative factors used to estimate the expected change in crashes after implementing a specific safety countermeasure, with values less than 1.0 indicating a reduction in crash risk (Al-Marafi et al., 2019). These factors are crucial for quantifying the effectiveness of various treatments and supporting evidence-based decision-making in road safety investments. The development of CMFs has evolved significantly over recent decades, with researchers employing various methodological approaches to estimate these factors accurately. CMFs can be developed through before-and-after studies, cross-sectional studies, and meta-analyses of existing research (Al-Marafi et al., 2019). Each approach has advantages and limitations, with the choice of method often dictated by data availability, study objectives, and the specific treatment being evaluated.

2.4.2 Cross-Sectional Method for CMF Development

The cross-sectional method has emerged as an important alternative approach for estimating CMFs when before-and-after studies are impractical to apply, such as when there is a lack of data from the period after implementing treatments (Al-Marafi et al., 2019). This method involves developing crash prediction models using data from multiple sites with varying geometric and traffic characteristics, then using these models to estimate the safety effects of specific design elements.A study by Al-Marafi and colleagues demonstrated the application of the cross-sectional method to develop CMFs for roundabouts using data from 49 roundabouts in Toowoomba City, Australia (Al-Marafi et al., 2019). The study used Generalized Linear Models with a Negative Binomial error distribution to estimate crash frequency based on measurable explanatory variables (Al-Marafi et al., 2019). Twenty-one explanatory variables describing traffic and road geometry were used in modeling as the most common factors associated with road crashes at roundabouts (Al-Marafi et al., 2019).

2.4.3 Methodological Considerations

The cross-sectional method requires careful consideration of several methodological issues to ensure valid and reliable CMF estimates. These include addressing potential confounding variables, ensuring adequate sample sizes, accounting for unobserved heterogeneity, and validating model predictions against independent data (Al-Marafi et al., 2019). The study by Al-Marafi and colleagues divided their datasets into two groups, with the first group used to develop crash prediction models based on three years of data (2010-2012) and the second group used for validation against additional years (2013-2015) of crash data for the same roundabouts (Al-Marafi et al., 2019).

Statistical modeling approaches for cross-sectional CMF development typically employ Generalized Linear Models with various error distributions. The Negative Binomial distribution is commonly used for crash frequency modeling due to its ability to handle over-dispersion in crash data (Al-Marafi et al., 2019). More advanced approaches, such as random-parameter models, have been developed to reduce unobserved heterogeneity and obtain higher dimensional models (Wang et al., 2020). These methodological advances have improved the accuracy and reliability of CMF estimates derived from cross-sectional studies.

2.4.4 Applications and Limitations

Cross-sectional CMFs have been applied to evaluate various geometric design elements, including lane width, horizontal alignment, vertical alignment, cross section, and superelevation (Wang et al., 2020). The Federal Highway Administration's Interactive Highway Safety Design Model uses these parameters as evaluation parameters to check design consistency (Wang et al., 2020). These applications demonstrate the practical utility of cross-sectional CMFs in supporting design decisions and safety evaluations.

However, cross-sectional methods have limitations that must be acknowledged. These methods may be subject to confounding if important variables are omitted from the models, and they assume that the relationships between geometric design elements and crash frequency are consistent across different contexts and time periods (Al-Marafi et al., 2019). Despite these limitations, cross-sectional CMFs provide valuable information for safety analysis when before-and-after data are not available, particularly for evaluating the safety effects of geometric design elements that vary across many sites.

2.5. Crash Severity Analysis

2.5.1 Factors Influencing Crash Severity

While crash frequency has received substantial research attention, understanding the factors that influence crash severity is equally important for developing effective safety interventions. Crash severity is influenced by a complex interplay of factors including geometric design, traffic volume, driver behavior, vehicle characteristics, weather conditions, and lighting (Ashqar et al., 2024). Research has shown that different factors may influence the likelihood of crashes versus the severity of crashes, necessitating separate analyses for these two outcomes.

A comprehensive analysis of crash severity in roundabouts found that rear-end severity is primarily influenced by posted speed limits, violation type, collision partner, single-vehicle collision, and vehicle age (Vinayaraj & Vedagiri, 2024). In contrast, type of violation, collision partner, and presence of road surface condition were identified as critical influencing factors for determining the severity outcomes of angle collisions (Vinayaraj & Vedagiri, 2024). These findings highlight the importance of considering crash type when analyzing severity factors, as different collision mechanisms may involve different causal pathways.

2.5.2 Geometric Design and Crash Severity

Geometric design elements have been shown to influence not only crash frequency but also crash severity. Research on roundabout crashes found that the absence of road lane markings might lead drivers to become confused when driving through the roundabout, potentially affecting crash severity outcomes (Vinayaraj & Vedagiri, 2024). Road surface condition also significantly affects crash severity levels, with good road surface conditions (no cracking, no potholes, smooth surface) associated with decreased probability of accident propensity (Vinayaraj & Vedagiri, 2024).

Specific geometric features have been associated with increased severity outcomes. A study examining fatal intersection crashes found that the odds of fatal injury occurrence are higher as the width of the entry approach increases and as the roundabout island diameter increases (Awadalla & Albuquerque, 2021). These findings suggest that certain geometric design choices, while potentially beneficial for operational efficiency, may have unintended consequences for crash severity that must be carefully considered in design decisions.

2.6. Methodological Approaches in Crash Analysis

2.6.1 Statistical Modeling Techniques

Various statistical modeling techniques have been employed to analyze the relationship between geometric design parameters and crash outcomes. Researchers have used different regression techniques including log-linear regression, negative binomial regression, multiple logistic regression, and zero-inflated negative binomial regression to predict crash frequency at road segments (Vinayaraj & Vedagiri, 2022). These models have been found to follow log-linearity in their function, providing a foundation for understanding the relationships between explanatory variables and crash outcomes.

The Negative Binomial model has emerged as a particularly popular approach for crash frequency modeling due to its ability to handle over-dispersion in crash data (Vinayaraj & Vedagiri, 2022). Safety Performance Functions have been calculated using regression equations that take into account crash data, annual average daily traffic, and the length of road segments for determining crash frequency for particular site types (Vinayaraj & Vedagiri, 2022). These SPFs provide valuable information related to factors that can potentially contribute to the likelihood of increasing traffic crashes.

2.6.2 Machine Learning Applications

Machine learning techniques have increasingly been applied to crash analysis, offering new approaches for understanding complex relationships in crash data. Rule-based classifiers and Random Forest models have been constructed to comprehensively analyze roundabout crashes, with rule-based models offering interpretability and Random Forest models providing deeper analysis (Ashqar et al., 2024). These approaches can handle large datasets with many variables and identify complex non-linear relationships that may be difficult to detect with traditional statistical methods.

A study applying these techniques in Jordan found that CN2 results revealed that injury severity crashes are influenced by the time of day, driver age, day of the week, speed, and number of vehicles involved, while property damage-only crashes are affected by the number of lanes, time of day, type of driver fault, lighting conditions, speed, and day of the week (Ashqar et al., 2024). The Random Forest model analysis unveiled crucial factors influencing crash severity in roundabouts, notably the varying impact of driver age, time of day, the number of vehicles involved, seasonality, and vehicle speed (Ashqar et al., 2024).

2.6.3 Multi-Criteria Decision Making

Multi-Criteria Decision Making techniques have received growing attention worldwide for solving complex real-time problems because of their capacity to gather, structure, and analyze problems and prioritize alternative decisions (Suleiman et al., 2024). The Analytic Hierarchy Process method has been used to handle MCDM problems by conducting pairwise comparisons, ranking, rating, and trade-off analyses (Suleiman et al., 2024).

A study combining MRSS and AHP with statistical analysis found that geometric design accounts for 36% of accidents at roundabouts, followed by traffic operation at 22% (Suleiman et al., 2024). Conflicting and queuing lengths were responsible for about 20% of traffic accidents (Suleiman et al., 2024). These tools help geometric designers and city planners take necessary measures to minimize accidents and enhance traffic safety levels in urban areas (Suleiman et al., 2024).

2.7 Summary of literature

Road traffic crash studies show a strong link between geometric road features and crash frequency and severity, Road geometry elements (number of lanes and lane width, shoulder width, curves, grades, intersection design) are consistently associated with increased crash risks. Statistical modeling of the correlation between crash data and causal effects has continuously evolved to overcome limitations with basic linear models, with Negative Binomial models highly adapted for over-dispersion often found in crash count data. Several local studies have been conducted to identify Crash prone areas for various road users within Kampala yet in-depth analysis relating Crash frequencies and severities with geometric parameters in those localized crash prone areas are lacking, studies have been done in developed countries relating road geometry parameters and limited specific studies in Low and Middle income countries since the findings are not directly transferable making estimation of road design contributions empirical rather than practical.

Chapter 3 : METHODOLOGY

This study will adopt a quantitative, retrospective cross-sectional design. It will integrate spatial analysis techniques to identify crash hotspots with statistical modeling to analyze the relationship between road geometry parameters and crash frequency and severity.

3.1 Study Area and Data Collection

3.1.1 Study Area

The study focused on the Bwaise Interchange, Kawempe Division within Kampala, Uganda. This is selected due to its reported high incidence of road traffic crashes. Bwaise Interchange is situated at the intersection of Bombo Road, Sir Apollo Kaggwa Road and Northern Bypass in Kawempe Division, Kampala City (approximately 0.353° N, 32.561° E). The junction connects five major arterial roads and serves as a critical node in Kampala's urban road network, with surrounding land uses including residential areas and commercial establishments.

3.1.2 Study design

This study adopts a quantitative, cross sectional panel design. Twenty road segments were delineated: ten circulatory arc segments within the roundabout carriageway (between consecutive entry and/or exit points) and ten approach and/or exit leg segments connecting the roundabout to the surrounding network. Each segment was observed over five years (2020-2024), producing a balanced panel of 100 segment-year observation. The study adopted a quantitative, retrospective cross sectional design, it integrated the spatial analysis techniques to identify crash spots using ArcGIS pro 3.4.2 and statistical modelling to analyze the relationship between road geometry parameters and crash rates usng StataMp 13 (64-bit).

3.2 Data requirements and acquisition

i. **Crash data.** These data were primarily obtained from the Uganda Police Force's Directorate of Traffic and Road Safety database and the Bloomberg Philanthropies-funded KCCA Road Safety Database (BIRGS system). Access were sought through formal requests. Physical crash records obtained from the Kawempe Police Station Traffic and Road Safety Directorate covering the years 2020 to 2024. These manual Traffic Accident Report (TAR) register entries provide crash-level data including the TAR reference number, date and time, crash location description, vehicles involved, victim information, crash severity (nature), collision type, suspected cause, weather condition, road character, and road surface condition. A total of **102 discrete crash events** (TAR entries) were identified across the five-year period at and around the Bwaise interchange. Digitized person-level crash records were obtained from the Bloomberg Philanthropies-funded KCCA Road Safety Database (BIRGS system) for the years 2020-2024. Unlike the manual register, the database provides **person-level records** with significantly richer attributes including GPS coordinates (latitude and longitude), road user class, injury severity, vehicle type, vehicle ownership, detailed crash descriptors, time codes, and collision geometry. A combined total of **116 person-level records** were obtained from this source across the study years. When person-level dataset were combine to give crash-level data as in the police record, a total of 88 crash counts with geo-coordinates were obtained. Crashes will be assigned to segments based on proximity to the start and end points. Segment length will be used as a proxy measure of exposure and incorporated into all regression models as a log-transformed offset:

$$log(\mu_i) = \beta_0 + \beta_{1,i}x_1 + \cdots + \beta_k x_{k,i} + log(L_i) \qquad \text{……………………(3.1)}$$

Where L_i is the length of segment i. the estimated coefficients will reflect crash rates per unit segment length, accounting for differences in exposure across segments.

ii. **Road geometric data**. These were acquired through two methods. Firstly, as-built engineering drawings were acquired through two methods. First, as-built engineering drawings were obtained from Ministry of Works and Transport (MoWT) through Directorate of Roads and Bridge works and high resolution Google Earth Pro Software. These included parameters such as; Radius of horizontal curve, segment lengths, gradient or grade, lane width, shoulder width, number of lanes. The geometric design data received from the MoWT were purely polyline feature lines showing the road features, the supplementary data obtained from Google earth as pathfile format were used to obtain the elevation of the centerline points and used for profile analysis.

3.2 Analysis of crash data and road geometry parameters

i. Crash data cleaning and spatial analysis.

A structured cross-matching exercise was conducted for all five study years to reconcile crash records between the Kawempe Police Station Register and the Bloomberg/KCCA BIRGS

Database. The purpose was to assess reliability and the degree of overlap between sources, identify field completeness, and eliminate duplicate counting. The cross-match was guided by TAR reference numbers as the primary linkage key, supported by date, location description, and collision type for verification. However, the final dataset used were the KCCA data since it has every crash count coordinates that assisted in locating the crashes in their specific points within the roundabout segment, some of the crash counts that mapped outside the roundabout were ignored and not used in the regression analysis. The crash data spatial mapping procedure converted the tabular CSV file into a georeferenced point feature class within ArcGIS Pro 3.4.2 and configured labels and symbology to display both year and location information on the map. To do this, the csv file format crash data was dragged and dropped under the content pane in ArcGIS pro, in the map tab, layer button, Add Data was clicked, then data from table, then XY Table to Point, this opened a geoprocessing tools.

In the tool dialog the following settings were applied:

Table 3-1 Showing the procedure followed to plot the geo-referenced crash counts within the roundabout for Segmentation

Table	The file Mappedspot.csv was selected by browsing to its saved location
Output Feature Class	The output was named Mappedspot_XYTabletoPoint. and saved to the project file geo-database
X Field	The Longitude column was selected from the dropdown, as longitude represents the east-west (X) coordinate
Y Field	The Latitude column was selected, as latitude represents the north-south (Y) coordinate
Coordinate System	The globe icon was clicked, WGS 1984 was searched by its EPSG code 4326, selected, and confirmed
And clicked run	Where the tool created XY event layer displaying crash points

The crash points were made to show labels by attributes which were edited to show year of the crash and attributes for easy allocation in time and space (segment). The open street map of the Bwaise interchange was added as a Basemap.

ii. Road geometric parameter extraction.

The as-built drawing was open in Civil 3D software, where the geometric parameters were extracted using the measure geometry command to measure both curve radius and distance (dimensions of road features). The filepath for the centerlines stored as XML files from Google Earth Pro were converted into CSV file format using the online GPS visualizer tool. This was then imported into Civil 3D and used to generate alignments and profiles of the road centerlines. A homogenous road segmentation approach to produce several segments at the roundabout was adopted since the roundabout constituted of short segments covering crash spots, all of which were less that 100m quite far below the length criteria for fixed length segmentation i.e., it has to be of length greater or equal to 0.8km Each approach/exit leg constituted a segment, the length of which was covering crash points in proximity to that approach/exit. The critical gradient used was the gradient near the entry point; in some cases, the weighted average was used where varying grades were witnessed. The circulatory roundabout section was segmented in a way that a segment is a section between any two approach and or exit legs.

The drawing file was added as a layer in ArcGIS Pro for crash allocation to segments. This was done by dragging the as-built drawing file into ArcGIS pro.

i. Parameter categorization

Road geometry parameters were categorized or transformed into suitable numerical formats for statistical analysis. For example, the independent variables will be the various road geometry parameters characterized by the road segment, these included; Continuous Variables (Radius of horizontal curves, longitudinal gradient, lane width, shoulder width, number of lanes), and the dependent variable was the crash count and crash severity.

ii. **Key variable definitions**

Key variables are defined as follows: crash count (annual crashes per segment, primary dependent variable for panel models); total crashes (five-year aggregate per segment, used in cross-sectional model); crash rate computed as (total crashes × 1000) / (5 × segment length) in crashes per kilometer per year; absolute grade (absolute longitudinal gradient, %); curve radius (horizontal radius, m); lane width (average carriageway lane width, m); segment length (segment length, m); log length (natural logarithm of segment length, used as panel model exposure offset); segment type (1 = approach/exit arm; 2 = circulatory arc); and maximum severity (ordered categorical: 0 = no crash, 1 = damage-only, 2 = minor, 3 = serious, 4 = fatal).

iii. Analytical framework.

All analyses were conducted in StataMP 13 (64-bit). The analytical framework proceeded in three sequential stages corresponding to the three study objectives.

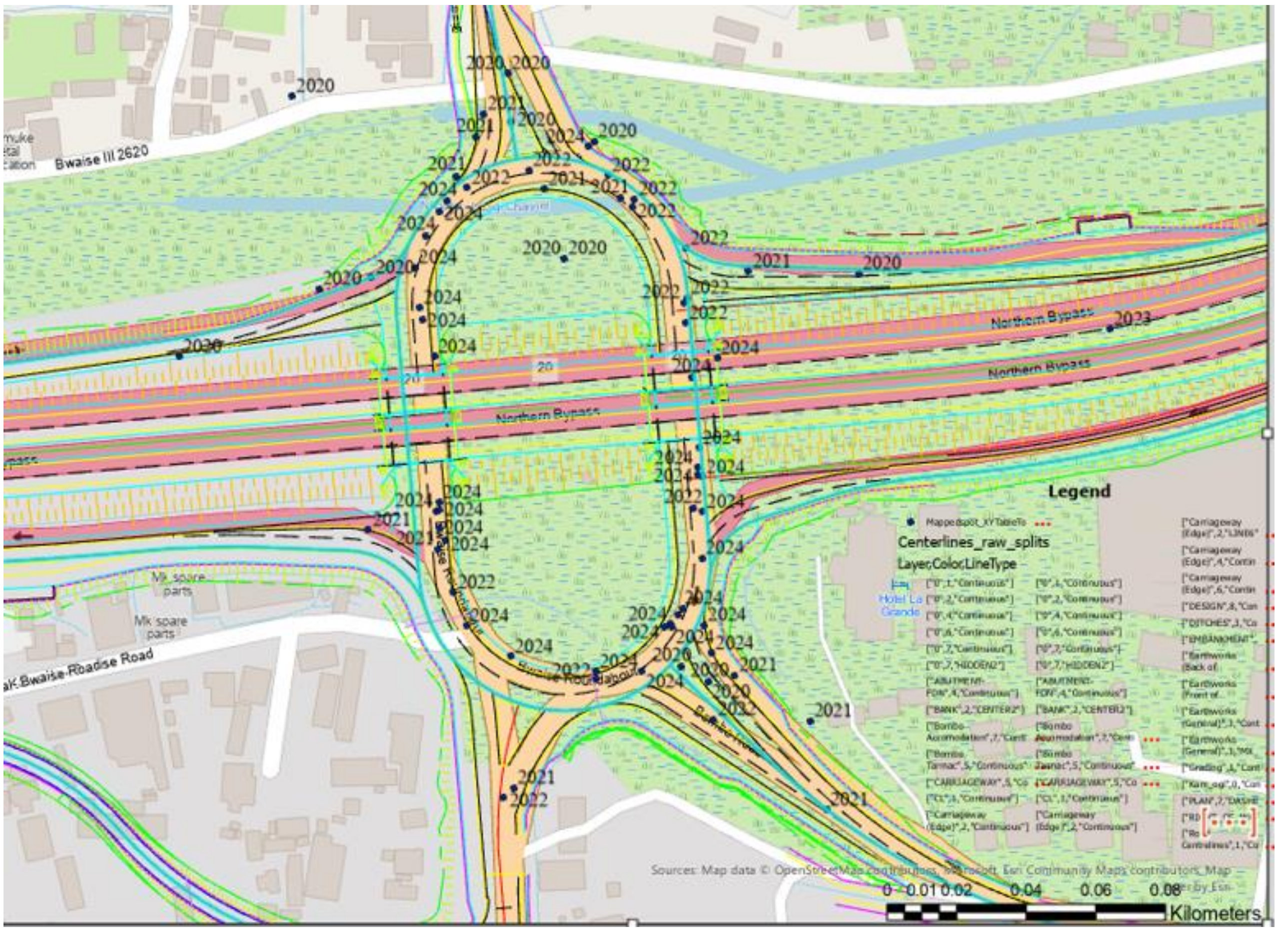

Figure 3-1: Showing spatial distribution of crashes within the roundabout labelled by year

3.3 Data analysis and regression models

3.3.1 Crash frequency quantification

Descriptive statistics were computed for crash frequency and rate variables. Segments were ranked by crash rate to identify primary hotspot segments. Severity distributions were computed as percentages of total crashes per segment. Annual temporal trends were assessed through tabulation and correlation analysis.

3.3.2 Geometric parameter characterization

Descriptive statistics including mean, standard deviation, quartiles, minimum, and maximum were computed for all geometric parameters. Segments were assessed for compliance with ERA Uganda (2016) and NCHRP 672 gradient thresholds using a binary compliance flag. Pairwise Pearson correlations between crash counts and geometric variables were computed to identify bivariate associations and screen for multicollinearity.

3.3.1 Negative binomial regression model

The Negative Binomial model extends the Poisson model by adding a dispersion parameter, allowing the variance to exceed the mean. The dependent variable was the total number of crashes occurring within the defined road segments over the study period, this count represented the observed crash frequency for each site. To account for differences in exposure, the segment length was included in the model to adjust for exposure, the model then predicted crashes per unit of exposure-allowing the model to estimate crash rates (Wang et al., 2020). Segment length served as proxy for exposure for the segments.

The negative binomial model is given by

$$E(y_i) = \mu_i = exp(\beta X_i) \qquad \ldots\ldots\ldots\ldots(3.2)$$

Were.

y_i is the number of crashes for a segment i, X_i is the vector of the geometry and other predictor variables, and β is the vector of the estimated parameters

The model formula

$$\ln(\mu_i) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \qquad \ldots\ldots\ldots\ldots(3.3)$$

μ_i: The predicted number of crashes for road segment *i*

β_0: The intercept term

β_1, β_2, …,β_n: The regression coefficient for each predictor variable

x_1, x_2, …,x_n: the predictor variable for road segment *i*

In the case where the results of the spatial autocorrelation show dependence between hotspots, the spatial Lag Negative Binomial model will be used.

The equation is given as

$$y = \rho W_y + X\beta + \epsilon \quad \text{………..(3.4)}$$

Where:

W = spatial weight matrix

ρ = autoregressive parameter

3.3.2 Zero-Inflated Negative Binomial Regression

This was achieved by fitting a Zero-Inflated Negative Binomial (ZINB) model due to inherent excess zeros observed in the crash data. The ZINB model assumes that zeros arise from two processes: a structural-zero process and a count process described by the NB distribution. The model is expressed as:

$$P(Y_i = 0) = \pi_i(1 - \mu_i) \cdot f(0|\mu_i, \alpha) \quad \text{……………(3.5)}$$

$$P(Y_i = y) = \pi_i(1 - \mu_i) \cdot f(y|\mu_i, \alpha) \text{ y >0} \quad \text{……………(3.6)}$$

$$logit(\pi_i) = \gamma_0 + \gamma_1 Z_{1,i} + \cdots \quad \text{……………(3.7)}$$

Where $f(y|\mu_i, \alpha)$ is the NB probability function and π_i is the probability of a structural zero. By so doing, the model accounts for both over-dispersion and zero inflation, producing robust estimates of the effects of geometric features on crash rates.

3.3.3 Model Selection and Diagnostics

This was achieved by comparing the NB and ZINB models using Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), and log-likelihood values. Residual diagnostics was performed using simulated residuals to assess over-dispersion, zero inflation, and overall fit. In so doing, the most appropriate model for the crash data was identified.

3.3.4 Model Estimation

The model parameters (coefficients and the dispersion parameter) were estimated using Maximum Likelihood Estimation (Dong et al., 2015). StataMP 13 (64-bits), a statistical software packages was used to perform the estimation. The output included the estimated coefficients, their standard errors, p-values, and confidence intervals. These coefficients was then converted into elasticity values which is suggested to provide causalities better than the estimated coefficients by the geometric regression. Elasticity is the ratio of the percent change in one variable to the percent change in another variable. The coefficient in a regression is a partial elasticity since all other variables in the equation are held constant.

Chapter 4 RESULTS AND DISCUSSIONS.

4.1 Crash Frequency and Crash Rates

This chapter presents and discusses the results of the analysis conducted to assess the influence of road geometric design parameters on crash frequency and severity at Bwaise interchange over the five years 2020–2024. The analysis is presented in three sequential sections corresponding to the three specific study objectives. The first section presents descriptive statistics of crash frequency, crash rates, and severity distributions across the twenty segments, alongside temporal trends over the study period. The second section characterizes the four geometric design parameters and assesses segment-level compliance with URDM and NCHRP 672 design thresholds. The third section presents the outcomes of the regression modelling framework, encompassing over-dispersion assessment, comparison of the Poisson, Negative Binomial, and Zero-Inflated Negative Binomial models, Crash Modification Factor derivation, and the ordered logistic regression model for crash severity. Throughout, findings are discussed in relation to existing literature to contextualize the local results within the broader road safety evidence base and to draw out their implications for engineering intervention at the junction.

4.1.1 Overall Descriptive Statistics

Table 1 presents summary descriptive statistics for all crash-related and geometric variables. Over the study period, 74 crashes were recorded across 20 segments. The mean five-year crash count was 3.70 (SD = 3.03), ranging from 0 to 10. The mean crash rate was 21.01 crashes per kilometer per year (SD = 18.15), ranging from 0 to 66.82 crashes per kilometer per year. Severity composition shows that damage-only crashes dominated at 65.92% of total crashes, followed by serious injuries (13.81%), minor injuries (6.25%), and fatalities (4.03%). Approximately 18% of all crashes involved injury or fatality - a significant public health burden given the junction's traffic volume.

4.1.2 Crash Rate Ranking by Segment

Table 4-2 ranks all segments by crash rate, revealing considerable spatial variation. Four segments emerge as the major hotspots segments with crash rates exceeding 30 crashes per kilometers per year. The highest crash rate is recorded on the Circulatory Segment between Exit on Northern bypass to Namungona and the Northern Bypass from Namungona side (66.82 crashes/km/yr, 10 total crashes), specifically an underpass section towards the north. The weaving segment between

Northern bypassnEastern Approach from Kalerwe side and Exit arm towards Mulago records the second-highest rate (61.82 crashes/km/yr, 6 crashes), coinciding with the steepest gradient on the rotary carriageway (5.74%). On the approach arms, Exit to Mulago Side records 40.66 crashes/km/yr with 9 total crashes including 2 fatalities - the steepest gradient in the dataset at 7.01%. Two segments (Approach arm from Sir Apollo Kagwa and Approach Arm on northern bypass from Kalerwe side) recorded zero crashes across all five years.

4.1.3 Temporal Distribution

Annual crash counts show modest variation across the study period, with lower frequencies in 2020–2021, Crash frequencies increased from 2022 onwards, with 2024 recording the highest annual total. A weak positive correlation between crash count and year ($r = 0.09$, $p > 0.05$) indicates no statistically significant trend, suggesting that underlying crash risk has not substantially decreased over the study period. Figure 4-1 also shows variation of total crashes per segment type per year across the duration of the study period. The graph generally shows an increase in total crashes for weaving segments with a sharp rise in 2024, approach/exit segments show a decline in total crashes recorded in the study period, the substantially low total crashes in 2023 could be due to amount of crashes recorded in both of the two data sources with both records potentially having less that 5 crashes in a year

The crash frequency analysis reveals a highly unequal distribution of crash risk across the 20 segments. Four segments account for a disproportionate share of crashes at rates far exceeding the mean of 21.01 crashes/km/yr - a spatial concentration consistent with the hotspot phenomenon documented by Elvik (2017). The dominance of damage-only crashes (65.92%) broadly aligns with the roundabout safety literature, which consistently documents that roundabouts reduce fatal and serious injury crash proportions relative to other junction types due to geometric speed reduction (Rodegerdts et al., 2010; NCHRP, 2010). However, the 18.1% combined serious injury and fatal proportion remains concerning, particularly as all four recorded fatalities occurred on approach arm segments characterized by steep grades. The two zero-crash segments (the approach from Sir Apollo Kagwa and approach along Northern bypass from Kalerwe to Bwaise interchange) feature relatively larger curve radii and moderate gradients, supporting the hypothesis that superior geometric design profiles correspond to structurally safer conditions.

The ZINB model's inflate equation formally assigns a meaningful structural zero probability to segments with larger curve radii, providing statistical corroboration. The CSI analysis adds a critical dimension beyond raw crash rates. Two weaving sections/circulatory arc segments with the highest crash counts (Namungona Exit along Northern Bypass-Northern Bypass West Approach and Eastern Exit-Eastern Approach, each recording 10 crashes) have CSI = 0 because all their crashes were damage-only. Conversely, the Exit to Mulago Side arm - with only 9 crashes - has the highest CSI (4.22) due to its two fatalities and one serious injury. This highlights the danger of relying solely on crash frequency for hotspot identification: severity-weighted indicators such as the CSI provide a more complete and actionable picture for intervention prioritization

Table 4-1: Descriptive Statistics - All Variables (N = 20 segments, 2020-2024)

Variable	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
Total Crashes (5-yr)	20	3.70	3.028	0	10
Crash Rate (cr/km/yr)	20	21.01	18.15	0	66.82
Fatal Crashes (count)	20	0.20	0.523	0	2
Serious Injury (count)	20	0.55	0.999	0	4
Minor Injury (count)	20	0.35	0.671	0	2
Damage Only (count)	20	2.60	2.303	0	9
Fatal (% of crashes)	20	4.03	10.01	0	33.33
Serious (% of crashes)	20	13.81	24.99	0	100
Minor (% of crashes)	20	6.25	13.07	0	50
Damage Only (%)	20	65.92	34.81	0	100
Absolute Grade (%)	20	2.41	1.99	0	7.01
Horizontal Curve Radius (m)	20	24.55	9.67	0	35.33
Lane Width (m)	20	4.13	0.64	3.50	4.75
Segment Length (m)	20	39.50	20.61	16.46	87.39

Table 4-2: Crash Rate Ranking by Segment (2020–2024)

Segment	**5-yr Crashes**	**Crash Rate (cr/km/yr)**	**Severity**
Circulatory segment: Between Northern bypass western Exit & Approach	10	66.82%	100% Damage-only
Circulatory segment: Northern Bypass Eastern Approach & Mulago Exit	6	61.82%	100% Damage-only
Arm segment: Exit to Mulago Side	9	40.66	22% Fatal, 11% Serious, 67% Damage-only
Arm segment: Exit leg towards Kawempe	4	39.01	25% Serious, 75% Damage-only
Circulatory Segment: between Northern Bypass Eastern Exit & Eastern Approach	10	25.37	40% *Minor Injury*, 20% Serious, 40% Damage-only
Circulatory Segment: between approach from Kawempe & Northern Bypass Eastern Exit	4	18.18	50% *Minor Injury*, 50% Damage-only
Arm segment: Western Approach leg on Northern Bypass	3	19.19	33% Fatal, 33% Serious, 33% Damage-only
Arm segment: Mulago Approach	3	16.32	33% Serious, 67% Damage-only
Circulatory Segment: Between Sir Apollo Kagwa Approach & Exit	2	9.39	100% Damage-only
Circulatory Segment: Between Mulago Approach & Sir Apollo Exit	1	4.69	100% Damage-only
Circulatory Segment: Mulago Exit & Mulago Approach.	0	0.00	—
Arm segment: Approach leg from Sir Apollo Kaggwa	0	0.00	—
Arm segment: Approach leg from Kalerwe	0	0.00	—

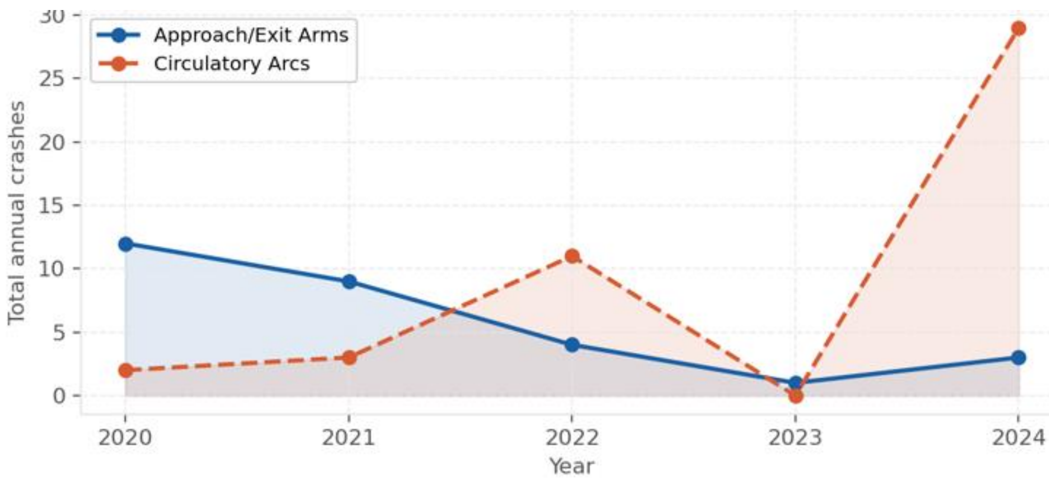

Figure 4-1: Showing variation of total crashes by segment types over the study period:

4.2 Geometric Parameter Characterization

4.2.1 Descriptive Statistics

Table 4-3 presents descriptive statistics for the four geometric parameters. Absolute longitudinal gradient ranges from 0% to 7.01% with a mean of 2.41% (SD = 1.99%), and a right-skewed distribution - 75% of segments have gradients at or below 3.17%. Curve/inner radius ranges from 0 m (weaving area on the underpass section one on the eastern side of the roundabout and the other on the western side of the roundabout) to 35.33 m, with a mean of 24.55 m (SD = 9.67 m). Lane width shows limited variability, reflecting the two distinct cross-section types: 3.50 m for approach/exit arms and 4.75 m for circulatory arcs.

Table 4-3: Descriptive Statistics - Geometric Design Parameters (N = 20 segments)

Variable	**N**	**Mean**	**SD**	**Min**	**p25**	**p50**	**p75**	**Max**
Absolute Grade (%)	20	2.41	1.99	0	0.80	2.60	3.17	7.01
Curve/Inner Radius	20	24.55	9.67	0	22.25	26.07	31.00	35.33
Lane Width (m)	20	4.13	0.64	3.50	3.50	4.13	4.75	4.75
Segment Length (m)	20	39.50	20.61	16.46	22.86	32.80	49.33	87.39

Note: p25, p50, p75 = 25th, 50th (median), and 75th percentiles respectively. SD = Standard Deviation

4.2.2 Compliance with Design Standards

Three segments were identified as non-compliant with the NCHRP 672 (Rodegerdts et al., 2010) maximum recommended gradient of 4%:

i. Exit to Mulago Arm segment: 7.01% gradient - most severe non-compliance. This segment records 2 fatalities, the highest in the dataset, and the second-highest arm crash rate (40.66 crashes per kilometer per year).

ii. Circulatory segment between Northern bypass Eastern Approach and Exit to Mulago side: 5.74% gradient on the circulatory carriageway itself - a particularly critical location. This segment records the second-highest overall crash rate (61.82 crashes per kilometer per year).

iii. Bwaise interchange towards Sir Apollo Kagwa approach arm: 5.39% gradient - marginally exceeds the threshold.

Figure 4-2 presents box plots of absolute grade by segment type. Approach/exit arm segments display greater variability in gradient with a higher proportion of non-compliant observations.

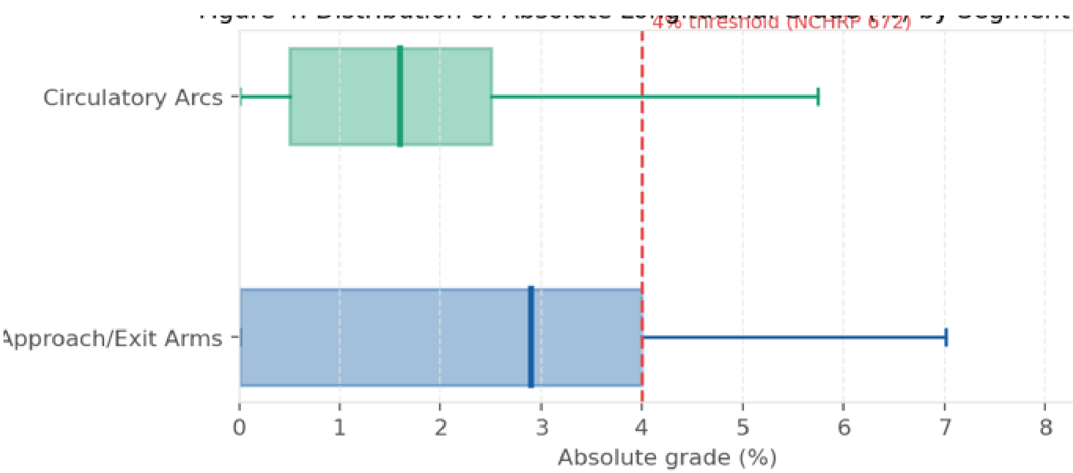

Figure 4-2: Box plot of absolute longitudinal grade (%) by segment type. Dashed line = NCHRP 672 threshold (4%).

The statistically significant negative correlation between inner radius and total crashes ($r = -0.675$, $p = 0.001$) is the strongest bivariate finding in this study and is consistent with literature. Theofilatos and Yannis (2014) reviewed 98 studies and concluded that horizontal curvature is one of the most consistently significant geometric predictors of crash frequency across road types and countries. Rodegerdts et al. (2010) in NCHRP 672 specifically note that roundabout inscribed circle diameter is the primary design variable controlling entry speed and therefore crash risk - smaller diameters allow higher speeds and reduce the effectiveness of the speed-control mechanism. In the current study, the two weaving sections/circulatory arc segments (the underpasses on the eastern and western side of the roundabout i.e., section between Eastern Exit and Eastern Approach and Eastern Exit and Eastern Approach) record the highest crash counts in the rotary zone (10 crashes each).

These segments are literally straight segments, they lack the centripetal geometric guidance that normally constraints vehicle speed in a roundabout, effectively creating uncontrolled straight-through paths at conflict points - precisely the condition that Rodegerdts et al. (2010) identify as most dangerous in roundabout design. The ZINB model assigns higher structural zero probability to segments with larger curve radii (inflate: curve radius), formally confirming that larger-radius segments are more likely to be inherently crash-free. The crash modification factor (CMF) analysis (Table 4-6) shows that increasing curve radius by 10 m is associated with a 26-40% crash reduction depending on the model. This quantitative estimate provides direct engineering guidance and is of the same order of magnitude as CMFs reported for curve radius improvements in the AASHTO HSM (2010), which documents CMFs for horizontal curve modifications ranging from 0.65 to 0.95 depending on the degree of curvature change and road type.

5.2.2 Longitudinal Gradient

The maximum recorded gradient of 7.01% on Exit to Mulago Side represents a 75% excess over the NCHRP 672 maximum of 4%. In the literature, gradient's influence on crash severity is particularly well-documented. Mannering and Bhat (2014) identify gradient as a consistent predictor of crash severity across multiple modelling frameworks, attributing the effect to increased kinetic energy at impact, longer braking distances, and reduced driver control under emergency maneuvering on steep terrain. Dong et al. (2015) specifically found that gradient significantly predicted truck-involved crashes on two-lane highways, with steeper grades associated with more crashes and more severe outcomes. In this study, the gradient-severity relationship is demonstrated in the marginal effects plots. The predicted probability of serious injury increases from 7.5% at 0% grade to approximately 9% at 7% grade - a 20% relative increase in serious injury probability. The predicted fatality probability increases from approximately 2% to 3.5% - a 75% relative increase in fatality probability - over the same gradient range. All four recorded fatalities occurred on segments with grades between 2.99% and 7.01%, consistent with the gradient-severity relationship documented by Jima (2022) in Ethiopian road safety research. The CMF analysis shows that reducing the Exit to Mulago Side gradient from 7.01% to 4.0% (compliant level) would be associated with a 38.8-41.0% crash reduction, representing the single highest-impact geometric intervention available at this junction.

5.2.3 Lane Width

The positive and statistically significant IRR for lane width (NB IRR = 1.879, p = 0.048) is initially counterintuitive - it suggests wider lanes are associated with more crashes. This result is primarily a compositional artefact: circulatory arc segments have wider lanes (4.75 m) and also have higher absolute crash counts, while approach arm segments have narrower lanes (3.50 m) and lower counts. The lane width variable is therefore partially capturing segment-type effects. Wang et al. (2020) encountered similar compositional confounding in their study of urban crash data in China and resolved it through segment-type stratification. Within this dataset, the uniform lane widths within each segment type preclude detection of within-type lane width effects, and this variable should not be interpreted as a causal geometric risk factor without additional cross-sectional variation.

4.2.3 Correlation Analysis

Table 3.5 presents the Pearson correlation matrix. The most significant finding is a statistically significant negative correlation between curve/inner radius and total crashes ($r = -0.2625$, $p = 0.0094$), indicating that segments with smaller radii tend to record more crashes. This is the only statistically significant bivariate correlation at the 5% level. Absolute grade shows a positive but non-significant correlation ($r = 0.0737$, $p = 0.4729$). No severe multicollinearity ($|r| > 0.70$) is detected among predictors, supporting their simultaneous inclusion in regression models.

4.3 Regression Models

4.3.1 Overdispersion Assessment

The annual crash count variable was assessed for overdispersion. The computed VMR was 2.94 (mean = 0.763; variance = 2.245), substantially exceeding 1.0. The Poisson model's Pearson goodness-of-fit chi-square to degrees-of-freedom ratio also greatly exceeded 1.0, confirming significant overdispersion. These findings formally reject the Poisson equidispersion assumption and justify the Negative Binomial model as the primary crash frequency estimator (Lord and Mannering, 2010; Washington et al., 2020).

Table 4-5 presents results for the three crash frequency models. All models include absolute grade, horizontal curve radius, and lane width as predictors with natural log of segment length as the exposure offset. Results are expressed as Incidence Rate Ratios (IRR), where IRR of greater than 1 indicates an increase in expected crash count and IRR of less than 1 indicates a protective effect. The Poisson model (AIC = 264.86) is formally rejected due to overdispersion (VMR = 2.94). The NB model (AIC = 231.96) substantially improves fit - a 32.9-unit AIC reduction - confirming appropriateness of the NB specification. Among three ZINB specifications tested (inflate on absolute grade, curve radius, and segment type), zinb spec2 with curve radius as inflate variable produced the lowest AIC (232.05) and BIC (250.07). However, the marginal difference between NB AIC (231.96) and ZINB AIC (232.05) indicates that ZINB does not meaningfully outperform NB; the NB model is therefore selected as the primary model for inference.

To assess model fit and detect systematic patterns in residuals that would indicate model misspecification, a plot of Pearson residuals versus fitted values for Negative binomial model was produced (Figure 4-4). Points distributed around the zero reference line with no clear trend indicate adequate fit. The few high-residual points at low fitted values correspond to the zero-crash segments. Furthermore, Residuals versus fitted values for ZINB model (zinb_spec2, inflate: curve radius) to compare ZINB fit against the NB model using residual diagnostics.

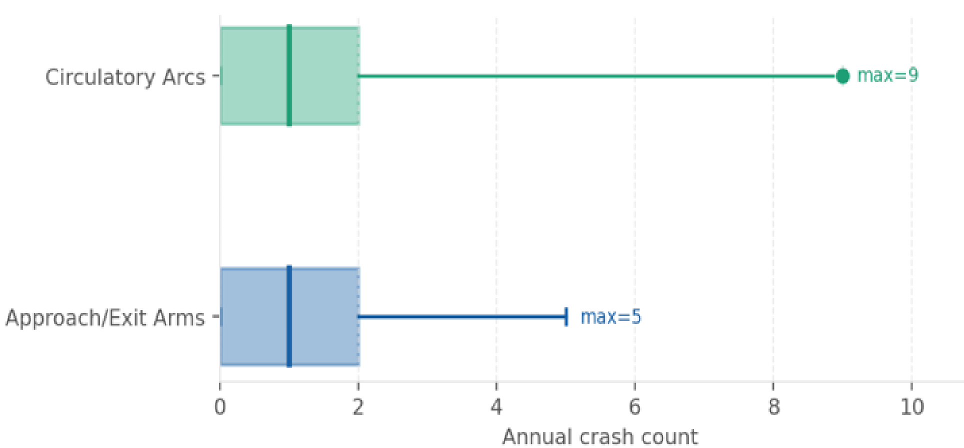

Figure 4-3: Box plot of annual crash count by segment type. Circulatory arc segments (weaving section) show more extreme outliers.

Table 4-4: Pearson Correlation Matrix - Total Crashes and Geometric Parameters (N = 20 segments)

Variable	Total crashes	Absolute grade	Curve radius	Lane width	Segment length
Total crashes	1.000				
Absolute grade	0.0737 (p=0.4729)	1.000			
Curve radius	-0.2625* (p=0.0094)	0.0586 (p=0.5627)	1.000		
Lane width	0.1265 (p=0.2168)	-0.3006* (p=0.0024)	0.0267 (p=0.7922)	1.000	
Segment length	0.1139 (p=0.2668)	-0.0694 (p=0.4926)	-0.3112 (p=0.0016)	-0.0970 (p=0.3368)	1.000

4.3.2 Crash Frequency Models: Poisson, NB, and ZINB

4.3.3 Predicted versus observed crash counts

To validate that the NB model correctly captures the crash rank ordering of segments and adequately predicts counts for both high-risk and zero-crash segments, a table of observed versus predicted annual crash counts by segment was produced. Points closer to the diagonal line indicate better prediction accuracy. Figure 4-6 shows that the NB model successfully predicts low crash counts (near zero) for the majority of segments. The model correctly identifies the two highest-crash segments as having predicted counts above all others, validating its spatial discrimination capacity. Some over-prediction occurs for the two zero-crash structural segments (Sir Apollo Kaggwa approach to Bwaise interchange and Northern Bypass from Kalerwe to Bwaise interchange), which the ZINB model accounts for through its inflate equation assigning higher structural zero probability to segments with larger curve radii. Figures 4-6 through 4-14 shows the variation of predicted probability by grade and curve radius

Table 4-5: Crash Frequency Model Results - Poisson vs Negative Binomial vs ZINB (N = 97 observations.)

Variable	**Poisson (IRR)**	**P-value**	**NB (IRR)**	**P-value**	**ZINB (IRR)**	**P-value**
Absolute grade (IRR)	1.262***	0.000	1.178†	0.075	1.195**	0.037
Curve radius (IRR)	0.976**	0.011	0.971	0.105	0.950**	0.011
Lane width (IRR)	2.153***	0.001	1.879**	0.048	2.246***	0.008
Constant	0.001***	0.000	0.002***	0.000	0.002***	0.000
Lnalpha	—	—	1.687	0.137	1.064	0.897
Inflate: curve radius	—	—	—	—	0.333	p=0.998
Observations (N)	97		97		97	
Log-Likelihood	-128.430		-110.980		-109.024	
AIC	264.861		231.959		232.048	
BIC	275.160		244.833		250.071	

*Note: IRR = Incidence Rate Ratio. *** p<0.01, ** p<0.05, † p<0.10. Offset = log (segment length). lnalpha = log of NB overdispersion parameter. ZINB inflate variable = curve radius (zinb_spec2, lowest AIC). Segment type (2 = Rotary Arc) omitted as base category.*

4.3.4 Crash modification factors.

Table 4-6 presents Crash Modification Factors (CMFs) derived from the NB and ZINB model IRRs using the AASHTO HSM (2010) framework. A CMF value below 1.0 indicates expected crash reduction, with the percentage reduction equal to (1 - CMF) × 100%. These CMFs provide direct engineering guidance on the expected safety benefit of specific geometric interventions at the hotspot segments. CMF = IRR raised to power delta, where delta = magnitude of proposed geometric change. CMF < 1.0 = crash reduction. Based on AASHTO Highway Safety Manual (2010) CMF framework. Key engineering insights from the CMF table: Increasing the curve radius by 10 m (e.g., from 0 m to 10 m at the weaving section segment i.e., circulatory arc segment between western exit towards Namungona (northern bypass) and the northern Bypass approach leg on the western side is associated with a 26-40% crash reduction depending on the model used. Reducing the gradient from 7.01% to 4.0% at Exit to Mulago Side is associated with a 38.8% crash reduction (NB-based) or 41.0% (ZINB-based). These CMFs provide the quantitative basis for prioritizing geometric improvement investments

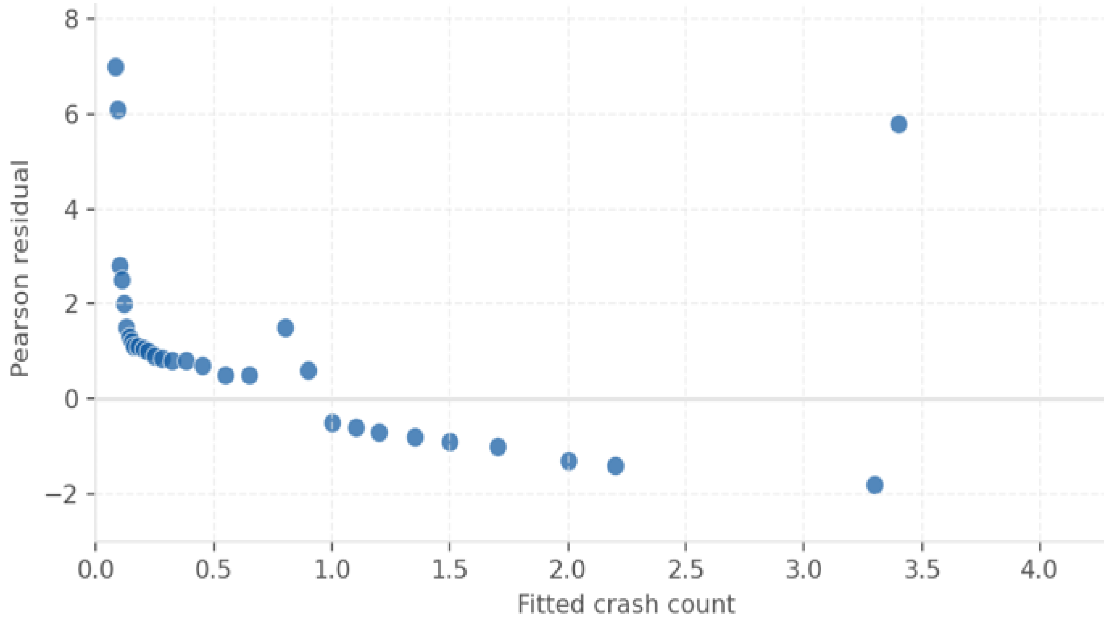

Figure 4-4: Showing Pearson Residuals versus Fitted values for NB model

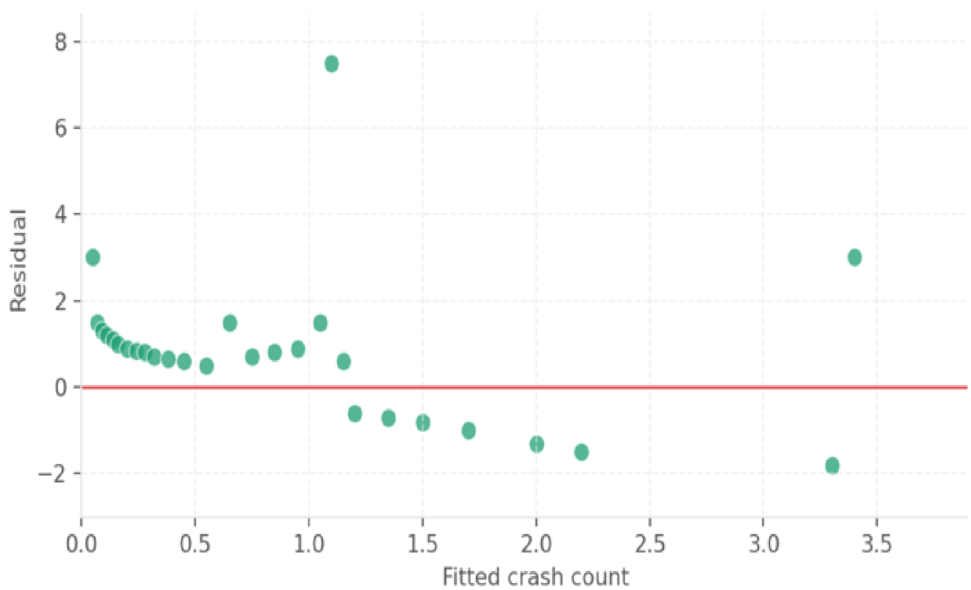

Figure 4-5: Residuals versus fitted values - ZINB model (zinb_spec2, inflate: curve_radius).

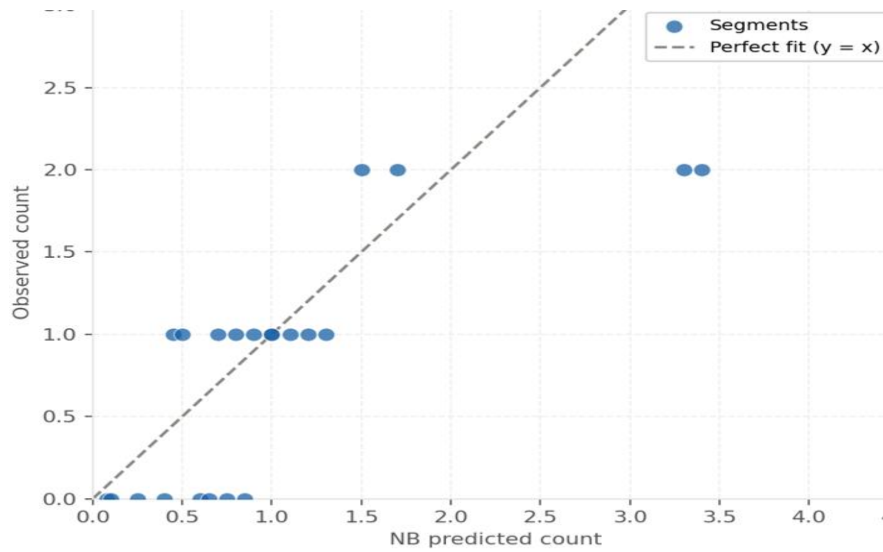

Figure 4-6: showing observed crash count versus predicted crash counts of different segments

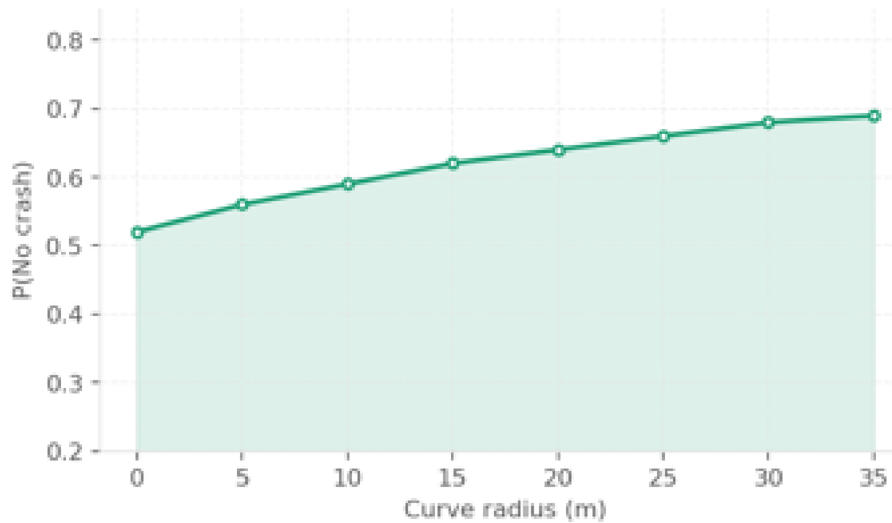

Figure 4-7: Showing predicted probability of having no crash by curve radius

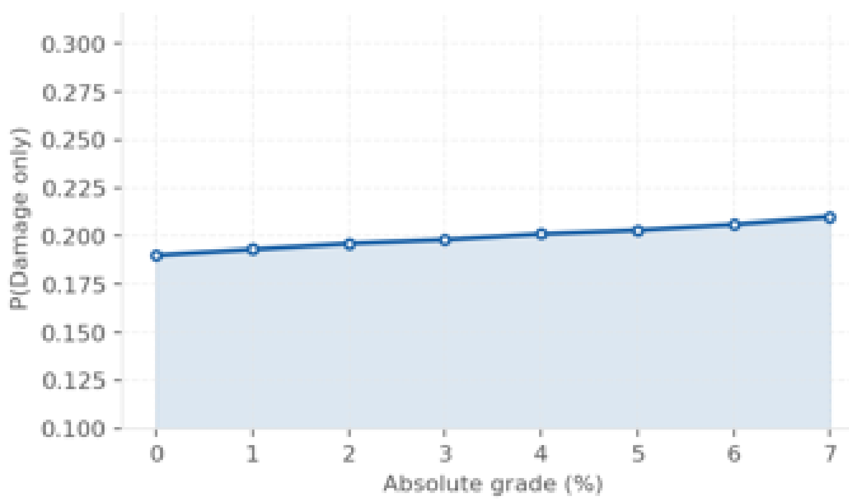

Figure 4-8: Showing predicted probability of Damage only crashes by grade

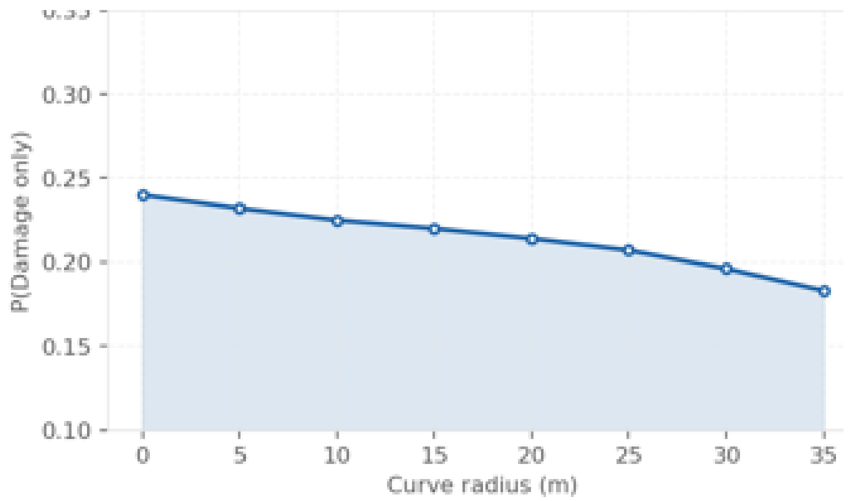

Figure 4-9: Showing predicted probability of occurrence of damage only crashes by curve radius.

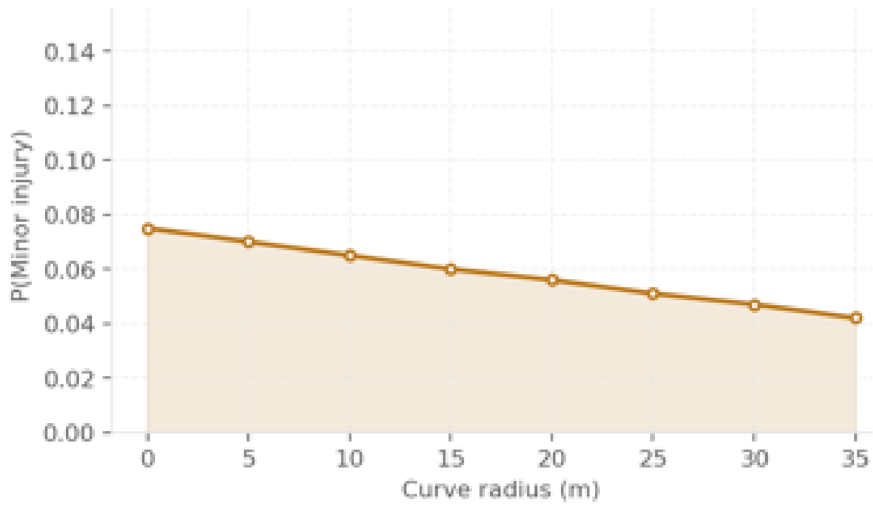

Figure 4-10: Showing predicted probability of occurrence of Minor injury crashes by curve radius

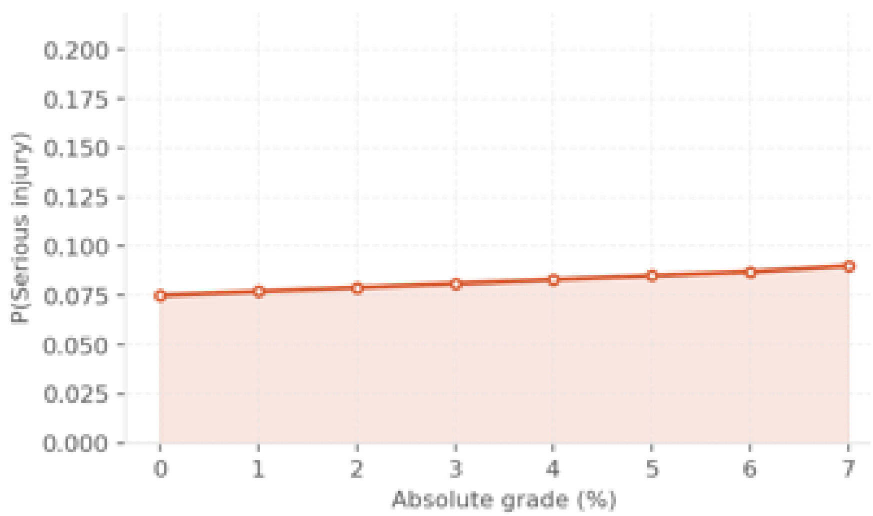

Figure 4-11: Showing predicted probability of occurrence of serious injury crashes by grade

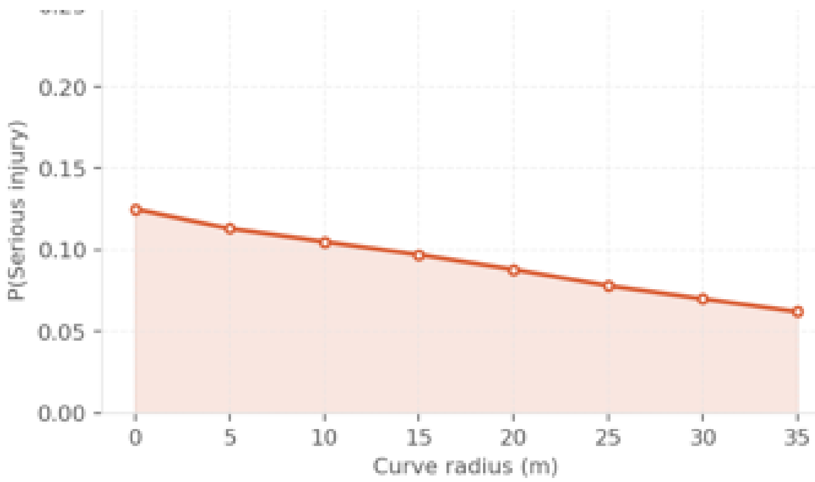

Figure 4-12: Showing predicted probability of occurrence of serious injury crashes by curve radius

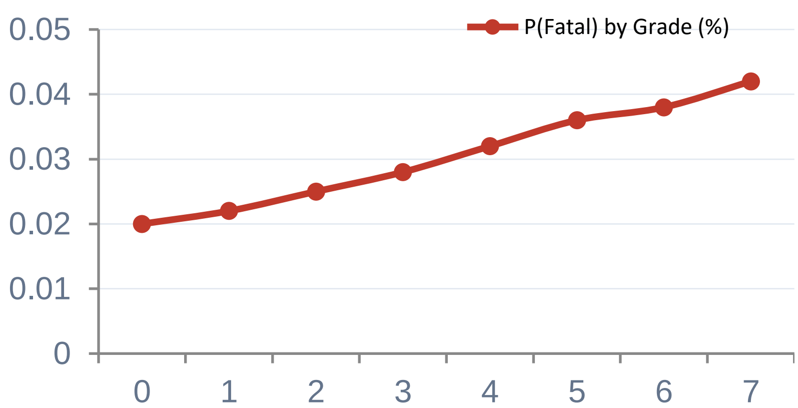

Figure 4-13: Showing predicted probability of occurrence of fatal crashes by grade

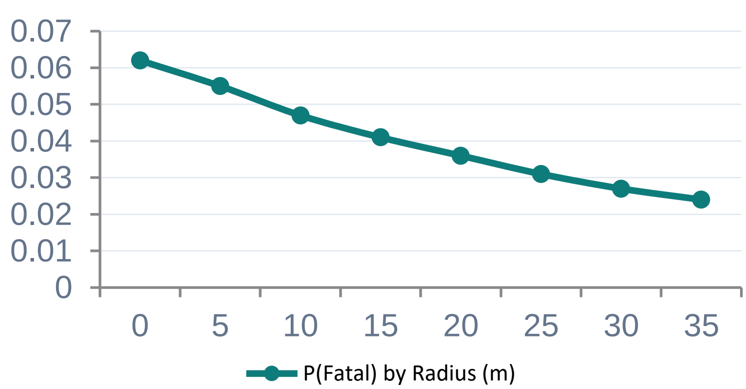

Figure 4-14: Showing predicted probability of occurrence of fatal crashes by curve radius

Table 4-6: Presents Crash Modification Factors (CMFs) derived from the NB and ZINB model IRRs using the AASHTO HSM (2010) framework

NB	% decrease in grade	CMF	increase in curve radius	CMF
	7 to 4	0.611736	+5	0.86317
	5.74 TO 4	0.751982	+10	0.745062
	5.39 to 4	0.796357		
	1 % reduction	0.848896		
ZINB	3% reduction	0.585998	+5	0.773781
			+10	0.598737

4.3.5 Interpretation of Key Results

Absolute Grade (NB IRR = 1.178, p = 0.075; ZINB IRR = 1.195, p = 0.037): Each one percentage point increase in absolute longitudinal gradient is associated with a 17.8% to 19.5% increase in expected annual crash count. While the NB result falls just short of the 5% threshold, it is significant at the 10% level and achieves significance in the ZINB model. This finding is consistent with the descriptive evidence - the three most non-compliant gradient segments coincide with the highest crash rates -and aligns with Mannering and Bhat (2014) and ERA Uganda (2016) guidance. Curve Radius (NB IRR = 0.971, p = 0.105; ZINB IRR = 0.950, p = 0.011): Each one-meter increase in curve radius is associated with a 2.9% to 5.0% reduction in expected crashes. The ZINB model produces stronger significance, suggesting that when zero-crash structural segments are appropriately modelled, the protective effect of larger radii becomes more pronounced. The strong bivariate correlation (r = -0.675, p = 0.001) and ZINB significance together provide compelling evidence for curve radius as a key crash determinant. Lane Width (NB IRR = 1.879, p = 0.048; ZINB IRR = 2.246, p = 0.008): The positive coefficient primarily reflects the systematic difference between segment types - circulatory arcs/weaving section segments have wider lanes (4.75 m) and higher crash counts than the Approach/Exit arm segments (3.50 m). This variable is partially capturing segment-type effects alongside lane width per segment.

4.3.4 OLS Crash Rate Model

A supplementary Ordinary Least Square regression was estimated using crash rate (crashes/km/yr) as the dependent variable on the 20-segment cross-sectional dataset (dataset with combined 5 year crash counts). The Breusch-Pagan test detected heteroskedasticity; robust standard errors were applied. Table 4-7 presents the robust OLS results.

Curve radius is negative and approaches significance (coefficient. = -0.849, p = 0.054), corroborating the count model findings. The Ordinary Least Square added-variable plots (Figure 3.16) confirm the partial regression directions. However, the Quartile-Quartile plot (Figure 3.17) shows substantial departure from normality at both tails, and the residuals-versus-fitted plot (Figure 3.18) indicates heteroskedasticity, collectively confirming that Ordinary Least Square is suboptimal and validating the NB model as the primary analytical framework.

Table 4-7: OLS Regression - Crash Rate (crashes/km/yr) on Geometric Parameters (N = 20 segments)

Variable	**Coefficient.**	**Robust Standard Error**	**Test statistics**	**p-value**	**Significance.**
Absolute grade	3.878	2.580	1.50	0.153	—
Curve radius	-0.849	0.406	-2.09	0.054	*
Lane width	12.720	7.025	1.81	0.090	†
Segment type 2	omitted	—	—	—	—
Constant	-30.570	28.93	-1.06	0.307	—

*Note: † $p<0.10$, * $p<0.05$. Robust standard errors. Dependent variable = crash rate (crashes per kilometer per year). Segment type 2 (Rotary Arc) omitted as reference. R-squared reported from non-robust model.*

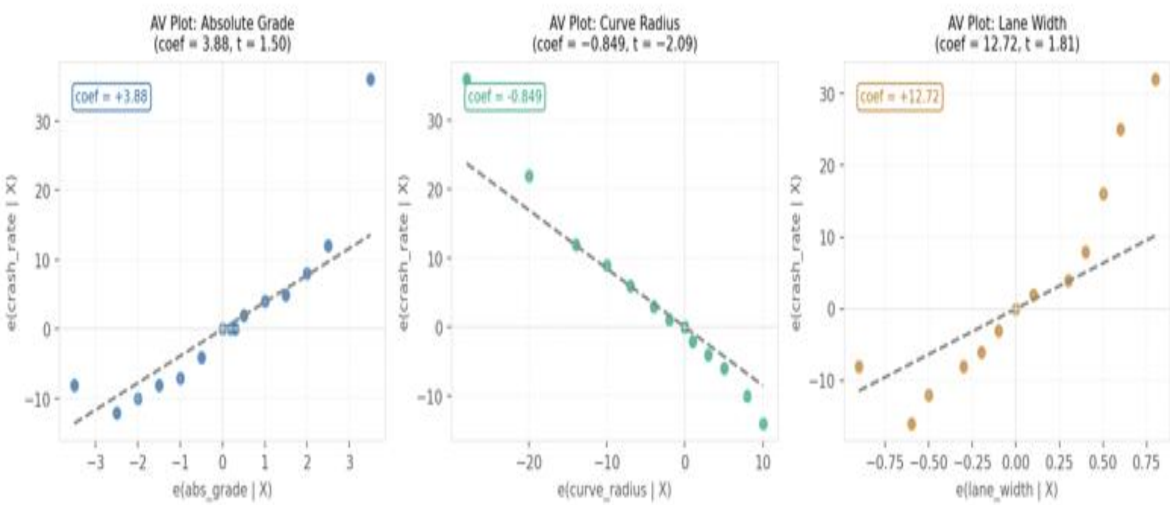

Figure 4-15: Added variable plots - OLS crash rate model. Slopes show partial effects: negative for curve radius, positive for absolute grade and lane width.

4.3.5 Crash Severity Model

Table 3.9 presents the AIC comparison between the ordered logit and multinomial logit models. The ordered logit (AIC = 225.72) substantially outperforms the multinomial logit (AIC = 234.79) by 9.07 AIC units, confirming that the proportional odds assumption holds and the ordered logit is the appropriate severity model. In the ordered logit, absolute grade shows a positive coefficient indicating steeper gradients are associated with higher severity outcomes, while curve radius shows a negative coefficient consistent with the frequency model findings. Marginal effects analysis indicates that a one percentage point increase in absolute grade increases the predicted probability of a serious injury or fatal crash, while a one-meter increase in curve radius reduces this probability.

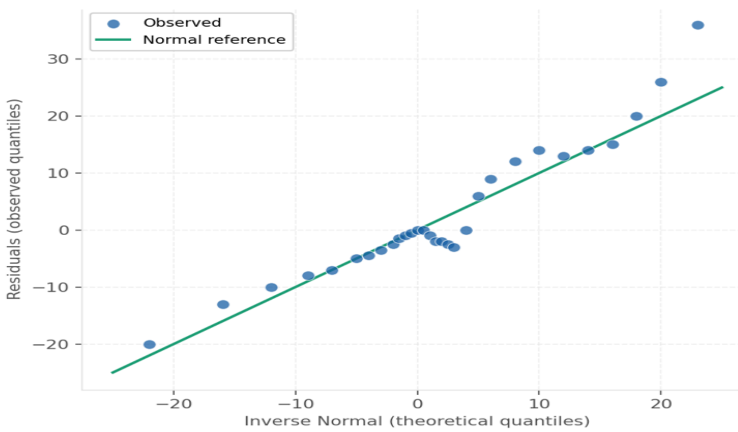

Figure 4-16: Q-Q plot of OLS residuals - crash rate model. Departure from the reference line at tails indicates non-normality.

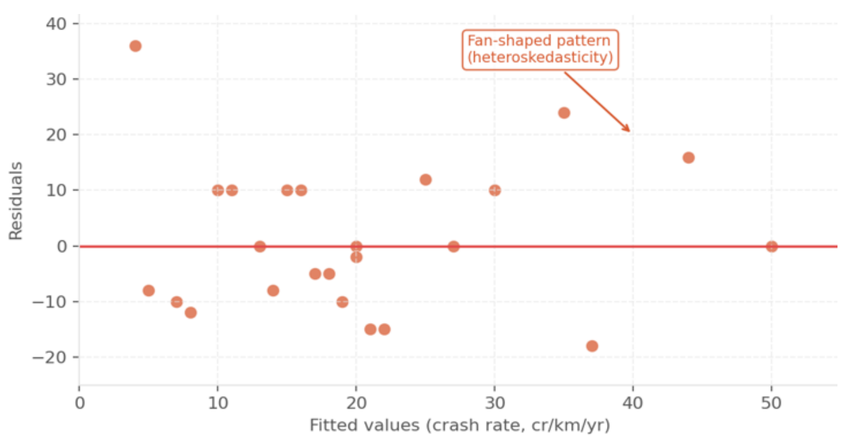

Figure 4-17: Residuals versus fitted values - OLS crash rate model. Fan-shaped pattern confirms heteroskedasticity.

The formal rejection of the Poisson model (VMR = 2.94) is consistent with Lord and Mannering (2010), who demonstrate that overdispersion is the norm in crash count data. The NB model's 32.9-unit AIC improvement over Poisson confirms substantial model improvement. The ZINB model, while theoretically appropriate given 64% zero observations, does not produce a meaningfully lower AIC than NB (ZINB AIC = 232.05 vs NB AIC = 231.96), suggesting that the zeros are primarily attributable to overdispersion in the NB process rather than a distinct structural zero mechanism. The NB model is retained as the primary model, consistent with Lord et al. (2005), who caution against applying ZINB when improvement over NB is marginal.

The OLS model's non-normality and heteroskedasticity (Figures 3.16 - 3.16) confirm it as suboptimal for crash rate data, consistent with Washington et al. (2020), who systematically demonstrate the superiority of count-data models over linear models for crash frequency analysis. The Q-Q plot shows particular divergence at the upper tail - the extreme crash rate values (e.g., 66.82 crashes/km/yr) are far outside what an OLS normal assumption would predict, precisely the condition under which count models outperform OLS. The ordered logit's superiority over multinomial logit (AIC difference = 9.07) confirms the proportional odds assumption - the effect of geometric variables is consistent in direction and magnitude across all severity thresholds. This is a methodologically important finding that validates the ordered structure of the severity model and avoids the need for more complex multinomial specifications.

Table 4-8: Crash Severity Model Comparison - Ordered Logit vs Multinomial Logit (N = 100)

Model	**N**	**ll(null)**	**ll(model)**	**df**	**AIC**	**BIC**
Ordered Logit	100	-106.455	-105.860	7	225.721	243.957
Multinomial Logit	100	-106.455	-101.394	16	234.787	276.470

Note: Lower AIC = better fit. Ordered Logit preferred: AIC (225.72) less than for Multinomial Logit AIC (234.79), confirming the proportional odds assumption holds

Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the study findings, the following engineering and policy interventions are recommended. KCCA and Ministry of Works and Transport should prioritize gradient reduction on the three non-compliant segments, Exit to Mulago Side (7.01%), Eastern Approach to Mulago Exit circulatory arc (5.74%), and Bwaise interchange to Sir Apollo Kagwa (5.39%), to the ERA Uganda and NCHRP 672 maximum of 4%, with the Exit to Mulago Side intervention estimated to yield a 39–41% crash reduction and warranting immediate capital prioritization. Geometric realignment of the two weaving section circulatory arcs, lacking defined inner radii, should be undertaken to restore the speed-control function of the roundabout. Supplementary safety measures, including rumble strips, advanced gradient warning signs, and raised entry platforms, should be installed on the steepest approach arms. The Crash Modification Factor framework applied in this study should be adopted by KCCA and the Ministry of Works and Transport as a standard tool for ranking geometric improvement investments across other high-risk urban junctions in Kampala.

Future research should address the primary limitation of this study by establishing systematic Annual Average Daily Traffic counts at Bwaise interchange and other urban junctions, enabling vehicle-kilometres-travelled-based exposure modelling that replaces segment length as a proxy and improves the precision of crash rate estimation. The methodology developed here should be replicated across other Kampala roundabouts to build a locally calibrated Safety Performance Function database for Sub-Saharan African urban contexts. Future studies should additionally incorporate sight distance, entry width, and splitter island geometry as predictor variables, and consider random-parameter Negative Binomial models to account for unobserved site-level heterogeneity. A before-and-after evaluation study following implementation of the recommended geometric interventions at Bwaise interchange would provide empirical validation of the CMF estimates generated by this study and strengthen the local evidence base for evidence-based road safety engineering in Uganda.

5.2 Recommendations

Based on the study findings, the following engineering and policy interventions are recommended. KCCA and Ministry of Works and Transport should prioritize gradient reduction on the three non-compliant segments, Exit to Mulago Side (7.01%), Eastern Approach to Mulago Exit circulatory arc (5.74%), and Bwaise interchange to Sir Apollo Kagwa (5.39%), to the ERA Uganda and

NCHRP 672 maximum of 4%, with the Exit to Mulago Side intervention estimated to yield a 39–41% crash reduction and warranting immediate capital prioritization. Geometric realignment of the two weaving section circulatory arcs, lacking defined inner radii, should be undertaken to restore the speed-control function of the roundabout. Supplementary safety measures, including rumble strips, advanced gradient warning signs, and raised entry platforms, should be installed on the steepest approach arms pending full geometric redesign. The Crash Modification Factor framework applied in this study should be adopted by KCCA and the Ministry of Works and Transport as a standard tool for ranking geometric improvement investments across other high-risk urban junctions in Kampala.

Future research should address the primary limitation of this study by establishing systematic Annual Average Daily Traffic counts at Bwaise interchange and other urban junctions, enabling vehicle-kilometres-travelled-based exposure modelling that replaces segment length as a proxy and improves the precision of crash rate estimation. The methodology developed here should be replicated across other Kampala roundabouts to build a locally calibrated Safety Performance Function database for Sub-Saharan African urban contexts. Future studies should additionally incorporate sight distance, entry width, and splitter island geometry as predictor variables, and consider random-parameter Negative Binomial models to account for unobserved site-level heterogeneity. A before-and-after evaluation study following implementation of the recommended geometric interventions at Bwaise interchange would provide empirical validation of the CMF estimates generated by this study and strengthen the local evidence base for evidence-based road safety engineering in Uganda.

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Appendix

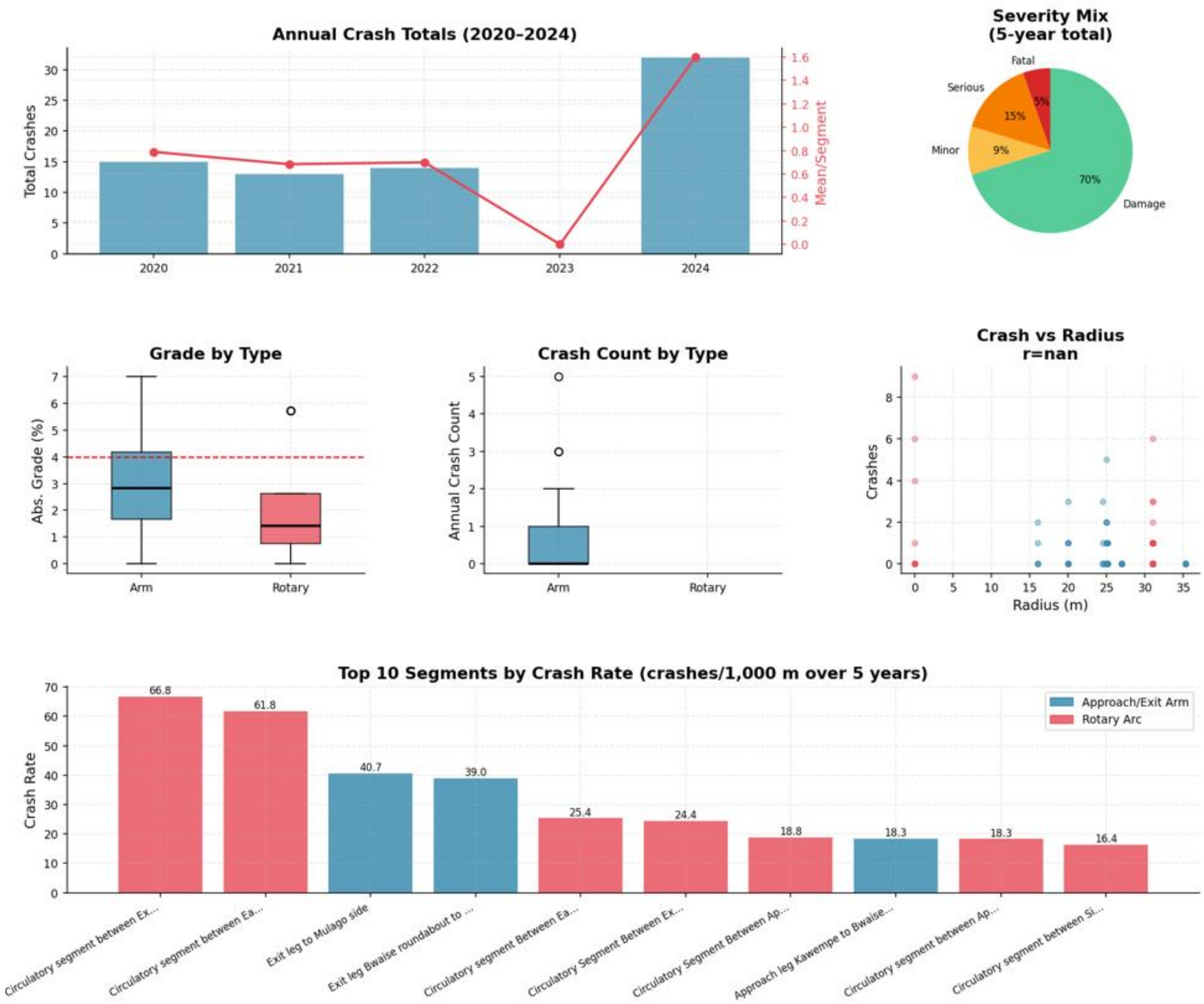

Figure 5-1: Summary dashboard

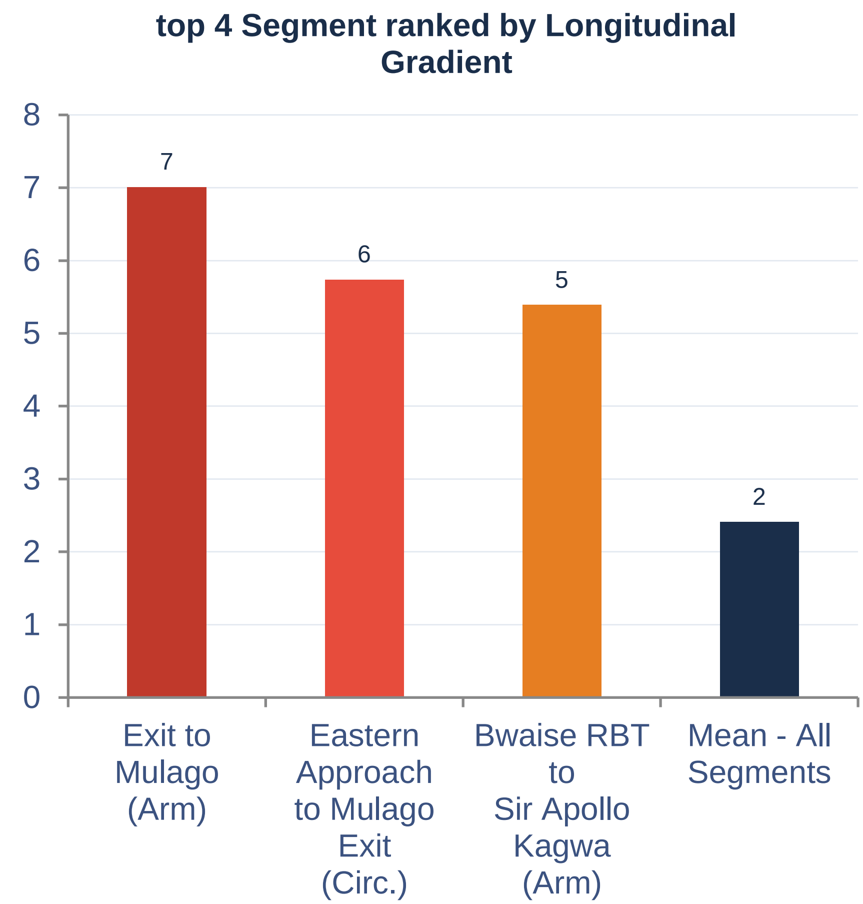

Figure 5-2: Aerial view of the study area