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# Road Geometry and Topographic Formation - Center of Traffic Crash Attraction and Severity Level

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# Executive summary

The proportions and configurations of a roadway's visible elements, particularly geometry formation, had an impact on the occurrence of traffic crashes. Identifying road geometry-based probable causes of traffic crashes and methods of analysis are basically used to uphold the safer road. This thesis presents models and frameworks aimed at predicting traffic crash occurrences and identifying related factors, locating centers of attraction zones and determining their severity level and formulating desired operating speed. Lack of tractable information about the impacts of road geometry formation on traffic crashes creates interference for the decision makers to make effective interventions. Multinomial logistic regression and multilayer perceptron artificial neural networks were introduced to analyze determinant factors and the relationship between traffic accidents and road geometry formation. The analysis of traffic crash attraction centers based on road geometry formation was conducted using point and kernel density estimation, as well as multipoint-to-multipoint distance proximity levels. The severity level based on the geometry formation of the road was explored using the existing severity indexing and an alternative method that promotes combined parameter approaches. At bend road, the severity level is aggravated due to the speed and poor pavement surface integration. Using the analytical framework, a newly empirical model that was used to analysis the desired operating speed at bend road across the design period of the road was formulated. Topographic formation is another concern that attracts traffic crashes and their outcome. To analysis the impacts of topographic formation on traffic crashes and their severity level, the triangular irregular network was introduced, which uses elevation difference, slope variation, and terrain formation interpretation parameters. Micromobility is our current issue that causes losses of life and physical injuries. The explanatory research design was introduced to explore micromobility accidents, accident causes, and other related mishaps. The result showed that based on the geometry formation a higher distribution and frequency of road traffic crashes and their outcomes is observed on straight roads. In the study area light conditions, collision type, alcohol consumption, speed limit, and road geometry formation have significant impacts on the occurrences of road traffic crashes and their outcomes. A bend road has a positive and significant relationship with road traffic fatalities. Whereas one-lane and three-lane roads have a positive impact on the occurrences of fatalities. An intersection zone with a high number of legs concord with a high number of road traffic crashes and their outcomes. In both the existing and an alternative approach, the severity level of the bend road segment of the study area was higher. Road surface roughness, type, block, and condition of tire as a basis in defining the side friction factor that determines the comfort of road users and vehicular movement. In the study area, the majority of traffic crashes were reported in locations with lower elevation and their difference, steeper or cliff slopes, and flat terrain formations. Most younger men with an age of 14 and above are affected by micromobility vehicles. Micromobility accidents basically happen due to technical problems that cause fire; riders not using helmets; collisions with other vehicles, pedestrians, and fixed objects; the nature of the vehicles themselves; visibility; and seasonal variation. The thesis contributes to scientific development through a comprehensive framework that combines different approaches used to minimize road traffic crash occurrences, which policymakers can implement and ultimately ensure road safety.

# Table of Contents

# List of Table

# List of Figure

## List of Abbreviations

| | |
|---|---|
| $AC_a/AC_B$ | Annual average accident cost / Accident cost of base year |
| $\overline{x}$ | Mean |
| $\beta_i$ | Intercepts; for i = 1, 2, 3………n |
| $/\epsilon$ | Except |
| @ | At |
| $\{\bar{x}, \bar{y}, \bar{z}\}$ | Mean centre for the features |
| A | Dependent (predicted) variable (accidents) |
| $A_C$/AC | Accident cost / Alcohol consumption |
| $a_t$ | Total area of the study location |
| tab | Tabulation |
| C | Individual class frequency |
| CO-1/2/3 | Crash outcome -fatality/serious injuries/slight injuries |
| CT | Collision type |
| D/d | Density / Distance between point |
| $D_S$ | Desired operating speed |
| dk | Converted distance |
| ed | Euclidian distance |
| $e_{max}$ | Maximum superelevation |
| Equ. | Equation |
| $ES_{IA}$ | Existing severity indexing approach |
| f (x, y) | Density estimates at the location (x, y) |
| F | Fatality |
| $F_I$ / $f_I$ | Longitudinal force / Longitudinal coefficient of friction |
| $f_{max}$ | Side friction factor (Coefficient of friction) |
| $F_t$ / $f_t$ | Lateral force / Lateral coefficient of friction |
| G1/2/3 | Condition 1/2/3 |
| *h* | Bandwidth. |
| HC | Horizontal curve |
| i | i = 1, …, n are the input points (Number of data set) |
| I | Intersection |
| LC | Light condition |
| LI | Light injuries |
| MCA | Mean cost per accident |
| MLP-ANN | Multilayer Perceptron Artificial Neural Network |
| MNLR | Multinomial Logistic Regression |
| n | Total of number of data group/set/points/features |
| N | Normal force or Number of year |
| $N_A$ / $N_C$ | Number of accidents / Number of crashes |
| $N_c$ | Number of cells |
| NL | Number of Lane |
| NL-1/2/3/4 | One Lane / Two Lane / Three Lane and Above / Other (Unknown) |
| $NS_{IA}$ | New severity indexing approach |
| OL | One Lane |
| O | Others (Unknowns). |
| p | Population field value of point i |
| PD | Percentage Distribution (%) |
| PO | Probability of Occurrence |

| | |
|---|---|
| R | Growth rate (Inflation Rate) |
| r | Searching radius (radius of the cell) |
| $R_{CC}$ / $R_C$ | Relative crash cost / Relative cost per crash |
| $R_D$ | Relative difference |
| RG-1/2/3/5 | Intersection (cross) road / Bend road / Straight Road / Other (Unknown) |
| RG | Road Geometry |
| $R_{min}$ | Minimum radius |
| Rs | Reason |
| PS | Pavement Surface |
| RSI | Relative Severity Index, |
| RTC | Road traffic crashes |
| $S_A$ (%) | Relative percentage share of accident |
| $S_A$ | Share of traffic accident |
| $S_C$ | Share of traffic Crashes |
| $S_C$(%) | Relative percentage share of traffic crash |
| $S_{CC}$ | Share of crash cost |
| $S_{CC}$(%) | Relative percentage share of traffic crash cost |
| $SI_{E/N}$ | Existing/New severity value |
| SI | Severity Index or Serious Injuries |
| SR | Straight Road |
| SS | Severity Score |
| T | Period of time under review/ Total frequency |
| THL | Three Lane and above |
| TIN | Triangular irregular network |
| TL | Two Lane |
| $TN_C$ | Total number of crashes |
| V | Speed |
| ν | Variation |
| $v^2$ | Variance |
| $V_D$/VL | Design speed/ Speed Limit |
| WC | Weather Condition |
| X/x | Independent variable/ Observed data |
| $x_i$, $y_i$ and $z_i$ | Coordinates for feature i |
| β | Constant |
| B | Parameter estimate (Coefficient) |
| ε | Error term |
| $C\ (q, r)$ | Circular search area centered on q with a radius of r |
| $K$ | Kernel function. |
| $d_i$ | Distance between the location (x, y) |
| $i$ | Observation |
| $n$ | Number of observations |
| $\rho_q$ | Density at a location q |
| $\rho i$ | Values of points contained within the search area |
| µ | Mean |
| ϻ | Mode |

# Chapter 1

## 1. Introduction

### 1.1. Background

The proportions and configurations of a roadway's visible elements, particularly geometry formation, had an impact on the occurrence of traffic crashes. Numerous factors had an undesirable and significant contribution to the occurrences of traffic crashes. Poor road design, construction, and maintenance had a substantial impact on safety and capacity. Road geometry design is strictly related to the level of traffic crashes [1]. Planning, designing and constructing road infrastructure should give priority to safety and comfort for road users. Ironically, road infrastructure often becomes the cause of traffic accidents [2]. Studies suggested that rollovers crashes potentially correlate with the geometry formation of the roadways. This problem could potentially be reduced by developing road safety countermeasures (access management of driveways, straightening sharp horizontal curves, widening shoulder width, better design of centerline medians, and posting lower speed limits and warning signs) in the area with higher rollover tendency [3]. Others indicated that the reduction of road width, poor road geometry alignment, lack of channelization at intersections had a significant impact on crash occurrence [4]. In addition to this, lane number geometry design and pavement condition variables are most significant factors affecting accident rates [5]. As different study indicated, the formation of road geometry had a noteworthy impact on the occurrences of traffic crashes.

Identifying road traffic center of crash attraction and the proper method of assessment is a step towards reducing traffic crashes. A poorly designed road geometry can directly lead to a higher density of traffic crashes due to increased driver difficulty and potential for vehicle loss of control [6, 7]. Proximity between traffic crashes is also defined by the geometry formation of the road. Not only that, but also the density of traffic crashes and their severity level relate to geometry formation. Studies confirmed that the extensive existence of cross-zonal spatial correlation in crash occurrence [8]. Sharp curves with small radii are often associated with higher crash rates as they require drivers to significantly change their steering, increasing the risk of losing control, especially at high speeds [1]. This implied that the number of traffic crashes, center of crash attraction and the severity rate potentially related with the geometry formation of the road. Even though different study used different method to analysis center of crash attraction this study initiated to understand the most significant approach between point density and kernel density estimation. In addition to that this study tried to visualize the point distance proximity between traffic crashes using Multipoint-to-Multipoint approach.

Analyzing traffic crash, accident, and crash cost distribution is not sufficient to define the severity level of the road unless the combined effects are explored. A road's severity level depends on a combination of factors including the extent of damage to the road surface, the presence of hazards like potholes or cracks, the geometry of the road (curves, slopes), visibility conditions, traffic volume, weather conditions, and the surrounding environment; all of which can contribute to the potential risk of accidents and their severity when driving on that road [9, 10]. This implied that the severity level of road network depends on traffic crash occurrences and its geometry formation. A higher number of crashes on a road generally indicates a higher road severity level, meaning that crashes occurring on that road are more likely to result in severe injuries or fatalities [11]. A greater number of accidents, categorized as high severity road. Severe accidents results in a greater burden on the healthcare system and community wellbeing that includes huge economic losses [12, 13]. A higher road severity level directly correlates to a significantly higher accident cost, as more severe accidents typically involve greater property damage, higher medical expenses due to serious injuries, and potential loss of productivity from injured individuals being unable to work, leading to a substantial increase in overall accident cost [14]. As indicated, studies showed that the severity level of road segment depends on the number of traffic crashes, number of traffic accident and crash cost. Different study used different approaches to analysis the severity level of road segment based on different severity level indicators and determinant factors as leading variables. But most of the methods didn't used the combined effects of stated variables intermittently. Not only that, using the number of traffic crashes and accident has no significant implication in analysis severity level.

In road design, minimum radius ($R_{min}$), the maximum side friction factor ($f_{max}$) and maximum superelevation ($e_{max}$) are basic design parameters used to define the design (assumed) speed at horizontal road curvature. Due to excessive speed and unmanaged side friction factor road traffic crashes resulted. A direct correlation exists between traffic crashes and speed, meaning that as speed increases, the likelihood of a crash occurring also increases, and the severity of the crash is likely to be greater. Essentially, driving faster significantly raises the risk of a serious accident [15, 16]. For every 10 mph of increased speed, the risk of dying in a crash doubles. In practical terms, increasing driving speed from 60 mph to 80 mph increases the risk of a fatal crash by 4 times [17]. So, this implied that speed is the deadest list of road traffic. There is different factor that cooperate with speed to cause traffic crashes. Mostly unmanageable side friction factor (coefficient of friction) that resulted due to roughness of the road surface can causes huge losses of life and physical injuries. In traffic crash analysis, "side friction factors" refer to elements on the side of a roadway that can disrupt normal traffic flow, potentially contributing to traffic crashes/accidents [18, 19]. Side friction results in increased traveler discomfort, reduced speed behind stopped vehicles and abrupt volume rises on the roadway [20]. This implied coefficient of friction potentially had an impact on traffic speed that results discomfort and crashes. Side friction factor had a relation with the speed of traffic that causes the occurrences of crashes/accident. There is no empirical model that is used to analysis desired operating speed based on the existing condition of the roads surface.

Road traffic crashes and their severity level are likely caused by variations in elevation, slope, and terrain formation of the road topographic formation. Topography, referring to the physical features of a landscape like hills, valleys, and slopes, can significantly impact the occurrence and severity of traffic crashes [21, 22]. A significant elevation difference on a road, particularly steep inclines or declines, can considerably increase the risk of traffic crashes due to factors like reduced visibility, difficulty in vehicle control, and increased braking demands, making it a crucial factor to consider when analyzing accident hotspots on a road network [23]. A significant correlation exists between traffic crashes and slope variation on roads, meaning that areas with sudden changes in grade are more likely to experience accidents, particularly when drivers encounter unexpected steep downhill sections or sharp uphill climbs; this is because such slopes can affect vehicle control, braking ability, and overall driver perception, leading to increased risk of crashes [23] [24] [25]. Terrain formation can significantly impact the frequency and severity of traffic crashes by influencing factors like road design, visibility, and driver behavior, with features like steep slopes, sharp curves, blind corners, and uneven surfaces often contributing to higher accident rates in areas with complex topography [26, 27]. So, analyzing the impacts of topographic formation of traffic crashes and its outcome had significant correlation with center of crash attraction zone identification and understand proper remedial action to minimize road traffic crashes and its outcomes. Even though different method was used to analysis the impacts of topographic formation on traffic crashes and their outcome, as far as our knowledge is concerned, the triangular irregular network (TIN) was not used before to analyze dangerous zones of the road network that used spatial data.

Even if the rate of micromobility vehicle usage increases progressively, the conditions of accidents are at an alarming rate. The detailed review of this paper was screening the global trend of micromobility-related accidents and their causes and concerned demography, examining market and service trends, and proposing remedial action. To undertake this review, the study used an explanatory review [28, 29, 30]. Explanatory review is a research method that explores why something occurs when limited information is available [31]. It is also a technique used to gain a deeper understanding of the underlying reasons for, causes of, and relationships behind a particular issues [32]. Even though a different review approach was available, this study considered an exploratory research design because it was used to investigate an undefined/unclear problem and to gain a better understanding of the current problem [33, 34]. So, reviewing service and market trends of micromobility, related accidents and their causes, and other related mishaps with maximized safety of micromobility vehicles.

### 1.2. Research gaps and motivations

Road geometry formation and its impact on traffic crashes showed different attributes and their level of contribution. Most of the studies focused on a microscopic level, such as selected road segments, specific numbers of lanes, small road networks, etc. Analyzing the impact of road geometry formation on road traffic crashes and their severity levels at a macroscopic level, the intended gaps. As per the study review in Budapest city, the impact of geometry formation on road traffic crashes and their severity rate was not in consideration.

In road traffic crash analysis, identifying blackspots is crucial in defining the probable causes and their countermeasures. Most studies consider selected road segments to define the blackspot location at a microscopic level. Even though different research was done to investigate blackspot location using different methods, enormous road traffic crashes still happen due to a lack of defined proper methods for identifying blackspot location and distance proximity level based on its coverage and geometry formation. This would bring low intention to characterize the overall performance and liability. Identifying blackspot locations and proximity level between traffic crashes at a macroscopic level is a demanding issue. So, to overcome these problems, this study tried to analyze the blackspot location at a macroscopic level by using point density and kernel density estimation and its comparative illustration.

Although studies were done on traffic crashes to analyze distribution and frequency, hotspot locations, severity level, and other road safety-related issues based on the geometry formation of the road, this study identified a gap in analyzing the proximity level of traffic crashes to define the severity level of road segments. Even if different studies were done using single point-to-single point and single point-to-multipoint proximity using Euclidean distance or other approaches to analyze the traffic crash trend of the road network at a microscopic level, the multipoint-to-multipoint distance proximity approach was not empowered to analyze traffic crash proximity at a macroscopic level that pretends traffic crash attraction (point of interest) of the existing road based on geometry formation and its severity level.

Even though the combination of road traffic crashes, accidents, and crash costs had was applicable to defining the severity level of a road segment, in most studies the applications and the significance level of methods had uncertainty. As a result, this study grasps some common models used to analyze the severity level of the road network as shown in Table 1 to designate alternative approaches. The stated equation considers the number of traffic crashes, the number of traffic accidents, and traffic crash costs. The concept of the combined parameter approach used the number of traffic crashes, the number of traffic accidents, and traffic crash costs as a basic pillar jointly used to analyze the severity level of the road section/segment.

Table 1. Severity level analysis approaches and parameter

| Source | | Equation | Missing Variable |
|---|---|---|---|
| [35, 36] | $SI = \frac{N_A}{N_C}$ | Equ. A1 | $C_C$ |
| [37, 38] | $RSI = \frac{\sum_{i=1}^{n} RC}{TNG}$ | Equ. A2 | $N_A$ |

This study agreed on the applicability and its implication of the combined effects of two parameters in equations shown in Table 1 to define the severity level, but significance and correctness of the outcome was a doubting issue in defining the severity level due to the exclusion of the combined effects of the third/missing parameter depicted in Table 1.

The change of side friction factor of the road surface across the design period influences the desired operating speed that falls out of traffic crashes. Even though defining the design speed using Equation 1 is proper, the conceptual underpinning of the mathematical models is incorrect to define the desired operating speed across the design period of the road except at the opening phase of the road. The conceptual basis stated by the AASHTO recommendation and various scholars is that when the side friction factor (coefficient of friction) increases, the design speed contradicts the general formula mentioned in Equation 1 [39] [40] [41] [42].

$$V_D = \sqrt{127}\,\sqrt{R_{\min}\left(0.01\,e_{\max} + f_{\max}\right)} \qquad \text{Equ. 1}$$

There is a significant association between the formation of the landscape and road traffic crashes. In order to understand the trend of traffic crash occurrences and its correlation with the variations in elevation, slope, and terrain formation between the road networks, a proper method for identifying dangerous road locations based on their coverage and geometry formation is essential. This would provide a precise definition of the unsafe zone on the existing road network. To assess and simulate traffic crashes and determine the risky zone of the road network, this study proposed a triangular irregular network (TIN) approach. This method is applicable to any form and location of the road network that is affected by traffic crashes.

Micromobility accidents and related causes, demography, socio-economic, behavioral, and cultural factors, and other factors that affect micromobility usage and proposed remedial action were not in-depth reviewed. As a result, this study tried to incorporate a case study that deals with trends of selected micromobility types and accidents, regional population size and micromobility market share, and facilities for micromobility and development.

In general, this dissertation was initiated to acknowledge evidence and theoretical gaps, as well as methodological and empirical gaps in road safety analysis. In addition to this practical knowledge and conflict gaps being inconsiderate, this motivates this research work. As a result, the above-depicted research gaps were addressed accordingly.

## 1.3. Dissertation objectives

In this dissertation, five thesis points are presented to cover the research gaps identified as an impact of road geometry formation on traffic safety. This research work primarily focuses on addressing the following aims:

- Analyzing the impact of road geometry formation on traffic crash occurrences.
- Assessing the pertinence of the density estimation and proximity level of traffic crashes using point and kernel density estimation, and multipoint-to-multipoint approach.
- Evaluating road severity level based on existing and an alternative combined parameter approach using traffic crash, accident, and crash cost relative percentage share.
- Examining an empirical model for the desired operating speed due to the variation of the side friction factor at horizontal road curvature.
- Scrutinizing the interaction of topographic formation and traffic crashes using triangular irregular network (TIN).
- Assessing micromobility factors contributing to accidents, market and service trend, and related mishaps.

## 1.4. Contributions of the dissertation

Road traffic crashes are a common problem worldwide. Even though different research was undertaken, and remedial actions were proposed, it’s still a global concern. This dissertation contributes to the scientific community by introducing innovative ideas that are used to analyze traffic crash-related issues to minimize the number of accident that promote safety. Mostly, this dissertation presents the impacts of road geometry formation on traffic crashes, comparative implications of density estimation approach preference and proximity level analysis, an illustration of existing and an alternative approach that is used to analyze severity level, defines a desired operating speed formula that is used to minimize the effects of speed on traffic crashes, and proposes topographic formation of an earth impact on traffic crash occurrences using triangular irregular networks. Finally, policy implications are formulated to help the stakeholders that used to minimize traffic crash occurrences and encourage road safety.

The key contributions from each thesis point are presented as follow:

- **Thesis point 1:** The impacts of road geometry formation on traffic crash occurrences and their outcomes were presented. Several aspects of road geometry and its impacts were analyzed. Determinant factors for the occurrences of traffic accidents and the relationship with latent variables are explored. This thesis reveals that the primary reasons for the occurrences of traffic crash at an intersection, horizontal curve, and straight road. The traffic accident prediction model was introduced for the study area.
- **Thesis point 2:** The comparative preference of point and kernel density estimation was presented. A newly distance proximity level analysis approach between traffic crashes was introduced that was used to identify hazardous road segments. Based on the distance proximity approach, a newly severity level indexing approach was introduced. This thesis reveals which density estimation approach is preferable and capable of investigating black spot location at the macroscopic level of the road network to analyze highly extreme dense traffic crash locations. In addition, it reveals which road geometry (alignment) with a higher proximity level in terms of traffic crash experiences.
- **Thesis point 3:** A new modeling approach to examine the severity level of road segments that used a combined parameters (variables) method was presented. The comparative implication of the number and the relative percentage share was explored to analyze the severity level. This thesis reveals, in comparison to the existing and newly severity level approach, which method was preferable to identify severe road.
- **Thesis point 4:** A new modeling approach that was used to examine the desired operating speed of a curved road was introduced. Several aspects of curved roads and designed speed were identified. This thesis reveals which aspects of the bend (horizontal curved) road had a significant impact on defining vehicular maneuver speed across the design period of the road.
- **Thesis point 5:** A new method was introduced to examine the unsafe zone of the road network considering the topographic formation of the earth. Several aspects of the topographic formation of the road network were examined, and their relationships with traffic crash occurrences were explored. This thesis reveals which features of topographic formation are preferred to analyze the dangerous zone of the road network.
- **Thesis point 6:** Collective information about micromobility vehicle service and market developments was presented. Factors cause micromobility vehicle accidents, and their trend was conferred. Demographic representation of accidents and accessibility of micromobility was described. Economic, social, and other factors influencing the occurrences of micromobility vehicle accidents and their remedial solutions were endowed. This thesis reveals which user group/region accesses micromobility vehicles and highly infected by accident was explored that used to minimize risk.

## 1.5. Applied scientific methods

Multinomial Logistic Regression (MNLR) was an appealing statistical approach in modeling the severity of road traffic crashes because it allows for more than two categories of the dependent variable and does not require the assumption of normality, linearity [43, 44]. Multilayer Perceptron Artificial Neural Network (MLPANN) is a type of artificial neural network that is used to analyze and model complex patterns and prediction problems [45, 46]. Pearson Correlation Coefficient used to analysis the relationship between variables.

Pythagorean (Euclidean) distance is a distance calculated from the cartesian coordinates of the points using the Pythagorean theorem [47]. Multipoint-to-multipoint distance proximity is calculating distances between multipoint or distances from each point of an input multipoint feature to each point of the near multipoint, and the smallest of these distances is the distance between the two multipoint features. Skewness is a measure of the asymmetry of a distribution. A distribution is asymmetrical when its left and right sides are not mirror images [48].

Combined parameters approach is a method that allows severity index to use both severity level indictor and determinant factor as parameters to analysis severity value interdependently. Relative percentage share is the percentage obtained by dividing the aggregate value of the share consideration by the aggregate consideration value [49, 50]. Analysis of variance is the statistical procedure of comparing the mean of a variable across several group of individuals [51, 52]. It is a statistical measurement that is used to determine the spread of numbers in a data set with respect to the average value or the mean [53]. Severity score is a value that indicates the level of severity of injuries, disability or vulnerability.

Point Density Estimation (PDE) tool used to calculates the density of point features around each output raster cell [54]. Whereas the Kernel Density Estimation (KDE) tool is used to calculate the density of features in a neighborhood around those features [55]. Bandwidth Estimation is an algorithm used to determine the default search radius for spatial analysis.

Triangular Irregular Network (TIN) are often generated using the triangulation of a point coordinate (x, y, z). The fact that the points are distributed differently depending on an algorithm that ascertains which points are most essential to produce an accurate representation is one benefit of utilizing a TIN [56]. In addition to resolution the quality of TIN measured by elevation difference (z-factor) between input TIN surface and interpolated output surface [57]. While the elevation difference between point is zero, that means the z-factor is 1.

Explanatory review is a research method that explores why something occurs when limited information is available [31]. It is also a technique used to gain a deeper understanding of the underlying reasons for, causes of, and relationships behind a particular issues [32]. Exploratory research design can be defined as research conducted to investigate an undefined/unclear problem. It is carried out to gain a better understanding of the current problem [33, 34].

## 1.6. Dissertation outlines

This dissertation contains ten chapters. The first chapter contains the introduction part. The second chapter examines the impacts of road geometry formation on traffic crashes, which is thesis point one. Chapter three analyzes road geometry formation and the center of the traffic crash attraction zone, which is considered thesis point two. Thesis point three contains chapter four of the dissertation that shows the road traffic crash severity level analysis approach and its alternatives. Meanwhile, Thesis Point Four, which demonstrates the empirical models of desired operating speed at bend road segments, is depicted under Chapter Five of the dissertation. Chapter six presented road topographic formation impacts on traffic crash occurrence, which is thesis point five. Chapter seven presented micromobility accidents, contributing factors, and other mishaps, which is thesis point six. Chapters eight and nine deal with the application of the scientific outcomes, and the limitations and future works of the dissertation, respectively. The final part is chapter ten, which deals with the summary (overall conclusion) of the dissertation.

## 1.7. Terminology

To have a clear understanding and avoid confusion, some scientific words that are used in road safety management and some words used in the study that need unblemished definitions and consensus are described below.

a. **Road traffic crashes:** is a collision in which at least one motor vehicle is involved for the occurrence of accident [58]. Others, traffic crash indicates that someone caused the car wreck to happen or that someone is actually at fault [59]. A law firm defines a traffic crash as a collision due to the fault of one or more parties [60].
b. **Road traffic accidents:** in which at least one person is injured/killed/property damaged due to traffic crashes [61]. It implies that a car crash happened through the fault of nobody in particular [59]. A law firm defines as an unexpected happening that causes losses that is not due to the fault of a person [60].
c. **Traffic crash costs**: an economic cost (e.g., medical bills, lost wages) and quality-adjusted life years (QALY - commonly thought of as the cost for pain and suffering) [62].
d. **Severity Index:** is a dimensionless value indicating the hazardousness of a spot on the road [63, 64].
e. **Determinant factor:** a factor that makes something leads directly to a decision [65, 66].
f. **Severity Index:** is a dimensionless value indicating the hazardousness of the road [63, 64].
g. **Relative Severity Index:** measures the severity of crashes based on a monetary value to each crash type [67, 68]. Average monetary crash costs are assigned to each crash at a site, and the total average crashes cost for a site is compared to the average crashes cost for the reference population [37, 38].
h. **Mean:** is the average or the most common value in a collection of numbers. It’s a set of numbers in a data set that is obtained by adding up all the numbers and then dividing by the size of the data set [69, 70].
i. **Mode:** is the value that appears most frequently in a data set. The mode is one of the values of the measures of central tendency. This value gives us which of the items in a data set tend to occur most frequently [71, 72].
j. **Critical point:** is point at which design speed of the vehicle start to decline.
k. **Critical zone**: is a region at which the speed increases or decreases at the coefficient of friction (side friction factor) vary with different radius of the horizontal road curvature across the design period.

# Chapter 2

## 2. Imprints of Road Geometry Formation on Traffic Crashes

### 2.1. Introduction

Unsafe and insufficient road infrastructure is a fundamental issue for the occurrence of traffic crashes (RTC) and their outcome. RTC occurrences are significantly influenced by road geometry formation [73]. It can be fragmented into alignment, profile, and cross-section. Mostly, road width, cross slope, road margins, traffic separators, and curbs can be considered basic physical elements [74, 75]. The intention of geometry design is to optimize efficiency and safety so that it minimizes cost and environmental damage. To analyze the impact of road geometry formation on traffic crashes and their severity levels, this study used 5-year (2017-2021) Budapest city traffic crashes data that was collected by Hungary's transport authority. The study area was selected due to the nature, availability, and convenience of the data. In the city of Budapest, there was a high concentration of traffic crashes that were recorded yearly. In the past 5 years, around 17,006 road traffic crashes have been registered. The crashes outcome classified as fatality (216), serious injury (3,999), and minor injury (12,791).

Different studies showed that road infrastructure, mostly geometry formation, had its own impacts on traffic crashes. Pembuain et al. (2018) indicated that the elements in road infrastructure formation had a significant effect on the risk of traffic accidents [76]. The report in Australia showed that the road is a causation factor in about 30% of all crashes [77]. A road defect directly triggers a crash, where some element of the road environment misleads a road user and thereby creates human errors [78]. The study showed that two-lane rural highways reduce crash rates by 44% versus high crash-rate infrastructure, at the 99% confidence level [79]. One of the important and cogent measures for reducing fatalities is continuously improving and maintaining the shape and condition of roads [80]. Road safety can be improved by implementing principles of road safety infrastructure management (RIS) [81]. It showed that road geometry elements can mislead road users.

A study in Texas indicated that sever crashes are likely to occur on horizontal curves with higher degrees of curvature [82, 83, 84]. Sarbaz Othman et al. (2009) stated that large-radius right-turn curves were more dangerous than left curves during lane-changing maneuvers. However, sharper curves are more dangerous in both left and right curves [85]. Overtaking on right curves was sensitive to the radius and the interaction of the radius with road conditions, while the left curves were more sensitive to super-elevation [86]. Even though the study shows that horizontal curves are a cause of severe road traffic crashes, it is better to analyze the overall impact of curved roads on RTC compared to other road geometric formations.

On straight roads, speed and distance were influenced by traffic accidents. The longest distance offered the highest risk of fatal [87]. Willy et al. (2020) discovered a strong relationship between side freedom and accident number [88]. MBESSA Michel et al. (2020) stated that the reduction in road geometric formation has a significant impact on crash occurrence [89]. In Singapore, road crashes at intersections contribute around 35% of the reported accidents and show that vehicle type, road type, collision type, driver's characteristics, and time of day are important determinants of the severity of crashes at intersections [90]. The study in the U.S. showed that the relative ratio analysis showed that intersection-related crashes were almost 335 times as likely to have "turned with an obstructed view" as the critical reason for non-intersection-related crashes [91]. So, road geometric formations, such as horizontal curves, side freedom, intersections, and straight roads have their own impact on the occurrences of road traffic crashes. It was better to visualize the interaction between stated variables and the number of lanes with intersection type.

Abbasi et al. (2022) stated that developing artificial lighting at intersections and LED-raised pavement markers on two-lane rural roads could lead to enhanced road safety under dark LCs [92]. Mehdi Hosseinpour et al. (2013) study results of REGOPM on crash severity showed that horizontal curvature, paved shoulder width, terrain type, and side friction were associated with more severe crashes, whereas land use, access points, and the presence of a median reduced the probability of severe crashes [45, 46]. In this case, further analysis was required to define the effect of natural light conditions on RTC.

Different study revealed that road geometry formation and its impact on traffic crashes showed different attributes and level of contribution. Most of the studies focused on a microscopic level, such as selected road segments, rural road networks, intersections, specific numbers of lanes, small road networks, etc. As far as our knowledge is concerned, there is a research gap in the impact of road geometry formation on traffic crashes and their severity levels at a macroscopic level, such as at the country or city level. Budapest City was selected due to the fact that the area was urban, with highly networked roads, large territory, and has a high concentration of vehicles and a dense population. In fact, the number of road traffic accidents recorded was also high, and the nature of the data and its accessibility encourages the choice of the city. Moreover, as per study review in Budapest city, the impact of road geometry formation on road traffic crashes at the macroscopic level and their severity rate was not taken into consideration. In spite of that, further investigation was needed to direct the impacts of road geometry formation on traffic crashes.

## 2.2. Methodology

Five Year (2017-2021) Budapest city road traffic crash data was considered as an input for further analysis of the impacts of unsafe and insufficient road geometric formation on traffic crashes [92]. For data management and analysis, the study used tools such as Ms. Excel for data organization, a statistical package for social science (SPSS-20) for data analysis and modeling, and Q-GIS for the analysis of location-related information, etc. Each variable and parameter were coded according to data type and priority.

Depending on the objective of the study and the type of data collected from the authorities, these studies consider variables as dependent and independent to facilitate the analysis. Accordingly, it considers road crashes (outcome) as dependent variables. Whereas the independent variable was described as hourly distribution, collision type, light condition, causes of a crash, geometric formation, pavement surface, number of lanes, speed, weather condition, alcohol consumption, responsible body, etc.

The study used relative frequency distribution to further investigate the occurrences and rates of road traffic crashes [43, 44]. Multinomial logistic (MNL) regression was used to analyze the determinant factors. Multilayer Perceptron Artificial Neural Network (MLP-ANN) was used to show the impacts of road geometry formation and their relationship with the severity level of traffic crash outcomes. It consists of three types of layers: the input layer, output layer, and hidden layer. The input layer receives the input signal (data) to be processed [93]. It is used to determine its suitability for traffic accident prediction and to analyze the increasing amounts and causes of road traffic accident using machine learning [94, 95, 96].

This study also used the Quantum Geographic Information System (Q-GIS) to enable the location of road traffic crashes and analyze spatial information [97] [98, 99]. That was used for mapping road traffic injuries, accident analysis, and the determination of hot spots [100, 101]. To analyze the severity level of road geometry formation that causes traffic crashes, the study used the Severity Index (SI). Empirically, the crash severity index is expressed [102].

$$\text{Seveity Index (SI)} = \frac{\text{Number of Injuries}}{\text{Total Number of Crash}} \text{ or } \frac{\text{Number of Death}}{\text{Total Number of Crash}} \qquad \text{Equ. 2}$$

To check the significancy of the data a multicollinearity test was conducted using the Pearson Correlation Coefficient. With a correlation coefficient less than 0.8 indicating the variables can be used for further analysis. Subjected to information from analysis, a relatively strong relationship was observed between light conditions and hourly distribution (0.289), alcohol consumption, and collision type (0.245). However, the ranges are still within the traditional tolerable limit, and the variables can be used for analysis. For more information, see Appendix A, Table A26

### 2.2.1. Latent variable dispersion (LVD)

A latent variable is a variable that cannot be observed. The presence of latent variables, however, can be detected by their effects on variables that are observable. So, checking overdispersion of both dependent and independent variables is used to select the proper model to analyze the determinant factor of road traffic crashes. The mean and variances of variables are used to define overdispersion. As shown in Appendix A, Table A25, the mean of dependent is greater than the variance. Not only that, more than 80% of independent variables indicated that their mean is greater than their variances. Based on the above evidence, a multinomial logistic regression model was selected to analyze the determinant factor of road traffic crashes.

### 2.2.2. Multinomial logistic regression (MNLR)

The study used multinomial logistic regression (MNLR) appealing statistical approach in modeling the severity of road traffic crashes because it allows for more than two categories of the dependent variable and does not require the assumption of normality, linearity, or homoscedasticity [43, 44]. It is also used to investigate multi-vehicle collisions in different forms and is appropriate for both non-interstate and interstate crashes [103, 104].

The model assumes that there is a series of observations (dependent variable) Ai for i = 1, 2... n. Along with each observation, Ai, there is a set of observed values $x_1, \ldots, x_n$ of explanatory variables. The output Ai is categorically distributed based on the crash outcome. So, this study categorized traffic crashes outcomes as dependent variables and the others as independent variables. The outcomes of the crash were fatalities, serious and slight injuries [105].

$$A_i \backslash X_i \ldots\ldots\ldots\ldots\ldots\ldots.. X_n, \text{for } i = 1,2,3 \ldots\ldots. n \qquad \text{Equ. 3}$$

Multinomial Logistic Regression is often written in terms of a latent variable model as:

$$A_i^{1*} = \beta_{1*}X_i + \varepsilon_1$$
$$A_i^{2*} = \beta_{2*}X_i + \varepsilon_2$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$A_i^{n*} = \beta_{n*}X_i + \varepsilon_n$$
$$\text{where}$$
$$\varepsilon \sim N(0, \textstyle\sum)$$

Based on the above relationships, the model that helps to predict road traffic accident can be defined as a predicting variable A.

$$A = \beta + \beta_1 X_1 + \beta_2 X_2 + \cdots \ldots\ldots\ldots\ldots\ldots\ldots\ldots. + \beta_n X_n + \varepsilon \qquad \text{Equ. 4}$$

### 2.3. Results

In the study area since 2017, traffic crashes in the past 5 years have been evenly distributed on the road network. For more information refer Appendix B, Figure B2. The study site has 23 districts. The study grouped the area into three traffic crash domain based on their concentration. Those, 0–3%, 3–6%, and 6–9% as high, intermediate, and low, respectively. The maximum and minimum traffic crash concentrations were observed in District XIV with 8.5% and XXIII with 1.9%, respectively. The red color indicates a highly concentrated road traffic crashes observed in districts X, XI, XIII, and XIV. Relatively, the green- and orangecolored districts had a low and intermediate concentration. For more information refer Appendix A, Table A1 & Appendix B, Figure B4.

The frequency distribution of traffic crashes in line with the geometry formation indicated that approximately 64.5% and 31.3% of road traffic crashes registered on straight and intersection part of the road network. In the study area the highest number of fatalities and injuries were registered on the straight part of the road network. A relatively significant number of fatalities and injuries are also registered at intersections part of the road network. For more information refer Appendix A, Table A6.

Table 2. Cross-tab. of crash outcome and road geometric formation

| Crash Outcome | Intersection | Horizontal Curve | Straight Road | Others | Total |
|---|---|---|---|---|---|
| Fatality | 46 | 20 | 143 | 7 | 216 |
| Serious Injuries | 1081 | 177 | 2693 | 48 | 3999 |
| Slight Injuries | 4192 | 529 | 7989 | 81 | 12,791 |

Based on Equation 2, and Table 2, as shown in Table 3, high level of severity in terms of death, serious and slight injuries is observed at the horizontal curve (bend), straight and intersection parts of the road network respectively.

Table 3. Road geometry formation and its severity level

| | SI @ I | SI @ HC | SI @ SR |
|---|---|---|---|
| Slight Injuries | 0.788 | 0.729 | 0.738 |
| Serious Injuries | 0.203 | 0.244 | 0.249 |
| Fatality | 0.009 | 0.028 | 0.013 |

Appendix A, Table A22 clearly defines collisions between vehicles (rear-end collisions) highly happen in all road's geometry formations of the road network. In addition to that, the collision of vehicles with pedestrians plays a great role in the occurrence of road traffic crashes and accidents. As shown in Appendix A, Table 28, collisions of vehicles with pedestrians result in a high number of road traffic fatalities. Not only the fatalities, but there were also numerous injuries as a result of rear-end collisions, and vehicle collisions with pedestrians.

As shown in Appendix A, Table A3, a high number of road traffic crashes was registered due to the improper use of traffic control devices such as traffic signs, signals, and marks. The causes and primary reason for the occurrences of a road traffic crash at an intersection, horizontal curve, and straight part of the road segment was improper use of road sign, road pavement condition, and stopping sight distance problem, respectively.

Appendix A, Table A2 indicated that in 1-hour distribution, the higher number of road traffic crashes were registered from 16:01–17:00. Concomitantly, as shown in Appendix A, Table A26 in 3-hour distribution, the maximum crashes were registered between 15:01–18:00. As a result, this study considers 16:01–17:00 as a peak hour for road traffic crashes at all roads geometric formations.

In the study area the highest number of road traffic crashes were observed at one-lane road geometry formations that accounted for more than 55.85%. at the same time Appendix A, Table A23 shows one-lane road had the highest number of traffic deaths and injuries.

Table 4 below shows that although the number of road traffic crashes on a one-lane road is high, in all lane formations, a high number of road crashes and their outcomes were registered at the straight and intersection part of the road network.

Table 4. Road geometry formation and number of lane for the occurrence of traffic crash

| Road Geometry | One Lane | Two Lane | ≥ Three Lane | Others | Total |
|---|---|---|---|---|---|
| Intersection | 3374 | 1284 | 633 | 28 | 5319 |
| Horizontal Curve | 451 | 181 | 84 | 10 | 726 |
| Straight Road | 5656 | 2992 | 2072 | 105 | 10,825 |
| Others | 2 | 2 | 2 | 130 | 136 |

Based on Equation 2, Table 5 indicates the highest level of severity in terms of fatalities, serious injuries, and slight injuries was observed at ≥ three, one-, and two-lane roads, respectively. Even if the number of deaths and slight injuries is high on one-lane roads, the level of severity is high at three-lane and two-lane road geometry configurations.

Table 5. Number of lane and severity level of road geometric formation

| **Crash Outcome** | **One Lane** | **Two Lane** | **≥Three Lane** | **Others** | **SI @ OL** | **SI @ TL** | **SI @ >THL** | **SI @ O** |
|---|---|---|---|---|---|---|---|---|
| Slight Injuries | 7107 | 3395 | 2119 | 170 | 0.749 | 0.761 | 0.759 | 0.623 |
| Serious Injuries | 2281 | 999 | 624 | 95 | 0.241 | 0.224 | 0.224 | 0.348 |
| Fatality | 95 | 65 | 48 | 8 | 0.010 | 0.015 | 0.017 | 0.029 |

As shown in Table 6, different partakers contributed to the occurrences of the road traffic crash to varying degrees. This study indicated that drivers contributed more than 82.6% of the occurrences of road traffic crash frequency of the study area. Appendix A, Table A24 indicates that drivers can contribute to a huge loss of life and injuries. Furthermore, pedestrians also play a significant role in the occurrence of road traffic accidents.

Table 6. Road traffic crashes frequency and responsible body

| **Responsible Body** | **Frequency** | **Percent** |
|---|---|---|
| Driver | 14,041 | 82.6 |
| Passenger | 76 | 0.4 |
| Pedestrian | 1,803 | 10.6 |
| Failure of Traffic Control Devices | 10 | 0.1 |
| Vehicular Failure | 1,056 | 6.2 |
| Others | 20 | 0.1 |

Specifically as shown in Table 7, in all road geometry formation driver was highly responsible for the occurrence of road traffic crashes. In addition to driver, vehicular failure plays a vital role in the occurrence of road traffic crashes at the intersection parts of the road network. Pedestrians also play a significant role. in the occurrence of road traffic crashes.

Table 7. Cross tab. of road geometric formation and responsible body in traffic crash

| **Responsible body** | **Intersection** | **Horizontal Curve** | **Straight Road** | **Others** | **Total** |
|---|---|---|---|---|---|
| Vehicular Failure | 740 | 11 | 304 | 1 | 1056 |
| Failure of Traffic Control Devices | 3 | 2 | 4 | 1 | 10 |
| Pedestrian | 169 | 42 | 1556 | 36 | 1803 |
| Passenger | 3 | 1 | 71 | 1 | 76 |
| Driver | 4403 | 666 | 8875 | 97 | 14,041 |
| Others | 1 | 4 | 15 | 0 | 20 |

### 2.3.1. Traffic accident determinant factors

The outcomes of the crash were fatalities, serious injuries, and slight injuries. To analysis the determinant factor of traffic accident the study used multinomial logistic regression (MNLR). The result of the analysis indicated that there was a relationship between road traffic accidents and their potential determinants. The cause-effect analysis of the variables listed in Appendix A, Table 29 revealed that fatality is highly caused by light conditions, collision type, alcohol consumption, and speed limit. Meanwhile, serious injuries are highly related to collision type, road geometric formation, and the reason for the occurrence of road traffic crashes.

On the basis of the findings, the model that helps to determine the significant level of road traffic accidents can be expressed using the following accident (A) predicting equation.

$$A = \beta + \beta_1 WC + \beta_2 LC + \beta_3 CT + \beta_4 RG + \beta_5 AC + \beta_6 R + \beta_7 PS + \beta_8 VL + \varepsilon(\text{error})$$

### 2.3.2. Artificial neural network (ANN): multilayer perceptron (MLP)

In this study, MLP-ANN was used to analyze and show the relationship between dependent and independent variables. To extract the output, the study used Statistical Package for Social Science (SPSS-20). It provides specific information on which variables have a significant impact on the occurrence of road traffic accidents. Appendix B, Figure B5 indicates the impact of road geometry formation and the number of lanes on traffic crashes and their outcome.

The model attempted to understand the relationship between the training data and be evaluated on the test data. In this case, 70% of the data is used for training and 30% for testing. The output of the model summary between the input of road geometry and number of lanes and the output of road traffic accidents indicated that the percentage of incorrect predictions for training was 25%. As shown in Table 8 the incorrect prediction for testing was less than 25%. So, the model was a good fit with a training and testing error of 25%. This shows that the model prediction level was correct and accurate above 75% [106].

Table 8. Model summary of error computations both the training and testing samples

| | | **Road Geometry** | **Number of Lane** |
|---|---|---|---|
| Training | Cross Entropy Error | 7355.623 | 7287.471 |
| | Percent Incorrect Predictions | 25.0% | 25.0% |
| Testing | Cross Entropy Error | 2993.791 | 3103.688 |
| | Percent Incorrect Predictions | 24.3% | 24.2% |
| Dependent Variable: Crash Outcome | | | |

The blue and gray lines in Appendix B, Figure B5 shows the positive and negative bond between the dependent and independent variables, whose synaptic weight is > 0 and < 0, respectively. In this diagram, road geometry, and the number of lanes were input (independent variables), and crash outcome (road traffic accident) was output (dependent variable).

### 2.3.3. Integration of traffic crashes determinant factors and accident type

This subtopic aimed to analyze the comparative implications of multinomial logistic regression (MNL) and perceptron artificial neural networks (ANN) in the context of road traffic crashes and accident analysis. Appendix A, Figure A27 depicted that even if the number of lanes is not a determinant factor based on multinomial logistic regression for the study area road network, relatively the number of lanes relates to the severe accident type that resulted from traffic crashes registered as shown in the perceptron artificial neural network diagram. This shows that the determinant factor doesn't describe the severity level.

The relationship between determinant factors and the severity level of a traffic accident is irrelevant. A variable defined as a determinant factor is not an assurance of determining the severity level. In this study, even if road geometry formation was a determinant factor for the occurrences of traffic crashes, the number of lanes has a high capability to create severe traffic accidents (fatalities) as a factor.

## 2.4. Discussion

Even if a high number of road traffic crashes are observed on the straight road segments, the intersection part of the road also contributes to significant road traffic crashes. Crashes are not only high at the straight part of the road; in comparison with aerial exposure, the rate of crashes at intersections is relatively high. Even though the straight section of the road had a high number of accidents, the intersection part of the road also played a significant role in the occurrences of road traffic accidents. Even if the number of deaths is high on the straight part of the road, the level of severity in terms of deaths cannot indicate this part of the road network. In the study area, horizontally curved road geometry was the most severe. It shows that as the number of lanes increased, there was a reduction in the number of crashes and their outcome. This depicted that the roads with ≥ 3 lanes have a minor role in the occurrence of road traffic crashes and their outcomes.

A high number of road traffic crashes were registered due to collisions happening between vehicles and vehicles with pedestrians on a stated road geometry formation. Mostly, vehicle collisions, such as rear-end collisions, play a significant role in the occurrences of road traffic crashes on straight and intersection segments of the road. In case the higher number of road traffic deaths and injuries are also registered due to collisions happening between vehicles and pedestrians and vehicles and vehicles (rear-end collision). Further investigation was needed to minimize pedestrian deaths and injuries. The occurrences of road traffic crashes due to stated collisions happened due to improper use of road traffic control devices. Particularly, most road traffic crashes happen due to the improper use of road traffic signs by drivers and pedestrians. The study demonstrated that drivers and pedestrians have a significant character in the occurrences of road traffic crashes at the stated road geometry formation. Drivers bear a large portion of the blame for road traffic crashes that result in massive loss of life and physical harm to other road users.

The multinomial logistic regression (MNLR) portrayed that light condition, collision type, alcohol consumption, road geometry formation, speed limit, and reason for road traffic crashes were determinant factors and had a significant effect on the occurrences of road traffic accidents at a p-value of 0.05. This depicted that, like other determinant factors, road geometry formation had a significant influence on the occurrences of traffic crashes and their outcomes.

The MLP-ANN outcome indicated that the intersection part of the road has a strong and positive contribution to the occurrences of road traffic crashes that cause fatalities, whereas the horizontal curve of the road network has a strong and positive impact on the occurrence of slight injuries. The straight section of the road has a positive but relatively minor impact on the occurrence of traffic accidents. In addition to that, one-lane and two-lane roads made a strong and positive contribution to the occurrence of road traffic injuries. Simultaneously, ≥ three-lane average roads had a significant positive and strong impact on the occurrences of minor injuries. It also has a relatively positive and slightly stronger impact on the occurrences of death. Based on the above observation, significantly, road geometry formation had an impact on the occurrence of road traffic accidents.

At all road geometry formation plays a vital role in the occurrences of traffic crashes in the study area. As a result, stakeholders must concentrate on those factors that cause road traffic crashes to reduce the number of accidents. Mostly, even though the number of traffic crashes and accidents was high in the straight road segment, the concerned body must emphasize minimizing road traffic crashes in the study area. To reduce the severe road traffic crashes, further investigation into traffic crash-related factors that encourage the horizontal curve of the road network is needed. Generally, it was advisable for the stakeholders to train road users, mostly drivers, how to properly use road traffic control devices and apply law enforcement that is used to minimize the occurrences of road traffic crashes and their outcomes in the study area.

**Thesis 1**

I developed an accident prediction model utilizing multinomial logistic regression (MNLR). Using multilayer perceptron-artificial neural network (MLP-ANN), the relationship between road geometry formation and traffic crash occurrences was analyzed. In addition to that, the impacts of road geometry formation on traffic crash occurrences and other determinant factors were identified.

⋆ Related publications to this chapter: [107, 108, 109]

# Chapter 3

## 3. Center of Traffic Crashes Attraction and Proximity Level

### 3.1. Introduction

In chapter two of this dissertation, the occurrences of traffic crashes and their outcomes conform with road geometry formation. Road traffic Crashes are a traffic collision that occurs when vehicles collide with other vehicles, pedestrians, animals, and other stationery objects that causes the loss of life, physical injuries, and property damage [110]. Even though the occurrence of road traffic crashes related to geometry formation, as stated above, traffic crashes registered in the study area mostly resulted from collisions happening between vehicles and vehicles with pedestrians. The geometry formation of the road also had a significant role in characterizing the road as a black spot/severe segment of a given road network. Blackspot is a portion of a roadway where bad road traffic accidents have historically been concentrated [111, 112]. The road section with blackspot can be a segments of the road [113]. The identification of crash blackspot has great significance for the prevention of traffic accidents [114]. To analysis the blackspot it was mandatory to define the duration of traffic crashes occurrences, the spacing between crashes and the number of crashes registered in specified period [115]. Studies indicated that the minimum data year for analyzing blackspot area is three years [116].

In road traffic crash analysis, identifying blackspots is crucial in defining the probable causes and its countermeasures. So, identification of a place where a high number of road traffic crashes registered in specified intersection zone of the road network is critical. Most studies consider selected road segment or intersection zone of road network to define the blackspot location at microscopic level. This would bring low intention to characterize and check overall performance and liability at macroscopic level. Identifying blackspot locations at a macroscopic level is a demanding issue. So, to overcome these problems this study tried to analysis the blackspot location at macroscopic level using density estimation approach.

Researchers used different methods to define blackspot location. Most of them use distance intervals, areal coverage etc. Some of the methods used sliding window [117], network screening [118], spatial autocorrelation [119], empirical Bayesian [120] etc. Even though different research was done to investigate blackspot location using different methods, enormous road traffic crashes still happen due to a lack of appropriate method to identifying blackspot location based on road network coverage and geometry formation.

Studies in Thrissur district, Kerala, India, road network using kernel density estimation, four road segments were identified as blackspot locations [121]. Other studies in the Budapest Road network analyze blackspot locations using the same method and identify 65 places. The assumption behind this study is that the bandwidth for analysis is 100 meters [122]. In the study done for identifying the blackspot location of the Gurgaon-Jaipur National Highway (NH-8), the researcher used a random value of 1500m through trial and error to characterize the raster cell size [123]. The study on 18 Michigan freeways using kernel and point density estimation described that kernel density estimation is more capable of pinpointing the blackspots [124].

To analyze this study, both density estimation approaches use the same set of data [125]. Point density estimation is an informal investigation of the properties of a given set of data that describes the number of points in each area [126]. Kernel density provides a better visual display than point density [127]. Bakker also stated that in both cases, the number of points around the cell count is affected by the shape and size of the neighborhood. Used to calculate the density of linear features about each output raster cell [128]. Studies indicated that kernel density has drawbacks: the data representation is poor, the data is represented vaguely [129].

In using the stated density estimation approach, rasterizing the data is another attempt. Rasterization is the task of taking an image described in a vector graphics format and converting it into a raster image [130]. Based on the types of data stored, the cell value can be an integer or a floating point [129]. In accordance with the nature of the data and its distribution pattern, traffic crashes have floating point formation [131]. Raster values stored in floating point cells are called "raster values," which are defined by extracting raster values to points [132]. To understand raster values, spatial resolution plays a significant role. Based on the resolution of the raster image and its value, this study characterizes the blackspot location.

As stated in chapter 2, road geometry formation plays a significant role in the occurrence of traffic crashes. Closeness between traffic crashes is also defined by the geometry formation of the road. Not only that, but also the density of traffic crashes and their severity level relate to the geometry formation of the road. Even though different approaches were used to analyze the relationship between traffic crashes and geometry formation of the road, this study tried to utilize distance proximity to analyze the impacts of road geometry formation in the occurrence of traffic crashes. Proximity means nearness or closeness [133]. Distance proximity refers to the physical distance between points or traffic crash locations that is measured in inches, meters, or miles [134]. Analyzing the distance and proximity between traffic crashes based on their geometry formation also has a significant role in defining the severity level.

The road segment with a highly closer traffic crashes tended to be highly severe. Based on geometry formation, a road segment affected by a closer traffic crash is most probably labeled as a severe road segment. So, analyzing the closeness of traffic crashes in a given road network played a role in defining the starkness level of road segments. Mostly the sensitivity connection between traffic crashes and the road section basically interacts with geometry formation.

A proximity analysis tool enables them to analyze spatial relationships between geographical points/features based on their distance [135]. Not only the distance between points or features, proximity can also be used to separate different ideas or objects. The distance between points may be measured as a straight line. Appendix B, Figure B6 showed the form/types of point-distance proximity and their formation.

Distance measurements will be most accurate when the input data is in an equidistance projected coordinate system [138]. Equidistant projections are projections that preserve the distances between certain points by maintaining the scale of a specified data set. Some of the distances will be true distances, which are the same distances at the same scale as the globe [139]. In spite of this, the study used a projected coordinate system to analyze distance proximity between traffic crashes and their interaction with the geometry formation of the road.

Point distance proximity is used to determine the distances from the input point to all points in the near features. By using the point-distance proximity conceptual approach, multipoint-to-multipoint proximity/networking enables interconnecting data center assets across many locations through a common network [140]. Multipoint just means that a feature is capable of having multiple points as part of its geometry, but they aren't required to have multiple [141]. Multipoint-to-multipoint distance proximity is calculating distances between multipoint or distances from each point of an input multipoint feature to each point of the near multipoint, and the smallest of these distances is the distance between the two multipoint features [138].

The data used in this study is the geometry coordinate (x, y) of points that was vector data. This coordinate is used to analyze the distance between points. To analyze the distance between points, the study used Euclidean distance [47] [142]. The Euclidean distance was postulated from Pythagoras theorem. Euclidean distance is calculated from the cartesian coordinates of the points using the Pythagorean theorem. The Pythagorean Theorem states that in any right triangle, the sum of the squares of the lengths of the triangle's legs is the same as the square of the length of the triangle's hypotenuse [143]. The theorem is represented by the formula:

$$\mathbf{c^2 = a^2 + b^2} \qquad \text{Equ. 5}$$

Proximity analysis is a very important tool for measuring the Euclidean distance in a vector and raster data model to analyze the shortest path between traffic crashes. As a result, since this study used coordinate data (x, y) of traffic crash locations to analyze the distance proximity between multipoint/traffic crashes, this study preferred the Euclidean distance formula.

## 3.2. Methodology

Road traffic crash location/vector data/coordinates (x, y) was used as raw input to analyze the distance proximity between traffic crashes and level of proximity between road segments based on the geometric formation. Secondary traffic crash data archived by the Hungarian central statistical office of transport was used as an input due to the nature of the data, convenience, availability, and curacy for further analysis [144]. To have more representative information, the study used five-year (2017-2021) road traffic crash data of Budapest city. In order to organize the data, MS Excel was used. Each variable and parameter were coded accordingly. For analysis and modeling, the study used coordinates (x, y) of traffic crash locations/points.

This study used frequency distribution to visualize the distance proximity between traffic crashes. Skewness was used to prioritize a road segment based on the proximity level between traffic crashes. ArcGIS used to figure out the dispersal of traffic crashes on the study area based on the geometric formation of the road, using Python programming language to develop a model that was used to analyze the distance between traffic crashes. Euclidean distance formula to analyze the distance between traffic crashes. The arch length formula/NASA unit conversion approach was used to convert decimal degrees to kilometers.

This study used individual point/traffic crash recorded data as coordinate pairs, that defined as vector data. Vector data is a geographic data type where data is stored as a collection of points, lines, or polygons along with attribute data. Individual points recorded as coordinate pairs, which represent a physical position in the world, make up vector data at its most basic level[145]. The vector data/coordinates can be specified in many units, such as decimal degrees, feet, meters, or kilometers; any form of measurement can be used as a coordinate system [146]. The data in this study used decimal degree as a measurement of coordinate pairs (longitude and latitude) or (x & y). As a result, this study used the coordinates to analyze the distance proximity between points based on the interface of the Euclidean distance formula that used decimal degrees as a measurement to define the proximity between traffic crashes.

This study used vector/coordinate data with a collection of all around 17006 points/traffic crash locations for further analysis registered in the past five years in the study area. To have an insightful result on traffic crash proximity based on the geometric formation, the study classified the data according to a stratified sampling approach [147]. Based on this concept, the researcher divides the road traffic crashes into subgroups as straight road, crossroad, and bend road based on the geometry formation of the road network. Based on the geometry formation of the road, from the total number of traffic crashes registered in the past five years in the city of Budapest Road network, around 10961, 5319, and 726 traffic crashes were registered on straight-road, crossroad, and bend-road, respectively. As shown in Appendix B, Figure B3, most traffic crashes were registered on the straight part of the road segment.

For density estimation and proximity analysis the study used MS Excel and ArcGIS tools to organize and model the data. For proximity analysis the data sheet contains three columns and multiple rows. The three columns contain sample IDs and coordinates (x, y) of points/traffic crash locations with decimal degree units. To have understandable data for the programming language and rational outcome, the study converts the data from Excel Workbook (*.xlsx) file format to CSV (comma-delimited) (*.csv) file format. Each variable and parameter were coded according to data type and precedence. To define the raster cell size and dense intersection zone, this study used the intersection road segment to define the radius of the cell. Since road traffic crashes are randomly distributed features, defining the raster cell size and raster value plays a role in characterizing the density of crashes.

### 3.2.1. Point density and kernel density estimation approach

Point Density Estimation tool calculates the density of point around each output raster cell. Conceptually, a neighborhood is defined around each raster cell, and the number of points that fall within the neighborhood is totaled and divided by the area of the neighborhood [54].

$$\boldsymbol{\rho_q = \frac{\sum \rho_i \epsilon (q,r)}{\pi r^2}} \qquad \text{Equ. 6}$$

Whereas the Kernel Density Estimation tool is used to calculate the density of features in a neighborhood around those features [55].

$$\mathbf{f_n(x, y) = \frac{1}{nh} \sum_{i=1}^{n} K \frac{d_i}{h}} \qquad \text{Equ. 7}$$

#### 3.2.1.1. Predicting the density for points

Equation 7 is used to predict density at a new (x, y) location. This equation is used to determine the estimate of the point density for specified raster cell output that is used to predict the location with a high density of points for a specified cell size with a defined radius [148].

$$\mathbf{D = \frac{1}{r^2} \sum_{i=1}^{n} [\frac{3}{\pi} p (1 - \left(\frac{d_i}{r}\right)^2)^2]} \qquad \text{Equ. 8}$$

For $d_i < r$

This bandwidth estimation formula is used to calculate the density of point for every location to be estimated. Since a raster is being created, the calculations are applied to the center of every cell in the output raster.

#### 3.2.1.2. Raster data cell size

In this study, we identify the concentration of crashes at a specified raster cell. It was considered that the cell was circular with a planar surface due to the spherical shape of the earth [149]. In case this study defines the radius of output cell size based on the study area boundary as a default setting, it accounts for 1.093 x $10^{-3}$ degrees with a neighborhood radius of 9.105 x $10^{-3}$ degrees. This is due to the fact that the default output resolution is determined by the coarsest of the input raster, and the smaller the cell size, the more effective it is to identify location, the concentration of the input data, and the distance between input points. To understand the spatial resolution for both methods with the default radius, refer Figure **1** below.

Due to the random distribution of the data and road geometry formation, this study tried to propose an alternative approach to define the radius of output cell size and neighborhood radius. If the cell size is specified as a numeric value, the tool will use it directly for the output raster. Even if nothing is specified in determining the radius, defining the neighborhood radius and its respective output cell size are the most concerning. Since the processing extent of this study is the Budapest city boundary, the radius of the output cell size is 1.093x$10^{-3}$ degree.

### 3.2.2. Neighborhood radius (bandwidth) estimation

In both Point density estimation and Kernel density estimation, defining the neighborhood radius is a preliminary issue. The algorithm used to determine the default search radius; the step shown below indicates how the algorithm of radius runs out:

**Step 1:** Calculate the mean center of the input points.
**Step 2:** Calculate the distance from the mean centers for all points.
**Step 3:** Calculate the median of these distances (Dm)
**Step 4:** Calculate the Standard Distance (SD)
**Step 5:** Apply the following formula to calculate the bandwidth (radius)

$$\mathbf{r = 0.9 * min\ (\sqrt{SD, \frac{1}{ln(2)}} * D_{m}) * n^{-0.2}} \qquad \text{Equ. 9}$$

Note that the minimum requirement for Equation 8 is defining the standard distance (SD). There are two methods for calculating the standard distance: unweighted and weighted. But the nature of the data used in this study has unweighted coordinate (x, y, z).

$$\mathbf{SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n} + \frac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n} + \frac{\sum_{i=1}^{n}(z_i-\bar{z})^2}{n}}} \qquad \text{Equ. 10}$$

The radius of the cell was expressed in degree or meter. Due to spherical formation of the earth ArcGIS uses degree as an input to define the radius. This study tried to convert degree to meter. As a result, this study attempted to analysis the inconsideration to the radius "r," is a line drawn from the center of the sphere to the circumference, the arc length "L" traced out when the angle changes by "A" the number of degrees is:

$$\mathbf{L = \frac{2\pi rA}{360}} \qquad \text{Equ. 11}$$

The radius of the earth is estimated to be 6,371km. So, convert directly from L to A and vice versa. Based on the equation A.6 above each degree of the earth radius sweeps to 111,139m [148].

Based on the geometry formation of intersection zone road network the following four options were considered for analyzing the neighborhood radius.

**Option 1: Minimum turning radius:** to define the neighborhood radius of the raster cell this study tried to consider the minimum radius of turning at intersection. Studies depicted that for urban settings smaller corner radii are preferred. Actual corner radii exceeding 15ft (4.572m) for private car and radii of >75-ft (22.86m) should be provided for arterial-arterial urban intersections [150]. Although studies indicated that the minimum turning radius was preferable at intersection this study considers the larger design radius 22.86m as a neighborhood. This assumption considered that the distribution of road traffic crashes was concentrated in specified area. Since traffic crashes have a random nature, this assumption has no ground to define neighborhood radius.

**Option 2: Spacing from intersection to crosswalk:** in this option studies indicated that it is safer if there is minimum 40m spacing distance from intersection to adjacent crosswalks [151]. This consideration plays a vital role in the reduction of road traffic crashes that happen to pedestrians. In case, the radius of the cell is equivalent to 0.00046 degree, that was lower than the default setting. As a result, it is recommendable to use it as a neighborhood radius. Even if this study considers this option still the raster cell size is lower than the cross-section of intersection that the point concentration considered in specified intersection missed due to the smaller in size of the cell. As a result, this option is not proper.

**Option 3: Divide the area to a number of points:** in this approach estimating how many cells laid end to end it would take to equal the diameter of the field of view was inconsideration. Then, divide the number of points (crashes) to obtain an estimate of the cell's size.

$$\mathbf{N_c = \frac{a_t}{n_c}} \qquad \text{Equ. 12}$$

So, the study area, Budapest city exist in central Hungary that accounts 525 square kilometers. The total road traffic crashes at intersection zone accounted for 5250 from 2017-2021. So, the total number of cells required to analysis the blackspot area was as shown below.

$$\text{Nc} = \frac{\text{at}}{\text{nc}} = \frac{525\text{km}^2}{5319} = 0.098703\text{km}^2 = 98{,}703\text{m}^2 \qquad @\ \text{at} = 525\text{km}^2 \ \text{ and } \ \text{nc} = 5319$$

Based on this analysis the minimum number of cells required to analysis the blackspot location of the study area is 98,703 cells with a cell size of 1m. Even if this approach was realistic for uniform distribution pattern. In road networks the distribution of traffic crashes is random in nature. As a result, this approach is not appropriate for this study.

**Option 4: Intersection spacing:** the minimum distance between intersections plays a vital role in defining the speed of the vehicle and traffic crashes reduction. This study considers minimum intersection spacing to define the neighborhood radius. A minimum spacing between intersection is one-quarter mile (two to three blocks) (1,320 feet ~ 403m) should always be maintained [152]. This spacing is preferable with intersections at a maximum urban speed of 50km/h. As a result, in the city of Budapest, the maximum speed is 50km/h, which fulfills the minimum requirement.

A given intersection has the possibility of sharing features and crashes with the nearby intersection and segment. This study suggests the share between intersections along the road segment is half of the confined total segment, which accounts for around 201.5meter (0.002 degree). This option has a good fit for this study to define the neighborhood radius. As a result, this study considers this option for further analysis.

#### 3.2.2.1. Blackspot analysis approach and raster cell size

To analyze the blackspot location in this study, two basic assumptions were defined based on the radius of the cell. To specify a given intersection zone as a blackspot location, the number and the distance between crashes play a vital role. Thus, this study considers the radius of the cell as an input to define the distance between crashes. In case the distance between crashes was approaches to radius or less than the radius of the cell the tendency of intersection zone to become blackspot location was higher comparatively compared to the crashes with a distance greater than the radius of the cell. This ambition is supported by Equation 8 indicated above. Whereas other studies indicated that, considering a given location as a blackspot, at list four road traffic crashes must be registered for a particular road section in the last three years [153].

### 3.2.3. Density visualization of raster data cell and blackspot location

The purpose of the density tools is to construct a surface that accurately reflects the probability of an event occurring in each cell. The points can be considered random samples from that probability distribution. It is often much more meaningful to report the expected count within a cell than it is to report the cell density value. Density ($\mathrm{D_c}$) is count ($\mathrm{C_p}$) divided by area (A), so multiplying the density by area will give an expected count.

$$\mathbf{D_c} = \frac{\mathbf{C_p}}{\mathbf{A}} \qquad \text{Equ. 13}$$

To define the blackspot location for the intersection zone road network, this study used raster data cell visualization. Visualization is an approach used to represent information in the form of a chart, diagram, picture, etc. In this study, all figures shown below with raster data cells indicate the variation in number of points and space. To prioritize and figure out the result, this study defines the raster cell using five different colors that represent the density of points allocated for a given cell. In this case, the red, yellow, green, blue, and white colors represent the cells with extreme high, high, medium, low, and no density, respectively. Even though the raster cell with a white color represents no density, no density does not imply no data. So, to define the blackspot location, this study considers an extremely dense raster cell.

### 3.2.4. Distance proximity analysis approach

Since the study used point/coordinate/vector data that was presented by (x, y) to represent the location of traffic crashes. This vector data represents the longitude (x) and latitude (y) of points/crash locations on earth in decimal degree. Subsequently, in the study area, the longitudes and latitudes of points were known; this information was used to calculate the distance between points/crash locations. According to NASA, the distance calculation is subtracting the smaller longitude from the larger and subtracting the smaller latitude from the larger. Then multiply the degree of separation of longitude and latitude by 111,139 to get the corresponding linear distances in meters [154].

Consider the line between the two points as the hypotenuse of a right-angled triangle with base "x" equal to the longitude and height "y" equal to the latitude between them. Calculate the distance between them (d) using the Pythagorean theorem:

$$\mathbf{d^2 = x^2 + y^2} \qquad \text{Equ. 14}$$

For further study of proximity level and its analysis, in addition to NASA distance calculation and unit conversion based on the Pythagorean theorem indicated above, this study tried to use the Euclidean distance technique to define distance proximity between points/traffic crashes [155]. The Euclidean distance formula, as its name revealed, revealed the distance between two points (or) the straight-line distance that assumed ($x_1$, $y_1$) and ($x_2$, $y_2$) are two points/traffic crash locations in a two-dimensional plane of earth that are expressed by decimal of degree. Based on the above parameters Euclidean distance formula was presented [47].

$$\mathbf{d = \sqrt{[(x_2 - x_1)^2 + (y_2 - y_1)^2]}} \qquad \text{Equ. 15}$$

Where: ($x_1$, $y_1$) are the coordinates of one point, ($x_2$, $y_2$) are the coordinates of the other point and d is the distance between ($x_1$, $y_1$) and ($x_2$, $y_2$). This study used the above distance analysis approach to define the proximity level of a traffic crash based on the geometry formation of the road segments. To support the analysis, the study used the Python programming language to define the Euclidean distance between traffic crashes and unit conversion critically.

#### 3.2.4.1. Data Coding and Modelling

Different studies used different coding and modelling approaches to analyse distance proximity between points/features. Since this study used coordinates (x, y) of an earth as references of a traffic crash's location that represented x-longitude and y-latitude. Since the goal of the study was to analyse the proximity level between traffic crashes based on the geometric formation of road segments, the study considered point data represented by (x & y).

To analyse the distance between points and their proximity, this study used the Euclidean distance formula. Due to the nature and amount of the data and difficulty of proximity analysis this study used the Python programming language to analyse multipoint-to-multipoint distance proximity between traffic crashes/points using Euclidean distance. Before applying this programming language, the study tried to analyse multipoint-to-multipoint distance proximity using ArcMap, but due to the large amount of data and its result, it's difficult to extract the output. In addition to distance measurement between points/crash locations, the model developed in this study also converts the distance unit from decimal degree to kilometre that was defined by the Euclidean distance formula and the NASA/arc length distance conversion method as shown in Appendix B, Figure B7.

The output of this model was used to analyse the proximity level of the road segments. The outcome was exported to an Excel file sheet for further analysis of the distribution of distance between points/traffic crash's location of the study area, skewness and other related traffic crash causes, and severity level of the road segments.

#### 3.2.4.2. Skewness

Skewness is a measure of the asymmetry of a distribution. A distribution is asymmetrical when its left and right sides are not mirror images. A distribution can have right (or positive), left (or negative), or zero skewness. It is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. Skewness measures the symmetry of a variable's distribution. If the distribution stretches toward the right or left tail, it's skewed. Negative skewness indicates more larger values, while positive skewness indicates smaller values [48].

No skew/normal distribution, also known as the Gaussian distribution, is a probability distribution that is symmetric about the mean, showing that data near the mean are more frequent in occurrence than data far from the mean. The normal distribution appears as a "bell curve" when graphed as shown in Appendix B, Figure B8. Properties of normal distribution are symmetric about mean, unimodal in nature, it has a single peak value, the curve is always bell-shaped, and mean, mode, and median are always the same[156]. If the mean is greater than the median and mode, the distribution is positively skewed (mean > median > mode). If the mean is less than the median and mode, the distribution is negatively skewed(mean < median < mode) [157, 158].

Based on the principle discussed above, this study used skewness to define the proximity of a traffic crash in the defined geometry formation of the road segments. Based on the concept illustrated above, if the distribution of distance between points/clash location is skewed to the left or positively skewed, the traffic crash proximity level of the road section/segment is high comparatively. While the result showed skewness to the right or negatively skewed, the proximity level between traffic crashes in a specified road segment is low.

At the same time, if the skewness shows normal distribution/no skew, the distance proximity level distribution between traffic crashes is normal. As a result, based on road geometric formation, this study used the above idea as an input to define the road section/segment with higher distance proximity between traffic crashes to suggest the severity level of the road section. From the perspective of others, the lower distance between traffic crashes implies higher proximity. The higher proximity level suggests that the higher severe road segment.

### 3.2.5. Severity level analysis approaches

To analysis the severity level of the road segment based on multipoint-to-multipoint distance proximity approach mean, mode, mean-mode variation and skewness were used. The mean with minimum value, the mode with the maximum value of distance distribution of the road segment was considered a highly severe road segment. If the distribution of distance between traffic crashes showed positive, negative, and normal skewness, the distance proximity between traffic crashes was high, low, and average.

#### a. Mean-Mode Variation

Mean-mode variation was used to analyze the severity level of road segments based on distance proximity analysis level. The formula indicated below is used to analyze mean-mode variation.

$$\boldsymbol{\nu} = \boldsymbol{\mu} - \mu \qquad \text{Equ. 16}$$

Based on the above mathematical model and distance proximity between traffic crashes, the higher the value of the variation between mean and mode, the higher the severity level.

### 3.3. Results

This data was from Budapest city road traffic crashes that were collected and archived by the Hungary transportation authority and contained well-documented coordinates. Based on geometry formation, this study tried to categorize the road network into three (3) segments. The first is straight road: is a road not curved or crooked, continuing in the same direction without deviating [159]. The second is crossroad: is the point/pace/road where two roads meet [160]. The third is the bend road: it's a corner or curve in the road [161].

In the study area public road is divided into two: roads managed by the city and managed by district municipalities. The main road coverage is 550 km, and other public transportation roads cover around 537 km. This showed that the study area was covered by 1087 km of road network [162]. Appendix B, Figure B1 illustrates the road network distribution of the study area. The traffic crashes recorded in the five years (2017-2021) of the study area indicated that around 10961, 5319, and 726 number of traffic crashes was disclosed on straight roads, cross roads, and bend roads, respectively. The distribution of road traffic crashes was displayed in Appendix B, Figure B3, which illustrated that the most traffic crashes happened in the straight part of the road network, followed by crossroads and bend roads. Since the study focus on intersection part of the road network, of the total traffic crashes around 31% were registered at intersection zone. Appendix B, Figure B1 & B2 indicates the study area road network and distribution of traffic crashes at intersection zone.

### 3.3.1. Intersection zone road traffic crashes density mapping and blackspot location using ArcGIS default setting

Density Mapping is the way to show how points are concentrated in each cell size. It helps to identify locations with greater numbers of data points and spacing. This approach is most effective when working with a data set containing several data points where there's substantial overlap between the marks on the map. Figure 1 shown is a map that was carried out with the default radius of output cell size and its neighborhood (for more information, see subsection 3.2.2). The raster cell is prioritized according to the raster value that defines the density of the cell. Color visualization indicates the crash distribution used to define the blackspot location.

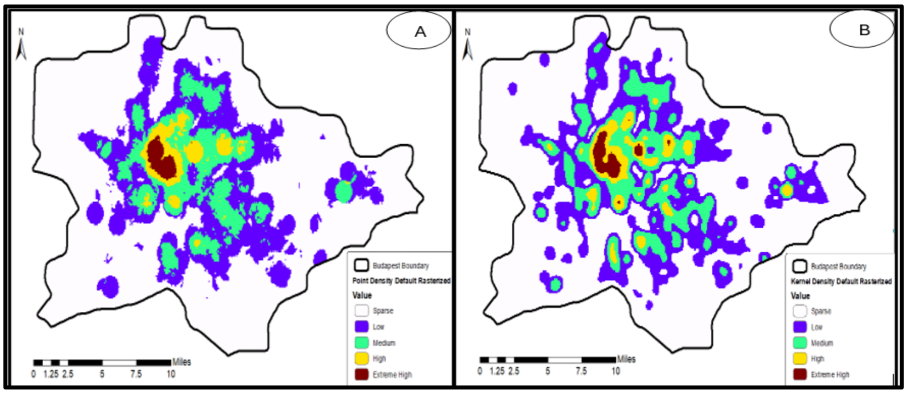

Figure 1. Crashes distribution pattern by Point Density Estimation (A) and Kernel Density Estimation (B) using default setting at neighborhood radius (r) of 0.009105 degree

Even if the result on Figure 1 is not appropriate to define blackspot location, the red color is used to visualize intersection zones with extremely high dense. To have appropriate results, this study enforced the use of the smaller neighborhood radius of 0.002 degree.

### 3.3.2. Intersection zone road traffic crashes density mapping and blackspot location at neighborhood radius (r) of 0.002 degree

Based on assumption indicated in subsection 3.2.2, option 4, the raster map prioritizes the cell according to the raster value as shown in Appendix B, Figure B9. The higher raster value indicates that the cell with higher density was represented by red color. The cell size with red color signifies the blackspot location at which high number of road traffic crashes were registered and the spacing between crashes is small. Based on point and kernel density estimation around five and twenty-five intersection zone of the road network considered as blackspot location.

### 3.3.3. Point pattern analysis (PPA) by extracting raster to point

Point pattern analysis (PPA) focuses on the analysis, modeling, visualization, and interpretation of point data. To analyze the point pattern and its density based on the raster value, raster-to-point extraction was undertaken, as shown in Appendix B, Figure B10. Based on the size of the point (dot), this study identifies the blackspot location accordingly. The cell with a higher raster value was an extremely high dense cell in comparison, while the sparse density cell was considered as the cell with a zero-raster value. In both density estimation approaches, at a neighborhood radius of 0.002 degree, the extraction raster to point showed that the bigger dot (point) was the location where a cell with extreme high-dense (blackspot location).

#### 3.3.3.1. Intersection zone road traffic crash distribution and blackspot location

As shown in Figure 2 (A) & (B) below, based on the distribution of road traffic crashes the number of blackspot locations were identified. At a neighborhood radius of 0.002 degree the extracting raster to point showed that around five and twenty-five intersection zone identified with extremely dense at which high road traffic crashes were registered respectively.

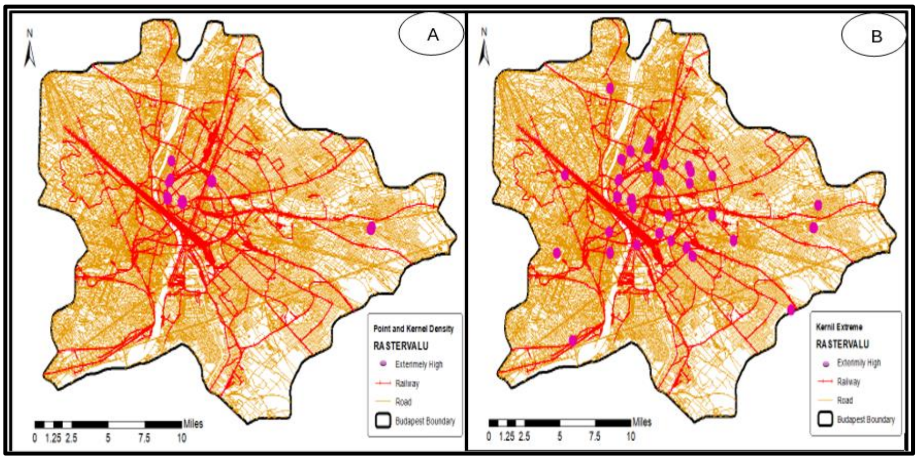

Figure 2. Blackspot location using Point Density Estimation (A) and Kernel Density Estimation (B) at neighborhood radius (r) of 0.002 degree.

The five-intersection zone depicted by point density estimation is also described as a blackspot location by kernel density estimation. As a result, this study considers those intersection zones as extremely high dense blackspot location for further analysis. Based on the location of the blackspot intersection zone of the road network, the open street map of Budapest city indicated that the five intersection zones identified as an extremely high dense traffic crash was depicted in Table 9.

Table 9. Number of traffic crashes and intersection blackspot location of Budapest City

| Intersection blackspot location | Number of Road traffic Crashes |
|---|---|
| Rákóczi Ut -Josef Korut (Blaha Lujza Ter aluljaro) | 13 |
| Josef Attila utca-Bajcsy Zsilinszky Ut-Andrassy Ut | 6 |
| Katona Josef utca-Vaci Ut | 5 |
| Hungaria Korut-Thokoly Ut | 13 |
| Pesti Ut-Ferihegyi Ut | 6 |

### 3.3.4. Road geometry formation of selected blackspot intersection zones

Based on the above overall assessment the five-intersection zone considered as blackspot and their geometry formation were as shown in Appendix B, Figure B11. The intersection zone with high number of legs concord with high number of road traffic crashes and its outcome. This depicts that road geometry formation has its own significant influence on the occurrences of traffic crashes and its severity level.

### 3.3.5. Traffic crash distance proximity of the study area road networks

The minimum distance proximity observed in all road segments was 0.46 km. This implied that in the study area, road network traffic crashes were registered with a range of 0.46 km minimum distance and 40 km maximum distance between traffic crashes. Based on the multipoint-to-multipoint distance proximity approach, more than 0.52million, 28 million and 120 million relative distances between traffic crash locations/points were detected to define the minimum and maximum distance between traffic crashes at bend, cross and straight road segment. As shown in Appendix B, Figure B12, distance proximity distribution, the minimum distance between traffic crashes observed in this analysis was 0 km, whereas the maximum distance was observed at 40 km.

### 3.3.6. Between traffic crash distance proximity distribution and skewness

Based on the multipoint-to-multipoint distance proximity approach, this study tried to visualize the distance distribution between traffic crashes and its skewness for a given road segment to define the level of severity based on the geometry formation of the road segments. Depend on the number of traffic crash locations/points, even though the distribution and skewness of distance proximity between traffic crashes vary. The skewness of the bend, cross, and straight road segment showed that it was positive.

Appendix B, Figure B12 indicated the distribution of bend, cross and straight road segment distance proximity between traffic crashes and skewness. The maximum and most distance registered between traffic crashes in the bend, cross and straight road segment of the study area was 10km, 9km and 8km respectively.

### 3.3.7. Distance proximity and severity level

Distance proximity between traffic crashes and severity level of road segment have direct relationship. Under this section, the study tried to visualize the severity level of the road segment for the study area based on the distance proximity level between traffic crashes.

#### a. Distance proximity mean distribution and road segments severity level

Based on the distance proximity mean distribution mean of road segments depicted in Appendix B, Figure B12, the distance proximity mean between traffic crash was 16.584 km, 11.99 km, and 13.35 km for bend, cross, and straight road segments, respectively. Crossroads were a highly severe road segment due to the mean proximity between traffic crashes was minimum, and that was followed by straight, and bend roads.

#### b. Distance proximity mode distribution and road segments severity level

Based on the distance proximity mode distribution of road segments depicted in Appendix B, Figure B12, frequently the distance proximity between traffic crashes was 10 km, 9 km, and 8 km for bend, cross, and straight road segments, respectively. Straight roads were a highly severe road segment due to the highly frequent distance proximity between traffic crashes observed with a minimum distance, and that was followed by crossroads and bend roads.

#### c. Distance proximity-based mean-mode variation and road segments severity level

Based on the concept that mean is greater than mode, the distribution is positively skewed (mean > mode). The variation between mean and mode plays a significant role in defining the severity level of the road segments. Table 17 showed the mean and mode of distance proximity distribution between traffic crashes for specified road segments and their variation. Based on the mean-mode variation analysis, the severity level of the bend road was higher than the rest of the road segment.

Table 10: Mean - Mode variation

| Road Segment | Mean (km) | Mode (km) | Mean-Mode Variation (km) |
|---|---|---|---|
| Bend Road | 16.584 | 10 | 6.589 |
| Cross Road | 11.99 | 9 | 2.99 |
| Straight Road | 13.35 | 8 | 5.35 |

#### d. Distance proximity skewness distribution and road segments severity level

Even though all road segment distance proximity distribution positively skewed, the level of severity varies. As a result, crossroads are relatively highly severe road segments, followed by straight roads, and the lowest severity level was registered in bend road. In general, based on the stated approach, crossroads, straight roads, and bend roads are considered severe road segments, accordingly. Table 11 summarizes the severity level.

Table 11. Distance proximity and severity level.

| Variables | Severity Level | | |
|---|---|---|---|
| | High | Medium | Low |
| Mean | Cross Road | Straight Road | Bend Road |
| Mode | Straight Road | Cross Road | Bend Road |
| Mean-Mode Variation | Bend Road | Straight Road | Cross Road |
| Skewness | Cross Road | Straight Road | Bend Road |

### 3.4. Discussion

Researchers' findings revealed that point density estimation (PDE) and kernel density estimation (KDE) have common attributes and differences. The finding of this study supports the findings of Bakker (2015) and Yin (2020) on the difference between using point density estimation to calculate point density around each output cell and using kernel density estimation to spread the known quantity of the population for each point out from the point location. Based on this rationale, the findings of this study revealed that five and twenty-five intersection zones were identified as blackspot locations using the stated method, respectively.

Even if the finding of this study supports the result of Abdulla Ali (2014) on the identification of accident blackspots on 18 Michigan freeways using GIS, the result showed that kernel density estimation is more capable of pinpointing blackspots than point density estimation. This finding can't define the severity level of those blackspot locations because it only emphasizes the number of blackspot locations. Even though this study supports Abdulla's finding, the finding of this study indicates that point density estimation is more capable of defining highly dense blackspot locations than kernel density estimation.

This research also supports the notion that point density estimation provides poor visual display while kernel density estimation provides superior visual display. Another study found that in point density, a population field with a probability of one point being counted twice can be used. This study contradicts the statement indicated above. However, the tendency points to being counted twice in kernel density estimation were observed. As a result, in the kernel density estimation approach, the probability of a given intersection zone of a road network being counted as a black spot is relatively higher than the point density estimation.

Different studies are carried out to define the raster cell size by defining the radius of the neighborhood using a trial-and-error mechanism. For instance, the study done by Ashokan Laila Achu (2019) in Thrissur District, Kerala, India, using kernel density estimation to analyze the blackspot location of the road network, uses the default setting of the software to define the blackspot location. At the same time, in the study done for the city of Budapest's road network (Menghwar, 2019), the researcher used 100 meters without any rational background as the radius of the neighborhood. In addition to that, the study done by H. A. S. Sandhu (2014) on identifying blackspot locations using kernel density estimation on a road segment that uses 1500 meters as the radius of neighborhoods through a trial-and error approach to characterize the raster cell size. In contrast, this study used a standard minimum spacing between intersection points to define the radius of the neighborhood.

Previous research and their findings emphasize the microscopic level of analyzing black spot location. The point density estimation and kernel density estimation approaches were using common parameters and the most significant methods for identifying a black spot location at a macroscopic level. Based on the five-year road traffic crash data at the intersection zone of Budapest city, the finding indicated that point density estimation is more capable than kernel density estimation in identifying highly extreme dense blackspot locations. In addition to that, this research work would bring a new approach to how to shape the radius of neighborhoods that used to define the cell size.

As shown in Table 9, the number of road traffic crashes registered in the past five years was indicated to characterize the level of severity of the stated intersection zone. The requirement stated by the Hungarian transport authority to have a minimum of three or four road traffic crashes registered in a specified road section at a specified period was well-defined. As a result, the stated intersection zone road network was considered an alarming black spot location. Even if the maximum number of traffic crashes registered on the straight road, the minimum distance between traffic crashes registered in all road geometries was the same.

Even if the number of traffic crashes in the bend road segment was relatively lower, the proximity between traffic crashes had the possibility of ranging from 0 to 40 km in the study area. In comparison to bend roads, in addition to the number of traffic crashes, the possibility of traffic crash occurrence in short distances between traffic crashes was higher in cross roads. This depicts that relative to the bend road, the crossroad was a severe segment. In comparison, even though the number of traffic crash was higher in the straight road, based on the distance proximity theory, the severity level is lower than the crossroad and higher than the bend road.

The distance proximity mean between traffic crashes in the bend road, cross road, and straight road segments was greater than the mode. That implied the proximity level between most traffic crashes was higher. This is directly related to the severity level of the road segments. Based on the skewness graph depicted in Appendix B, Figures B12, the severity level of the bend road was high. Even though the statistical mode showed that the sever road segment was a straight road, the mean of all road segments was greater than the mode that showed a positively skewed nature of the distribution.

The mean-mode variation analysis, the severity level of the bend road was higher than the rest of the road segment. Based on the information in Table 10, severity level of bend road > straight road > crossroad. This result support the concept that the road segment with the maximum value of mode has the higher severity level. Even though all road segments had the severity level based on the concept of skewness, the variation between the mean and mode also plays a vital role in defining the severity level of the road segments.

Based on the above concept, a relatively severity level of the road segment was identified based on the distance proximity distribution and its mean, mode, and the mean-mode variation and skewness. Grounded on the overview of the severity level and approaches depicted above, the crossroad was a severe road segment that depended on distance proximity mean distribution and skewness. Whereas straight roads were severe road segments based on distance proximity mode distribution. At the same time, the bend road was a severe road segment based on distance proximity distribution on mean-mode variation.

**Thesis Point 2**

I discovered the proper method used to analysis center of traffic crash attraction comparatively using point and kernel density estimation. I proposed a new concept used to define the raster data cell to analysis traffic crashes at the center of attraction based on the minimum spacing between the intersection zone to outline the bandwidth/radius of the raster cell size. To figure it out, the density-based blackspot location of the intersection zone of the road network was analyzed for the study area. Using a multipoint-to-multipoint distance proximity approach as a new tactic that exploited to analysis traffic crashes in the attraction zone using mean, mode, mean-mode variation, and skewness at the macroscopic level of the road network. Based on the distance proximity concept between the traffic crash location/point, a highly severe road geometry formation was analyzed.

⋆ Related publications to this chapter: [163]

# Chapter 4

## 4. Road Traffic Crash Severity Level Analysis and Alternatives Approaches

### 4.1. Introduction

As indicated in chapter three of the dissertation, the density of traffic crashes in a specified road section and its distance proximity play a significant role in defining the center of the traffic crash attraction zone. Not only is the center of the crash attraction zone/blackspot location, but also the number of traffic crashes and its proximity level in a given road network are used to define the severity level of the road segment. This correlated with geometry formation that used to define the severity level of the road segment. The geometry formation of the road is concerned with the positioning of the physical elements of the roadway [164, 165]. Road geometry can be broken as alignment, profile, and cross-section [166, 167]. The intention of geometry formation is to optimize efficiency in transportation and minimize cost [168, 169]. Most road traffic crashes and accidents are basically correlated with the geometry formation of the road [170, 171, 172]. Not only traffic crashes and accidents in various aspects, the severity level was associated with the geometry formation of the road [173, 174, 175]. Even if different research was done, enormous research gaps were still observed. Numerous studies used the number of traffic crashes, the number of traffic accidents, the traffic crash cost, and other determinant factor, and their combination to develop empirical model that used to define road severity level of the road [176, 177, 178].

Even though the combination of road traffic crashes, traffic accidents, and traffic crash costs had substantial implications and applicable to defining the severity level of a road segment/section, in most studies the applications and the significancy level of methods had uncertainty. As a result, this study grasps some common models used to analysis severity level of the road network as shown in Table 1 to designate an alternative approaches. Based on the nature and types of data, this study considered the conceptual framework of equations depicted in Table 1 to clearly define their uncertainty to bring an alternatives.

Even though the data type and nature imposed the study to focus on equations depicted in Table 1, the conceptual framework of this study was applicable for the other severity level analysis approaches. The stated equation considers the number of traffic crashes, the number of traffic accidents, and traffic crash costs. Basically, the first equation considered the number of traffic crashes and the number of traffic accidents that omit traffic crash cost to determine the severity level, whereas the second equation defines the severity level based on the number of traffic crashes and crash costs that omit the number of traffic accident. The concept of combined parameter approach used the number of traffic crashes, number of traffic accident and traffic crash cost as a basic pillar jointly used to analysis severity level of the road segment.

This study agreed on the applicability and its implication of the combined effects of two parameters in equations shown in Table 1 to define severity level, but the level of significancy and correctness of the outcome was doubting issue in defining the severity level due to the exclusion of the combined effects of missing parameter depicted in Table 1. To offset this argument, this study intended that it’s applicable and mandatory to use the combinations of traffic crashes, traffic accidents, and traffic crash costs for further analysis of severity level.

To have expressive result rather than using the number/amount defining the relative percentage share of traffic crashes, accidents, and crash costs, and its combined effects was more appropriate and had a potential to mark the severity level of the road segments. To support the findings of this study, average annual accident cost (ACa) and relative percentage share were used to analysis traffic crash economic losses and their interaction with road geometry formation. This study argued that for a given road segment, the relative percentage share of traffic crashes, traffic accidents, and traffic crash costs was different, except at condition where single traffic crashes that causes single traffic accidents (property damage only) (PDO) was registered across the review period. This argument is functional at conditions where a multiple traffic crash is registered with different accident type and number in a given study period. As a result, adopting an alternative severity level analysis approach is demanding.

## 4.2. Methodology

Budapest city road traffic crash used as a data source. The study used Ms. Excel for data organization, a statistical package for social science (SPSS-20) for data analysis and multicollinearity test. Relative percentage share was used for further investigation of the rates of road traffic crashes, traffic accident and traffic crash costs. The severity index (SI), relative severity index (RSI), and forecasting approaches were used to analyze and characterize the nature of the data. The study tried to visualize the existing and an alternative approach analysis severity level. The alternative severity level analysis approach used relative percentage share.

Combined parameters approach was used for further analysis of severity level of the road section. The study tried to visualize the existing and an alternative severity value/level based on severity level indicator and determinant factor. As the main pillar this study basically emphasized on severity level indicators. Most severity level analysis approach used parameters in a combined way. The indicated empirical models in Table 1 showed that the severity level analyses approach had some missing parameters. For more refer Appendix B, Figure B28.

Equations indicated in Table 1 and other related severity level analysis methods considered the number of traffic crashes, the number of traffic accident, and traffic crash cost as an input. Even though the stated approach considered the parameters indicated above and this study also agree with. The level of result correctness was prompted question that needs further assessment. As a result, this study considered that not only the number/amounts of traffic crashes, accidents, and crash cost to define the severity level and it's better to consider the relative percentage share and their combined effects to characterize the severity level of the road segments. This concept is not limited to the equations depicted in Table 1.

Table 12. Traffic crash, accident, and crash cost distribution and relative percentage share

| **Road Geometry** | **$N_C$** | **$S_C$ (%)** | **$N_A$** | **$S_A$ (%)** | **$R_{CC}$ (bill. Euro)** | **$S_{CC}$ (%)** |
|---|---|---|---|---|---|---|
| Straight Route | 10961 | 64.5 | 13006 | 62.3 | 0.77 | 67 |
| Cross Road | 5319 | 31.3 | 6926 | 33.1 | 0.32 | 28 |
| Road Bend | 726 | 4.3 | 952 | 4.6 | 0.06 | 5.22 |

The relative traffic crash cost expresses in monetary value. Whereas the number of traffic crash and accident expressed in number. As shown in Table 12, the relative percentage share of traffic crash of the road segment can't represent the share of traffic accident and its traffic crash cost, and vice versa. Due to this the accuracy level of the stated severity indexing approach to define appropriate risky location of the road network had uncertainty.

The assumption and uncertainty of equations in Table 1 was the relative percentage share of traffic crash or traffic accident is equal with the percentage share of traffic crash cost. This assumption brings clear vagueness in resolving the problem that used to analyses severity level. In spite of this, this study tried to correlate and define the severity level based on the existing and an alternative approach. In addition to the stated reflection the existing approach considered two interrelated variables to define severity levels. For instance, traffic crash and traffic accident, traffic crash and crash cost, traffic accident and crash cost, traffic crash and traffic volume, traffic accident and traffic volume etc. were used as combined parameter between severity level indicator and other determinant factors to define severity value.

Therefore, those approaches were not significant unless the combined effects of traffic crash, accident and crash cost considered together. Because each parameter has its own implication to define the severity level. For further analysis the following concept was considered.

**Concept 1:** if the relative percentage share of road traffic crash and traffic accident is different (SC(%) ≠ SA(%)). Under this situation based on severity level analysis approach of Equation A1 of Table 1.

$$\frac{N_A}{N_C} \neq \frac{S_A(\%)}{S_C(\%)} \text{ or } \frac{N_C}{N_A} \neq \frac{S_C(\%)}{S_A(\%)}$$

**Concept 2:** if the relative percentage share of road traffic crashes and crash cost is different ($\mathbf{S_C(\%) \neq S_{CC}(\%)}$). Under this condition based on severity level analysis approach of equation A2 of table 1.

$$\frac{\sum R_{CC}}{N_C} \neq \frac{S_{CC}(\%)}{S_C(\%)} \text{ or } \frac{N_C}{\sum R_{CC}} \neq \frac{S_C(\%)}{S_{CC}(\%)}$$

**Concept 3:** if the relative percentage share of road traffic accident and traffic crash cost is different ($\mathbf{S_A(\%) \neq S_{CC}(\%)}$). Like equations in table 1, in any severity level analysis approaches the stated condition below would happen.

$$\frac{\sum R_{CC}}{N_A} \neq \frac{S_{CC}(\%)}{S_A(\%)} \text{ or } \frac{N_A}{\sum R_{CC}} \neq \frac{S_A(\%)}{S_{CC}(\%)}$$

In particular, the relative percentage share of traffic crash, traffic accident and crash cost was different except at condition where the traffic accident type was single and property damage only (PDO) across the data review period of the road segment. Therefore, $\mathbf{S_C(\%) \neq (S_A(\%) \neq S_{CC}(\%) / \epsilon\ S_C(\%) = (S_A(\%) = S_{CC}(\%)}$.

Remarks: The stated concept works for road segment that is affected by any traffic crashes except road segment with single traffic crashes that resulted in single traffic accident (property damage only) for a given data review period. Even if the probability of several traffic crash occurrences with the same traffic accident type and number is unexpected, imaginary, or rare. This paper assumption works at conditions where a multiple traffic crash is registered with different accident type and number in a given study period. For more information about the concept depicted above see Table 13.

Table 13. Road traffic crash, traffic accident, and crash cost distribution and relativity

| **Geometry Type** | **$N_C$** | **$S_C$** | **$N_A$** | **$S_A$** | **$R_{CC}$** | **$S_{CC}$** | **$N_A/N_C$** | **$S_A/S_C$** | **$R_{CC}/N_C$** | **$S_{CC}/S_C$** | **$R_{CC}/N_A$** | **$S_{CC}/S_A$** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Straight Road | 10961 | 64.5 | 13006 | 62.3 | 0.77 | 67 | 1.2 | 0.96 | 0.07 | 1.04 | 0.06 | 1.07 |
| Cross Road | 5319 | 31.3 | 6926 | 33.1 | 0.32 | 28 | 1.3 | 1.06 | 0.06 | 0.89 | 0.06 | 0.85 |
| Road Bend | 726 | 4.3 | 952 | 4.6 | 0.06 | 5 | 1.3 | 1.07 | 0.08 | 1.16 | 0.08 | 1.09 |
| **Total** | **17006** | **100** | **20884** | **100** | **1.15** | **100** | | | | | | |

As shown in Table 12 & 13, the share of traffic crashes, traffic accident and traffic crash cost literally different for a given road segment for a specified data review period. To have more information on the existing approach and an alternative method this research recommends the newly developed approach shown in equation depicted in Section 4.3.3.

The severity level of the road section is characterized based on the measurements of the impacts of an accidents. So, this study considers a critical accident with very high impact, a major accident with significant impact and a minor accident with low impact. This study contemplated that the severity level of road section is characterized by the number of incidence and its severity. The impacts of the incident are basically characterized by economic costs.

To characterize the severity level of the road section and the stated approaches functionality the study considers the following conceptual framework. A given road section with higher in severity value would be the road section should fulfil.

**a.** When the empirical model of severity index contains the number of traffic crashes and the number of traffic accidents the maximum severity value will be observed at road segment (section) with $S_A(\%) > S_C(\%)$.

**b.** When the empirical model of severity index contains the number of traffic crashes, the number of traffic accidents and crash cost in combined way the maximum severity level must defined based on; $S_A(\%) > S_C(\%)$ and $S_{CC}(\%) > S_A(\%)$.

In rare cases, the share of traffic accident and crash cost equal. So, at most the share of traffic accident and crash cost ($S_{CC} \neq S_A$) except at condition where for a give traffic crash the number of accident is single (mostly property damage only). If the share of traffic accident and crash cost ($S_{CC} = S_A$) the existing severity level analysis approach depicted in Table 1 is appropriate.

### 4.2.1. Severity Score (SS)

In road traffic accidents statistics, the severity score is an ordinal scale of 1-6 [179]. This study used this scale to describe the severity score between road segments based on the internationally accepted standard for severity scoring indicated in Appendix A, Table A31.

### 4.2.2. Combined parameters approach

Method that allows severity index to use both severity level indictor and determinant factor as parameters to analysis severity value interdependently. Mostly the study emphasizes the combined effects of traffic crashes, accident and crash cost in determining the severity level of the road section. Even though variables like determinant factors are used to analysis severity level in this study it was not the main aiming factor. Despite of the existing method an alternative approach incorporated the number of traffic crashes, accidents and crash cost in combined way in tolerance with all existing approaches instead of the missing parameters. To incorporate all parameters this study multiplied all existing approach by $S_{CC}/S_A$.

$$\mathbf{NS_{IA}} = \frac{\mathbf{ES_{IA} S_{CC}}}{\mathbf{S_A}} \qquad \text{Equ. 17}$$

Based on the above assumption this study considered relative percentage share to combine the existing approach with traffic accident and crash cost in order to develop new method.

$$\mathbf{NS_{IA}} = \mathbf{ES_{IA}} * \frac{\mathbf{S_{CC}(\%)}}{\mathbf{S_A(\%)}} \qquad \text{Equ. 18}$$

The result of the newly severity indexing and the existing approach would become equal or the same at which percentage share of traffic accident and crash cost for a given road segment the same. Unless the value of the new and existing severity indexing approach remain different. The value of $NS_{IA}$ = The value of $ES_{IA}$ @ $S_{CC}$ (%) = $S_A$ (%). This implied that; $\frac{S_{CC}(\%)}{S_A(\%)} = 1$

### 4.2.3. Systematic basis for nominator and denominator allocation

To the extreme level, the road segment severity level analysis depends on crash cost. The combine parameter approach was used to define the numerator and denominator of an alternative severity level analysis method. The amount of crash cost depends on the number of traffic accidents. Whereas the number of traffic accidents depend on the number of traffic crashes. Intentionally, crash cost depends on the number of traffic crashes. So, based on this argument, the dependent variable is the numerator, and the other parameter is the denominator.

To incorporate the stated parameters into the existing approaches, this study considered the stated systematic technique to integrate the numerator and denominator. So, if the existing severity level analysis approach contained the number of traffic accidents and crashes, the newly developed approach used crash cost as the numerator and the number of accidents as the denominator. At the same time, if the existing severity level analysis approach used the number of traffic crashes and crash cost, the newly developed approach incorporates crash cost as the numerator and the number of traffic crashes as the denominator. The stated mechanisms used to incorporate the missing variables indicated in Table 1.

### 4.2.4. Forecasting road traffic accident cost

Forecasting is a technique that uses historical data as input to make informed estimates that are predictive in determining the future direction of past trends [180, 181]. Equation 19 is used to analyze the annual forecasted and back casted accident costs. Since the study used 5-year

(2017–2021) accident data, Due to a lack of annual accident costs for all years, and to have precise data, this study considered the 2019 road traffic accident cost as the base year [182].

$$\mathbf{AC} = \mathbf{AC_B}\left(\mathbf{1} \pm \frac{\mathbf{1}}{\mathbf{100}}\mathbf{R}\right)^{\mathbf{2}} \qquad \text{Equ. 19}$$

Remark: Instead of the growth rate, this study used the annual inflation rate of Hungary [183, 184]. The positive and negative signs of the growth rate show back casting and forecasting of accident costs.

#### 4.2.5. Road traffic crash cost

Traffic crash, traffic accident and crash cost are interdependent. Before analyzing the severity level identifying traffic crash cost was compulsory. In order to define and analysis traffic crash cost, identifying the types of traffic accident is essential. Most road traffic accident categorized as death (fatal), serious injuries, slight injuries, and property damage. The cost of traffic accident / crash cost mostly affected by the types of accident registered. Even though the number of crash and accident had magnificent impact to characterize severity level mostly crash cost played a ground role. Because, crash cost related with the age of fatal traffic accident, the age and type of traffic injuries and the property damaged during the traffic crash occurrences and other losses expressed in monetary values that interrelate with traffic crashes.

Road crashes result an economic cost. The economic consequences were high [185, 186]. Equation 20 & 21 are used to analyze crash costs [187].

$$\mathrm{AC_a} = \frac{\mathrm{MCA}}{\mathrm{T}} \qquad \text{Equ. 20}$$

$$\mathrm{AC_a(F + SI + LI)} = \frac{\mathrm{A(F)*MCA(F)+A(SI)*MCA(SI)+A(LI)*MCA(LI)}}{\mathrm{T}} \qquad \text{Equ. 21}$$

#### 4.2.6. Relative percentage share

Relative percentage share is obtained by dividing the aggregate value of the share consideration by the aggregate value [49, 50]. It is a frequency distribution in which the individual class frequencies are expressed as a percentage (%) of the total frequency equated to 100. Also known as relative frequency distribution [188, 189, 190]. A relative percentage distribution shows the proportion of the total number of observations associated with each value.

$$\mathrm{PD} = \frac{\mathrm{C}}{\mathrm{T}} * 100 = \frac{100\mathrm{C}}{\mathrm{T}} \qquad \text{Equ. 22}$$

#### 4.2.7. Probability of occurrence (PO)

The probability of occurrence is the likelihood that an event will happen. It is expressed as a percentage or a fraction. The formula for calculating the probability of occurrences P(O) is to divide the number of favorable events (f) by the total number of possible events (N) [191, 192]. This approach was used to analyze the sensitivity level of the road segment in the occurrences of traffic accidents comparatively.

$$\mathrm{PO} = \frac{\mathrm{f}}{\mathrm{N}} * 100 = \frac{100\mathrm{f}}{\mathrm{N}} \qquad \text{Equ. 23}$$

#### 4.2.8. Data and result quality

This part of the study visualizes the data quality and result appropriateness and its significancy.

##### 4.2.8.1. Data period

For analysis of traffic crash related severity level of road section, different research argued that a minimum of a 3-5 year enough sample of data was requested [193]. This study used 5-year traffic crash data for further analysis of severity level of the road section. The amount of data used for the study in the specified review period was sufficient to define the severity value and level of the road section.

### 4.2.8.2. Multicollinearity test

A multicollinearity test was conducted using the Pearson correlation coefficient, and the relationship between most of the variables is not significant [194]; with a coefficient less than 0.8, indicating the variables can be used for further analysis [195, 196, 197]. According to information from the analysis, road geometry has a relatively strong relationship with collision type (0.242). However, the ranges are still within the traditional tolerable limit, and the variables can be used for analysis. For more information refer Appendix A, Table A32.

### 4.2.8.3. Analysis of variance (ANOVA)

Analysis of variance is the statistical procedure of comparing the mean of a variable across several group of individuals [51, 52]. It is a statistical measurement that is used to determine the spread of numbers in a data set with respect to the average value or the mean [53]. Variance is used to evaluate how stretched or squeezed a distribution is. In this study, it was used to analyze data reliability in a specified data group or subset.

$$\mathbf{v^2 = \frac{\sum_i^n (x_i - \bar{x})^2}{n-1}} \qquad \text{Equ. 24}$$

### 4.2.8.4. Relative difference (R<sub>D</sub>)

Relative difference was used to characterize the severity level of the road sections based on the difference between existing and an alternative approach.

$$\mathbf{R_D = SI_N - SI_E} \qquad \text{Equ. 25}$$

When the relative difference ($R_D$) between the severity value become positive and higher in amount the road section is categorized as higher in severity level.

## 4.3. Results

These section attempted to explore the findings of the study. It contains three basic subsections. The first portion deals with a general overview of road geometry formation related traffic crash and accident distribution. The second subsection emphasized on road geometry formation and traffic crash cost (economic losses). For the last subsection the above stated subsections used as an input to analysis and investigate the severity level using the existing and the alternative approach stated above.

### 4.3.1. Overview of road geometry formation and traffic crash related issues

Around 65% of road traffic crashes and 62% of accidents registered in the past 5 years are correlated with the straight road of the study area road network. For more information refer Appendix A, Table A6 and Appendix B, Figure B13.

As shown in Table 14, based on Equation A1 of Table 1, even though the road traffic crash and accident frequency were high in straight routes, the severity index showed that the bend road and crossroad (intersection) road segment had the highest severity value. In addition to that, in all geometry formations in the study area, the probability of a traffic accident occurrence showed that for every one traffic crash, approximately two traffic accidents were expected. The expected traffic accident would be a fatality, serious injury, or slight injury. For more information refer Appendix A, Table A6 & A19.

Table 14. Road geometry, traffic accident distribution and cumulative severity index

| Road Geometry | Number of Accident | Number of Crash | Severity Index (SI) |
|---|---|---|---|
| Straight Route | 13006 | 10961 | 1.19 |
| Cross Road | 6926 | 5319 | 1.30 |
| Road Bend | 952 | 726 | 1.31 |

Appendix B, Figure B14 depicts the trend of road traffic crashes with respect to accident number. The finding showed that most traffic crashes registered in the study area had only one accident record. From the total traffic crashes in the study area in the past five years, the maximum number of fatalities, serious injuries, and slight injuries was observed 3, 5, and 20, respectively. For more information refer Appendix A, Table A7. As shown in Table 15, the annual crash severity index showed that, in the study area even if the number of traffic crashes and accidents registered in 2020 was relatively higher, based on Equation A1 of Table 1, relatively the severity level was lower.

Table 15. Annual traffic crash and accident distribution, and cumulative severity index

| **Year** | $N_C$ | $N_A$ | **SI** |
|---|---|---|---|
| 2017 | 3016 | 3749 | 1.24 |
| 2018 | 2910 | 3594 | 1.24 |
| 2019 | 3117 | 3836 | 1.23 |
| 2020 | 5505 | 6693 | 1.22 |
| 2021 | 2458 | 3012 | 1.23 |

In addition to that, Appendix B, Figure B15 showed that the severity index was lowest with fatal traffic accidents in 2020 compared with other years. For more information refer Appendices A, Table A8, A12 & A13.

Appendix B, Figure B16 indicates the relative percentage share of traffic crash, accident, and crash cost annually. The result showed that the relative percentage share substantially fluctuated. In 2020, even if the relative percentage share of traffic crashes was high, the share of traffic accidents and crashes cost relatively less. At the same time, the trend in 2021, even if the relative percentage share of traffic crashes was lower, the share of traffic accidents and crashes cost relatively more. The above justification is functional for different data subsets. For more information refer Appendix A, Table A20. To visualize the reliability of the data and its relative percentage share the study analyzed the variance based on Equation 24. Appendix A, Table A30 shows variance based on relative percentage share is greater than the mean.

As shown in Table 16, in the study area based on Equation A1 of Table 1, the average severity index showed that the probability of a slight injury occurrence was relatively higher than other forms of traffic accidents. For every one traffic crash, the likelihood of one slight injury occurrence was observed. The possibility of serious injury for every traffic crash occurrence was a quarter (1/4). At the same time, for every fifty (50) traffic crashes, the probability of one fatality was expected in this study area.

Table 16. Traffic accident distribution and average severity index

| **Accident Type** | **F** | **SI** | **SLI** | **Total $N_A$** | **Total $N_C$** |
|---|---|---|---|---|---|
| Accident Number | 224 | 4180 | 16480 | 20884 | 17006 |
| Average SI | 0.013 | 0.246 | 0.969 | | |

Even if the maximum number of traffic crashes and accidents were registered on the straight road segment, based on Equation A1 of Table 1, as shown in Table 17 in terms of accident type the highest severity level was registered on the road bend. Based-on accident distribution severity value of road bend was higher in both fatality and serious injury, slight injury was high for crossroads. In all accident types, the severity value for straight routes was lower.

Table 17. Road geometry related accident severity index (SI)

| **Road Geometry** | **F** | **SI** | **SLI** | **Total Crash** |
|---|---|---|---|---|
| Straight Road | 153 | 2849 | 10004 | 10961 |
| ***SI** | 0.014 | 0.26 | 0.91 | |
| Cross Road | 47 | 1134 | 5745 | 5319 |
| ***SI** | 0.009 | 0.21 | 1.08 | |
| Road Bend | 24 | 197 | 731 | 726 |
| ***SI** | 0.033 | 0.27 | 1.01 | |

As shown in Table 18, from the total number of crashes registered in the road network, around 4.53% of the crashes resulted in ≥ 3 accidents at a time in the study area. From the total number of accidents, around 13.21% (2759) accidents were registered, with a traffic crash rate of 4.53% (770). The higher crash distribution with traffic accidents ≥ 3 per crash was observed at crossroads. Based on Equation A1 of Table 1 the severity level of the road bend (curved road) of the study area was high in conditions with traffic accidents ≥ 3 per crash. Based on this sensitivity analysis, the road segment that was affected by a traffic crash with ≥ 3 accidents showed that for every single traffic crash, the probability of four (4) accident occurrences was observed for the study area. For more information refer Appendix A, Table A9 & A10.

Table 18. Road geometry traffic crash distribution and sensitivity analysis using severity index for road segment with a number of accident ≥ 3 per crash

| **Road Geometry** | **Total $N_C$** | **Accident ≥ 3** | | | |
|---|---|---|---|---|---|
| | | **$N_C$** | **$N_A$** | **Perc (%)** | **SI** |
| Straight Road | 10961 | 386 | 1401 | 3.52 | 3.63 |
| Cross Road | 5319 | 340 | 1193 | 6.39 | 3.51 |
| Road Bend | 726 | 44 | 165 | 6.06 | 3.75 |

Appendix B, Figure B17 shows the crash severity index, the higher severity values registered (2017 and 2021—road bend) and (2018, 2019 and 2020—cross road) indicated that the straight road segment had a lower annual severity index. The most annual crash severity index, cross-roads, are more severe than others. But the average severity index showed that the higher severity value was registered on bend road. For more refer Appendix A, Table A11.

### 4.3.2. Overview of road geometry formation and traffic crash cost

In order to identify the weighted value for accident severity for a given road segment, it is mandatory to define the annual accident cost. Even if the study considers 5-year (2017-2021) data for the analysis purpose, based on data availability, the study used the 2019 traffic accident cost of Hungary as a base year. Based on this, the study forecasted the remaining annual accident cost. The study considered the inflation rate instead of the growth rate to fill the information gap. Equation 19 indicated above was used to forecast accident costs.

Table 19 indicates that the trend of the inflation rate (growth rate) was in ascending order. That showed that the accident cost of Budapest was also increasing. In the past five years (2017–2021), an average 3.4% inflation rate (growth rate) was registered. Based on this statistical data, on average, around 0.8 million, 0.2 million, and 0.02 million euros were lost due to single fatalities, serious and slight injuries registered due to traffic crashes, respectively.

Table 19. Forecasted annual accident cost

| **Year** | | **Accident Cost (EUR)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **2017** | **2018** | **Base Year (2019)** | **2020** | **2021** | Average |
| **Inflation Rate (%)** | | 2.35 | 2.85 | 3.34 | 3.33 | 5.11 | 3.396 |
| **Accident Type** | Fatality | 675288 | 695098 | 719116 | 743063 | 781034 | 722720 |
| | Serious Injury | 165877 | 170743 | 176642 | 176429 | 185445 | 175027 |
| | Light Injury | 14716 | 15147 | 15670 | 16192 | 17020 | 15749 |

*Source:* Base year (2019) traffic accident cost of Hungary and Inflation Rate [182].

In Appendix B, Figure B18, even if the number of slight injuries was relatively high, a higher crash cost was recorded due to serious injuries. As shown in Table 20, based on Equation A2 of Table 1, in the past 5 years (2017–2021), even if a higher inflation rate was registered in 2021, the maximum annual crash cost was recorded in 2020. While compared with the annual relative severity index, the maximum severity value was registered in 2021. For more information refer Appendix A, Table A14.

Table 20. Crash cost and relative severity index

| **Year** | **$N_C$** | **$N_A$** | **Total $C_C$ (EUR)** | **Annual $C_C$ (%)** | **RSI)** |
|---|---|---|---|---|---|
| 2017 | 3016 | 3749 | 205147629 | 17.8 | 68020 |
| 2018 | 2910 | 3594 | 187441638 | 16.3 | 64413 |
| 2019 | 3117 | 3836 | 220924292 | 19.2 | 70877 |
| 2020 | 5505 | 6693 | 363263605 | 31.5 | 65988 |
| 2021 | 2458 | 3012 | 175613119 | 15.2 | 71446 |

Based on Equation A2 of Table 1, as shown in Table 21, in the past 5 years (2017–2021), a higher number of traffic crashes and related accidents were registered in the straight part; on the contrary, the maximum relative severity index was observed in the bend road. While comparing the average relative severity index, the minimum severity level was observed in the crossroad geometric formation of the road network. Even if a higher crash cost was registered on the straight part of the road network, the highest relative severity index was observed on the bend road. For more information refer Appendix A, Table A15.

Table 21. Road geometry crash distribution, accident cost and relative severity index

| RG | $N_C$ | $N_A$ | Total $C_C$ (EUR) | $C_C$ (%) | RSI |
|---|---|---|---|---|---|
| Straight Route | 10961 | 13006 | 768569209 | 66.7 | 70119 |
| Cross Road | 5319 | 6926 | 320631336 | 27.8 | 60280 |
| Road Bend | 726 | 952 | 63189738 | 5.5 | 87038 |

As shown in Appendix B, Figure B19, in all road segments, the number of serious injury-related traffic crashes was high. Even if the number of slight injury distributions was high in the stated road network, relatively high crash cost distributions were registered due to serious injuries. In this study, in all road geometry formations, higher economic losses resulted due to serious injuries. For more information refer Appendix A, Table A18.

Appendix B, Figure B20 shows the maximum economic losses due to traffic crashes were registered in 2020, which accounted for approximately 0.3% of the GDP. It was the only economic loss greater than average annual economic losses of traffic crashes registered in the past five years. The cumulative effects of traffic crash on economic losses in the past 5-year period (2017–2021) registered due to traffic crashes in the city of Budapest, showed around 1.4 billion dollars. This implied in average annually, Hungary loses approximately 0.3 billion dollars. For more information refer Appendix A, Table A17.

In Table 22, due to road traffic crashes registered in the past 5- years (2017–2021) in the city of Budapest, of the total traffic crashes registered, Hungary lost around 0.9 billion dollars due to traffic crashes registered on the straight road.

Table 22. Road geometry formation, traffic accident and economic losses

| RG | $N_A$ | Total $C_C$ (bill Euro) | Avg. Exchange Rate | $C_C$ (bill \$) | Total GDP (bill \$) | Lost (%) |
|---|---|---|---|---|---|---|
| Straight Route | 13006 | 0.769 | 1.15106 | 0.8852 | 807.19 | 0.110 |
| Cross Road | 6926 | 0.321 | | 0.3695 | | 0.046 |
| Road Bend | 952 | 0.063 | | 0.0725 | | 0.009 |

### 4.3.3. Existing severity level analysis and its alternative approaches

Equation A1 of Table 1 depicted in Equation 26 was used to analyze the severity level of the road segment. The severity level of road segment analyzed is based on the number of traffic crashes and the number of traffic accidents. In this equation the concept of a combined parameter approach was missing traffic crash cost to define severity level of the road section.

$$\mathbf{SI} = \frac{N_A}{N_C} \qquad \text{Equ. 26}$$

Based on the drawback indicated above crash cost was incorporated as a forward as shown in Equation 27.

$$\mathbf{SI} = \frac{N_A}{N_C} * \frac{S_{CC}(\%)}{S_A(\%)} \qquad \text{Equ. 27}$$

The newly severity level analysis approach in Equation 27 bring the crash cost as main input to analysis severity value of the road section. This empirical model considered the relative percentage share of traffic accident and crash cost to advance the severity level. In this equation crash cost will play a significant role in defining the severity index as advancing parameters.

The assumption behind Equation 27 was $S_A(\%) = S_{CC}(\%)$. In reality it’s functional when the relative percentage share of traffic accident and crash costs is different [$S_A(\%) \neq S_{CC}(\%)$] according to concept 3 above. If the relative percentage share of traffic accident and crash costs is equal [$S_A(\%) = S_{CC}(\%)$] the Equation A1 of Table 1 (Equation 26) is most appropriate to define severity level. But the probability of having $S_A(\%) = S_{CC}(\%)$ is rare(zero), except the occurrences of traffic crash in a given road segment with a given data review period was single.

To support the concept of combined parameters and the inclusion of severity level indicators the Table 23 used to display the severity value depend on the existing and an alternative approaches (Equation 27).

Table 23. Severity value of existing and an alternative approach of the study area

| **RG** | **$N_C$** | **$S_C$** | **$N_A$** | **$S_A$** | **$R_{CC}$ (bill. Euro)** | **$S_{CC}$** | **SI (eq. 26) Existing** | **SI (eq.27) New** | **$R_D$** |
|---|---|---|---|---|---|---|---|---|---|
| Straight Road | 10961 | 64.5 | 13006 | 62.3 | 0.77 | 67 | 1.19 | 1.28 | 0.09 |
| Cross Road | 5319 | 31.3 | 6926 | 33.1 | 0.32 | 28 | 1.30 | 1.10 | -0.20 |
| Road Bend | 726 | 4.3 | 952 | 4.6 | 0.06 | 5 | 1.31 | 1.42 | 0.11 |

Based on Table 23 the result of the study both for existing and an alternative approach showed that maximum severity level was registered on road bend of the study area road network. Due to the inclusion of crash cost as pillar of severity level analysis the result of the alternative approach showed that bend road > straight road > cross road. While compare with the existing approach the severity level of straight road was become higher than the cross road.

According to Table 13, for both the existing and an alternative equation of severity level analysis, the severity score showed in the range of $1 < SS \leq 2$. Even if the road with a bend geometry formation had a higher severity value, according to the severity score ranking approach the severity levels of all road types exist under a moderate severity condition.

With the relative percentage share conceptual inclusion parameters Equation 28 used to analysis severity value. The assumption behind was $\frac{N_A}{N_C} = \frac{S_A(\%)}{S_C(\%)}$ and $S_C(\%) = S_{CC}(\%)$.

$$\mathbf{SI} = \frac{S_A(\%)}{S_C(\%)} * \frac{S_{CC}(\%)}{S_C(\%)} = \frac{S_A(\%) * S_{CC}(\%)}{(S_C(\%))^2} \qquad \text{Equ. 28}$$

In reality the conceptual background of Equation 28 is that the percentage share of traffic crashes and crash costs are always different [$S_C(\%) \neq S_{CC}(\%)$] according to concept 2 depicted above, except at which the number of traffic crashes and their outcomes (accidents) remain single or the same for all road segments across the review period. To support the concept of combined parameters and the inclusion of severity level indicators the Table 24 used to display the severity value depend on the existing and an alternative approaches (Equation 28).

Table 24. Severity value of existing and an alternative approach of the study area

| **RG** | **$N_C$** | **$S_C$** | **$N_A$** | **$S_A$** | **$R_{CC}$ (bill. Euro)** | **$S_{CC}$** | **SI (eq. 26) Existing** | **SI (eq.28) New** | **$R_D$** |
|---|---|---|---|---|---|---|---|---|---|
| Straight Road | 10961 | 64.5 | 13006 | 62.3 | 0.77 | 67 | 1.19 | 1.00 | -0.19 |
| Cross Road | 5319 | 31.3 | 6926 | 33.1 | 0.32 | 28 | 1.30 | 0.95 | -0.35 |
| Road Bend | 726 | 4.3 | 952 | 4.6 | 0.06 | 5.22 | 1.31 | 1.30 | -0.01 |

To support the alternative approach effectiveness and the significant impacts of the number of accident this study considered that the severity level of the road network basically depends on the impacts of accidents. In accordance with the quality of the data, the most sever road location affected by major traffic accidents characterize as higher in severity level. So, the Table 19 indicated that the road section with higher severity level was a road section with a higher percentage share of traffic accident and crash cost relatively.

Even if the road with a bend road geometric formation has a higher severity value, according to the severity score ranking approach depicted above, the severity levels of all road types exist under a moderate severity condition. According to Table 14, for the existing equation of severity level analysis, the severity score showed in the range of $1 < SS \leq 2$. At the same condition, an alternative approach showed that the severity score for bend roads ranged between $1 < SS \leq 2$. Meanwhile, the severity score of straight road and cross road range in $SS \leq 1$. This implied that the severity level of a road with straight and crossroad geometry formation had a minor severity condition.

In addition to the above severity score (SS), this study also used the relative difference ($R_D$) between existing and new severity values to define the severity level of road segments. Based on conceptual framework of Section 4.2.8.4 in both severity level analyzing methods showed above the relative difference between the existing and an alternative approach showed that the higher severity level was registered in bend (horizontal curved) road. But, due to combined effects of severity level indicators the second sever road segment by existing equation indicated the cross road. Due to the involvement of traffic crash cost, an alternative approaches in Equation 27 & 28 showed that the second sever road segment is straight road. So, in respect with Equation A1 of Table 1(Equation 26) the involvements of traffic crash cost with combined approach using relative percentage share concept had significant impact in determining severity level in more precise way according to assumption indicated above.

Equation A2 of Table 1 (Equation 29) the severity level of road segment analyzed based on the number of traffic crashes and the relative traffic crash cost. In this equation the concept of combined parameter was missing the number of traffic accident to define severity level.

$$\mathbf{RSI} = \frac{\sum_{i=1}^{n} R_C}{TN_C} \tag*{Equ. 29}$$

Based on the drawback indicated above the number of traffic accident was incorporated in the newly attempt. To have full flagged severity value that analyzed by using the combined parameters of the number of traffic crashes, number of traffic accidents and crash cost was depicted in Equation 30.

$$\mathbf{RSI} = \frac{\sum_{i=1}^{n} R_C}{TN_C} * \frac{S_{CC}(\%)}{S_A(\%)} \tag*{Equ. 30}$$

The assumption behind Equation 30 was $S_{CC}(\%) = S_A(\%)$. In reality this equation is functional when the relative percentage share of traffic accident and crash costs is different [$S_{CC}(\%) \neq S_A(\%)$] according to concept 3 depicted above.

The newly severity level analysis approach shown in Equation 30 above bring the number of accident as main input parameter to analysis severity value of the road section. This empirical model considered the percentage share of traffic accident and crash cost to advance the severity value. In this equation crash cost will play a significant role in defining the severity index. The percentage share of crash cost defined in a given data review years based on the severity of the accident. Based on the assumption indicated above, the severity value of the road section analyzed as shown in Table 25.

Table 25. Relative severity value based on existing and an alternative approach

| RG | $N_C$ | $S_C$ | $N_A$ | $S_A$ | $R_{CC}$ (bill. Euro) | $S_{CC}$ | RSI (eq. 29) Existing (Euro) | RSI (eq.30) New (Euro) | $R_D$ |
|---|---|---|---|---|---|---|---|---|---|
| Straight Road | 10961 | 64.5 | 13006 | 62.3 | 0.77 | 67 | 70249 | 75549 | 5300 |
| Cross Road | 5319 | 31.3 | 6926 | 33.1 | 0.32 | 28 | 60162 | 50892 | -9270 |
| Road Bend | 726 | 4.3 | 952 | 4.6 | 0.06 | 5.22 | 82645 | 89831 | 7186 |

As shown in Table 25, based on the existing and alternative severity level analysis approach the severity level of bend road > straight road > cross road. Based on the outcome the crash cost significantly determines the severity level of the road section. So, even though the existing and newly approach of severity level analysis approach was significant based on level of severity indicators and its inclusiveness, the alternative approach based on combined parameters as shown in Equation 30 was potentially more comprehensive.

To support the alternative approach effectiveness this study considered that the severity level of the road network basically depends on the impacts of accidents. In accordance with the data most sever road location affected by major traffic accidents characterize as higher in severity level. So, the Table 13 indicated that the road section with higher severity level was a road section with a higher relative percentage share of traffic accident and crash cost relatively.

Based on conceptual framework of Section 4.2.8.4 the road segment with higher relative difference was highly sever part of the road network. In both severity level analyzing methods showed above the relative difference between the existing and an alternative approach showed that the higher severity level was registered in road bend.

With the relative percentage share conceptual inclusion concept Equation 31 used to analysis severity value. Based on Equation 30, the assumption behind Equation 31 was $\frac{R_{CC}}{N_C} = \frac{S_{CC}(\%)}{S_C(\%)}$ and $S_A(\%) = S_{CC}(\%)$.

$$\mathbf{RSI} = \frac{S_{CC}(\%)}{S_C(\%)} * \frac{S_{CC}(\%)}{S_A(\%)} = \frac{(S_{CC}(\%))^2}{S_C(\%) * S_A(\%)} \qquad \text{Equ. 31}$$

The conceptual background of Equation 31 is that the percentage share of crashes and crash costs are always different [$S_C(\%) \neq S_{CC}(\%)$] according to concept 2 depicted above, except at which the number of traffic crashes and their outcomes (accidents) remain single (one) or the same for all segments of the road network across the review period. If the relative percentage share of traffic crash and crash cost is equal [$S_C(\%) = S_{CC}(\%)$] to have better result using alternative approach depicted in Equation 26 was more appropriate. If the above stated approach was not functional it's better to use Equation A2 of Table 1(Equation 25). To support the concept of combined parameters and the inclusion of severity level indicators the Table 26 used to display the severity value depend on the existing and an alternative approaches.

Table 26. Relative severity value using existing and an alternative approach

| **RG** | **$N_C$** | **$S_C$** | **$N_A$** | **$S_A$** | **$R_{CC}$ (bill. Euro)** | **$S_{CC}$** | **RSI (eq. 29) Existing** | **RSI (eq.31) New** | **$R_D$** |
|---|---|---|---|---|---|---|---|---|---|
| Straight Road | 10961 | 64.5 | 13006 | 62.3 | 0.77 | 67 | 70249 | 1.12 | N/A |
| Cross Road | 5319 | 31.3 | 6926 | 33.1 | 0.32 | 28 | 60162 | 0.76 | N/A |
| Road Bend | 726 | 4.3 | 952 | 4.6 | 0.06 | 5 | 82645 | 1.26 | N/A |

As shown in Table 26, based on the existing and an alternative severity indexing approach the severity level of road bend > straight road > cross road. Based on the nature of the existing and newly approach that the crash cost significantly determines the severity level of the road section. Based on severity value and its inclusion of severity level indicators an alternative approach (Equation 31) is potentially more comprehensive than the existing Equation A2 shown in Table 1 (Equation 29).

According to Table 13, for an alternative Equation 31 the severity score of bend road and straight road showed that in the range of $1 < SS \leq 2$. Even if the road with a bend road geometry formation has a higher severity value, according to the severity score ranking approach depicted, the severity levels of all road types exist under a moderate severity condition. At the same time, the severity score of cross road range in $SS \leq 1$.

To visualize an alternative approach effectiveness and the significant impacts of the number of accident this study considered that severity level/severity score of the road network. In accordance with the quality of the data the most sever road location affected by major traffic accidents characterize as moderate severity condition. This support the idea of the Table 13, the road section with higher severity level was a road section with a higher relative percentage share of traffic accident and crash cost relatively.

Even if the number of traffic crashes in bend road lower, the severity level is higher than others. Based on an investigation of 44 different reasons depicted as the primary cause of traffic crashes in the bend road, around 50% traffic crashes registered in the bend road were caused by road conditions (road layout and pavement quality).

In addition to pavement quality, the speed limit was another factor that causes traffic crashes. Speed limit of the study area within the maximum limit of 50 km/h [198]. From total crashes registered in the bend road of the study area, more than 82% were registered with a maximum speed limit and above (≥50 km/h). Around 15% of traffic crashes are registered with a maximum speed that ranges above the speed limit (>50 km/h).

Appendix A, Table A32 tried to visualize the interaction between straight and bend road due to the higher in number and severity. The trend of traffic crashes, accidents, and crash costs is proportional. To analyse the sensitivity of occurrences of traffic accidents in a given road segment, the study used Equation 23 of Section 4.2.7 to define the probability of occurrences (PO) of traffic accidents due to a given traffic crash.

Table 27. Traffic accident probability of Occurrences

| **Segments** | **$N_C$** | **A** | **$N_A$** | **PO in (%)** |
|---|---|---|---|---|
| Straight Road | 10961 | Fatality | 153 | 1.4 |
| | | Serious Injury | 2849 | 26 |
| | | Slight Injury | 10004 | 91.3 |
| Bend Road | 726 | Fatality | 24 | 3.3 |
| | | Serious Injury | 197 | 27 |
| | | Slight Injury | 731 | 100.7 |

Based on Table 27, the probability of occurrences of accidents due to traffic crashes in the bend road is higher than the straight road. The road segment with higher fatality occurrences leads to the severity level. The probability occurrences of fatalities in a single traffic crash showed that 3.3% and 1.4% on bend and straight road. The probability of slight injuries due to a traffic crash on a bend road is 100.7%. Comparatively, on a straight road, the probability of occurrence of slight injuries due to a single traffic crash was most probably one (1)(91.3%).

## 4.4. Discussion

Previous studies and the existing data showed that the occurrence of traffic crashes had a feasible linkage with road geometry formation. The weight of a single accident vs. multiple accidents per crash showed that from the total number of traffic crashes, around 14349 (84.4%) resulted in a single traffic accident. For every single traffic crash, the probability of fatality occurrences on a bend road was three (3) times more than on a straight road. Not only the fatality; in both injury types, the probability of occurrences on a bend road was higher.

In fact, even if the percentage share of traffic crashes was high on straight roads, the share of road traffic accidents was relatively low. In contrast to straight alignment, other forms of road geometry showed that the percentage share of traffic accidents was high. This illustrates that a road segment with a higher traffic crash doesn't represent a greater traffic accident. So, the severity level of a given road segment depends on the number of accidents registered due to a given traffic crash.

In the study area, the severity value is nearly the same across the study period, even if traffic accident distribution was higher in 2020. In a given data set having a lower number of traffic crashes doesn't show a smaller number or a slight traffic accidents. The variance of traffic crash, traffic accident, and crash cost annual distribution based on relative percentage share is greater than the mean. This revealed that the distribution of traffic crashes, traffic accidents, and crash costs was non-normal. Relative percentage share data supported that annual traffic crash, traffic accident, and crash cost distribution are not the same. This result is supported by the finding of Emilio C. Venezia [199]. Even if the number of traffic crashes and accidents registered in 2020 in the study area was high, the relative severity index was lower than the average annual relative severity index. This implies that the severity index basically depends on the types of accidents rather than the number of accidents registered due to traffic crashes.

With respect to data nature and existing approaches, most road traffic crashes occurred on the straight part of the road network. On the contrary, the higher severity index was registered on a road segment with a lower number of traffic crashes, accidents, and crash costs. As a result, there is uncertainty that confirms having more road traffic crashes, accidents, and crash costs were not an indication of the severity level. Based on the above hesitation, this study was initiated for the adoption of an alternative approach that incorporates the combined effects of the number of traffic crashes, accidents, and crash costs to prove the severity level. This study contemplated that the parameters considered for severity level analysis of the road segment would be affected by different aspects. Of that, the existing conditions of the road and environment, vehicles, and other users; collusion type; and time-based economic costs etc.

Based on severity value and its inclusion of severity level indicators, an alternative approach (Equation 27) is potentially more comprehensive than the existing Equation A1 shown in Table 1 (Equation 26). If the relative percentage share of traffic crash and crash cost is equal [$S_C(\%) = S_{CC}(\%)$] to have better and inclusive result using an alternative approach depicted in Equation 27 was more appropriate. If the stated approach was not functional it's better to use Equation A1 of Table 1 (Equation 26) than an alternative Equation 28. In addition to this, while compare with the existing approach the severity level of straight road was become higher than the cross road. This depicted that severity level indicators/pillar had significant impact in defining the severity level. Based on severity value and its inclusion of severity level indicators an alternative approach (Equation 28) is potentially more comprehensive than the existing equation. The finding of Equation 28 support an alternative Equation 26. Even if in equation 30 & 31 the rank of severity level of the road segment was similar to existing Equation A2 shown in Table 1 (Equation 29), the significance and level of accuracy of Equation 31 was high due to its appropriateness to define the severity level of the road segment.

Even though the bend road was the most severe road in both the existing and an alternative approach, due to the combined effects of parameters, the severity value of the crossroad reduced comparatively. This depicted that the involvement of severity level indicators have a significant impact. The main cause of traffic crashes in the bend of the road in the study area is primarily the pavement quality. So, the consequence of poor pavement quality and over speeding makes the road segment more sever. As a result, it is better to investigate the quality of the road pavement on the road with bent geometry formation in the study area. Based on the nature of the data, to reduce traffic crashes in the bend road reducing the speed below the design limit (<50 km/h) will bring safer traffic maneuver.

The amount of crash cost depends on the number and types of accidents registered in a given road segment. So, even if the number of traffic crashes, accidents, and crash costs were higher on the straight road segment, the probability of traffic accident occurrences was high on the bend road. Most of the economic losses caused by traffic crashes in the study area were related to serious injuries. The economic losses due to traffic crashes in the study area were about the losses in the economy of the annual GDP of some countries.

**Thesis Point 3**

I established a newly empirical model that was used to analysis road network severity level based on the traffic crashes, accidents, crash costs, other determinant factors, and their combined effect. The comparative implication of the newly and existing severity level analysis approach was properly examined. Based on the newly and existing approach of the severity value of the road network, its severity level was analyzed based on the geometry formation.

⋆ Related publications to this chapter: [200, 201]

# Chapter 5

## 5. Bend (Horizontal Curved) Road and Desired Operating Speed

### 5.1. Introduction

As stated in chapter two of the dissertation, speed is one of the determinant factors for the occurrences of traffic accidents. In addition to that, poor quality of pavement surface is another factor that determines the severity of accidents. At the same time, chapter four of the dissertation indicated that Bend Road is one of the segments highly affected by traffic accidents or a severe road segment in the study area. This implied that the traffic crash outcome basically resulted from overspeed registered on a bend in the road with poor quality of pavement surface that resulted in a change in roughness (coefficient of side friction) of the road. In road design, minimum radius ($R_{min}$), the maximum side friction factor ($f_{max}$) and maximum superelevation ($e_{max}$) are basic design parameters used to define the design (assumed) speed at horizontal road curvature. A limiting value of curvature for a given design speed is the minimum radius, which is derived from the maximum side friction factor and the maximum rate of superelevation [202]. Many geometry design elements of the roadway are determined by the chosen speed (design speed) [203]. The side friction factor represents the lateral friction between the tires and roadway surface [204]. The side friction factor (f) is simply the coefficient of friction between two surfaces (the design vehicle's tires and the roadway) that represented by dimensionless number [205]. Whereas superelevation is the amount by which the outer edge of a curve on a road is banked above the inner edge which expresses in percent or decimal [206]. Representing the ratio of the pavement slope to width ranging from 0.04 to 0.12 [207].

The empirical model on road geometry design manual of American Association of State Highway and Transportation Officials (AASHTO) considers side friction factor (f) and maximum superelevation (e) has indirect relation with the radius of the curve and direct relation with the design speed of the vehicle [202]. Not only the US but also other countries use this manual to enable road geometry design and its recommendations. In addition to that, they develop a model that shows the stated relationship [208] [40] [41] [42] etc. In most studies, the assumed and demanded side friction factors vary across the design period of the road [204] [209]. This study tried to consider the roughness of the roads surface and tier block gradual change that resulted due to variation in property, type and condition of the roadway and tire across. Mostly, roughness of the road is basic parameters used to define the coefficient of friction happen between the road and tire of the vehicle [210] [211].

Determining the minimum radius for horizontal road curvature depends on the assumed design speed ($V_D$), maximum superelevation ($e_{max}$) and side friction factor (f) [212]. For a given speed, the curve with the smallest radius is always the curve that requires the most centripetal force [213]. The maximum achievable centripetal force is obtained when the superelevation rate of the road is at its maximum practical value, and the coefficient of friction is at its maximum value. Any increase in the radius of the curve beyond this minimum radius would allow reducing the side friction factor, the superelevation rate, or both [39] [214].

Even though the assumed and recommended values of speed, superelevation, and side friction factor are used to explore the minimum radius of the curvature using Equation 33, across the design period of the road, the side friction factor can be changed due to a change in the roughness of the road surface and tire block. As a result, the assumed (designed) speed of the road is affected by the side friction factor that demands the desired operating speed for the existing road surface and tire block except at the opening phase of the road. The AASHTO manual of road geometry design basically considers maximum design (assumed) speed at a constant side friction factor. The change in side friction factor causes the change in design speed. This manual couldn't answer the speed that was caused by the change in side friction factor across the entire length of the road. This showed that Equation 1 cannot support the AASHTO recommendation depicted in Table 28.

For circular motion with inclined plane that induced friction in horizontal curved road the Equation 33 below has been formulated [39] [215] [208].

$$R_{\text{min}} = \frac{V_{\text{D}}^2}{1.27\, e_{\text{max}} + 127 f_{\text{max}}} \qquad \text{Equ. 32}$$

The measurement unit for speed and minimum radius are km/h. and meter (m) respectively, maximum superelevation in percent (%) that range from 1~12% [216] [217] and side friction factor (f) is unitless constant ranging from 0~1 [218].

Different road geometry design manuals recommend side friction factors depending on the radius of the road, design (assumed) speed, and maximum superelevation [39] [208] [40] [41] [42]. According to AASTHO recommendation as shown Table 28 the side friction factors decrease as curve desired operating speed increases, reflecting the fact that drivers desire less side friction demand at higher speeds. This concept contradicts the general formula and relationship between variables depicted on Equation 32. Side friction factors used in high-speed and low-speed design were determined using vehicle occupant comfort.

Table 28. AASHTO recommended side friction factor ($f_{\text{max}}$) at horizontal curved road

| $V_D$ (km/h) | $f_{max}$ | $R_{min}$ (m) | $e_{max}$ (%) |
|---|---|---|---|
| 30 | 0.17 | 30 | 8 |
| 40 | 0.17 | 60 | 8 |
| 50 | 0.16 | 100 | 8 |
| 60 | 0.15 | 150 | 8 |
| 80 | 0.14 | 280 | 8 |
| 100 | 0.12 | 460 | 8 |
| 120 | 0.09 | 710 | 8 |

*Source:* [39].

Based on AAASHTO recommendation indicated on Table 28 this study aimed in mounting an empirical model of vehicular speed in consideration of other factors that had their own impact on defining the desired operating speed by gradually altering the side friction factor at constant minimum radius and superelevation. Operating speed is the speed at which drivers are observed operating their vehicles based on the current status of the road and its tire block [219]. Study on road surface roughness that causes change in side friction factor (f) using regression model revealed that in average vehicle speed decreases 20.84km/hr. with every 1m/km increase of the road surface roughness [220] [221]. Also, the study done in 2018 indicated that pavement condition index (PCI) decreases the change in speed increases [222].

The change of side friction factor of the road surface across design period influences the desired operating speed. Even though in defining the design speed Equation 1 indicated above is proper, the conceptual underpinning of the mathematical models utilized to analyze the minimal radius (Equation 32) is incorrect to define the desired operating speed across the design period of the road except at the opening phase of the road. Even if the minimal radius, maximum superelevation, and maximum side friction factor is known (assumed), considering (calculating) the speed using Equation 1 is misleading (incorrect) through the design period of the road. Because the conceptual basis stated by AASHTO recommendation and various scholars that when side friction factor increases, design speed contradicts.

Not only the AASHTO empirical model and its recommendation, but other country speed prediction models ignore the impacts of the side friction factor of the road [39] [40] [41] [42]. As a result, examining the mathematical model used to determine the intended desired operating speed based on the conceptual framework of Equation 1 was necessary to demonstrate the relationship between side friction factor and the desired operating.

## 5.2. Methodology

This research used theoretical models to handle a specific research inquiry. Equation 1 used as a means and reference to analyze the relationship between speed and side friction factor across design period of the road. It used AASHTO recommendation of side friction factor at horizontal curvature of the road with defined minimum radius and maximum superelevation to have safe maneuver of vehicle across the design period of the road as a source of data and reasoning. On that basis, this manuscript attempted to investigate the influence of side friction factor on desired operating speed on a horizontally curved road.

To support the theoretical model of this study, AASHTO recommended side friction factors at horizontal curved road were considered. Based on Equation 1, this study realize that side friction factor affects speed along a horizontal curve of the road, whereas the following conditions are fulfilled. At a horizontal curve with the same minimum radius and maximum superelevation at side friction factor varies. Because of variations side friction factor of the road Equation 1 is a high degree of incredulity in defining the desired operating speed.

The desired operating speed depends on the current condition of the road during its design period. Analyzing the intended speed at a demonstrated radius of curvature at existing condition of the road contradicts the relationship between desired operating speed and side friction factor. As a result, this work attempted to construct a mathematical model that is used to determine the desired operating speed at a horizontal curved road segment across the design period of the road excluding opening phase of the road. The mathematical model indicated in Equation 1 is safe in defining the speed of vehicular maneuver at opening phase of the road. The study considers maximum superelevation, the same radius, and instabilities of side friction factor. Based on the above conceptual framework this study is structured to analyze the empirical model of desired operating speed at a horizontal road curvature.

## 5.3. Result

This part of the study tried to designate the findings. It contains the variable characterization and relation between variables. At all it tried to bring significant outcome and its implication that shows the impact of side friction factor on desired operating speed across the design period.

### 5.3.1. Empirical relation of radius, speed, superelevation and side friction factor

The concept and Equation 1 stated above basically used to determine the minimum radius of the curve at which side friction factor (f) and maximum superelevation ($e_{max}$) remain the same across the design period of the road. This empirical model also considers the vehicular design speed remain constant with defined side friction factor and maximum superelevation of horizontally curved road with predefined minimum radius ($R_{min}$) across the design period. But the speed at horizontal road curvature varies based on variation in side friction factor across the design period.

Whenever, Equation 32 stated above is used to determine the minimum radius for specified horizontal road curvature at maximum side friction factor ($f_{max}$), maximum superelevation ($e_{max}$) and defined design speed ($V_D$) across the design period. Not only minimum radius, equation A.2 indicated above used to analysis the design speed ($V_D$) Aat the opening phase of the road. Even if Equation 1 is used to analysis the design (assumed) speed, due to variation of side friction factor happen across the design period of the road the desired operating speed ($D_S$) determined based on the existing condition of the road surface roughness and tire block.

To illustrate the effect of side friction factor on speed at known minimum radius see Figure 3. This figure illustrated based on maximum superelevation 8%, AASHTO recommended minimum radius of curvature and side friction factor variation with 0.05. Studies indicated that the safest side friction factor ranges from 0.05 to 0.3 [223]. As a result, this study analysis effects of side friction factor on speed across design period of the road using Equation 1.

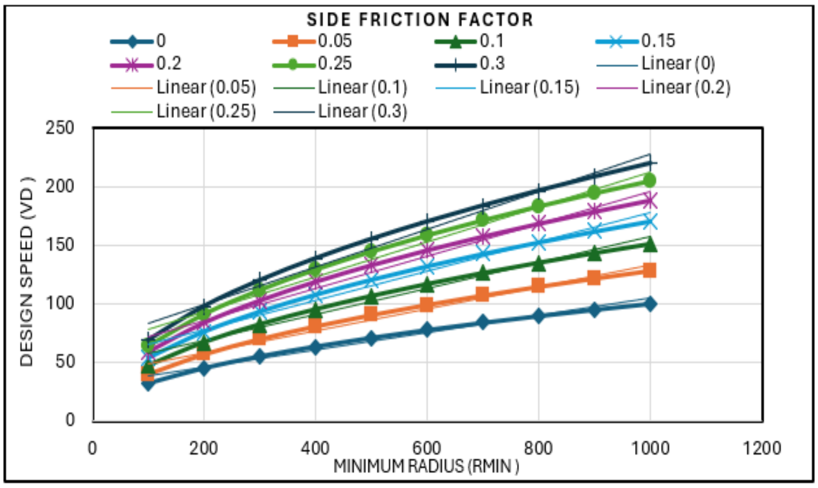

Figure 3. Desired operating speed and minimum radius at varying $f_{max}$ and $e_{max} = 8\%$

The Figure 3; based on Equation 32 for the analysis of minimum radius revealed that as the side friction factor increases the desired operating speed increases.

Basically, side friction factor depends on type and condition, and block of the road surface and tire. Appendix B, Figure 21 indicates the formation of longitudinal and lateral friction. Irregularities present on the road surface and tire block are often described as surface roughness. A recent study has reported that surface roughness with specific dimensions and patterns can effectively reduce friction [224]. Friction between road surface and tire block plays a vital role in keeping vehicles on the road. It develops the driver's ability to control vehicle movement in safer side. Higher friction at pavement tire interfaces the more control the driver has over the vehicle [225]

This study contests with the concept that the side friction factor resulted between tire and road surface remains the same across design period. This brings the inference that roughness of the road can vary across the serviceability period that causes a change of side friction factor. Due to this circumstance desired operating speed varies across the design period.

The upper limit of side friction factor is at which the tire is skidding. A skid happens when the tires lose their grip on the road, which can be caused by one of the four ways: Driving too fast for road conditions, braking too hard and locking the wheels, supplying too much power to the drive wheels, causing them to spin. Also, smooth surface roughness of the road or due to other factors. In all cases the AASTHO recommendation show a decrease in coefficient of side friction values for an increase in speed [227].

The minimum value of side friction factor is zero; it implies that no friction between tire and road surface [228]. While side friction factor is one means; the lateral frictional force is equal to the normal force [229]. A coefficient of friction that is more than one just means that the frictional force is stronger than the normal force. It indicates that the movement of vehicle remains static [230] [231]. While considering the type and block of the tires remain constant across the design period; the surface of the road plays a significant role in determining the side friction factor. As a result, not only the tire block but also the rough surface of the road play a critical role in defining the skidding nature of the tire.

$$f_{max} = \frac{V^2}{127\,R_{min} - 0.01\,e_{max}} \qquad \text{Equ. 33}$$

When the coefficient of side friction remains constant and varies across design period, the V(speed) becomes design speed ($V_D$) and desired operating speed ($D_S$) respectively.

This study identified that side friction factor has an impact on vehicular speed at horizontal curvature of the road. The increase of side friction factor results in a reduction in speed of the vehicle. Equation 1 cannot show the stated relation.

As indicated in Equation 32, the minimum radius of the curve has a direct relation with design speed. But it has indirect relation with the super elevation (e) and side friction factor (f). Even if Equation 32 fulfilled the conditions to analyze the minimum radius of the curve; this equation has a big uncertainty in using and defining the design speed ($V_D$) across design period of the road due to variation side friction factor except at the opening phase of the road.

### 5.3.2. Recommended side friction factor (f) for a given design speed and minimum radius

Figure 4 shown below indicated that how design speed is affected by the side friction factor. It implied that the speed of a vehicle at horizontal curvature of the road depends on side friction factor and minimum radius with maximum superelevation. As speed increases side friction factor decreases and the minimum radius of the curvature increases. This contradicts the mathematical model depicted on Equation 1 above except at the opening phase of the road.

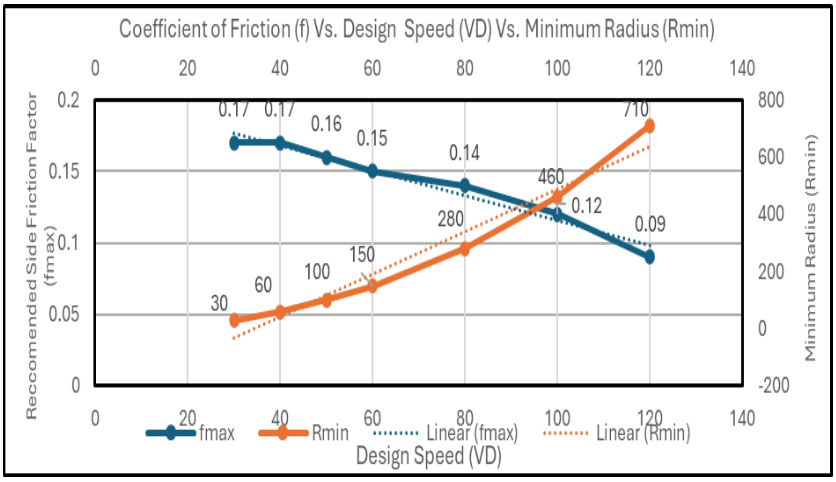

Figure 4. AASHTO recommended $f_{max}$ at horizontal curved road @ $e_{max}$ = 8%

The side friction factor basically depends on the surface of the road and the tire block. The hypothesis of this research depends on the ideal condition depicted on Figure 4. As a result of variation of side friction factor due to gradual change in roughness of the road surface the following condition can be take place.

Table 29. Relationship side friction factor and speed

| Side Friction Factor (f) | Speed (V) |
|---|---|
| Increase | Decrease |
| Decrease | Increase |

Table 29 indicates that vehicular maneuver speed depends on side friction factor. Based on overall relationship side friction factor and speed of the vehicle has an indirect relationship. To visualize and proof the research hypothesis depicted on Table 29 and Figure 5 proposed.

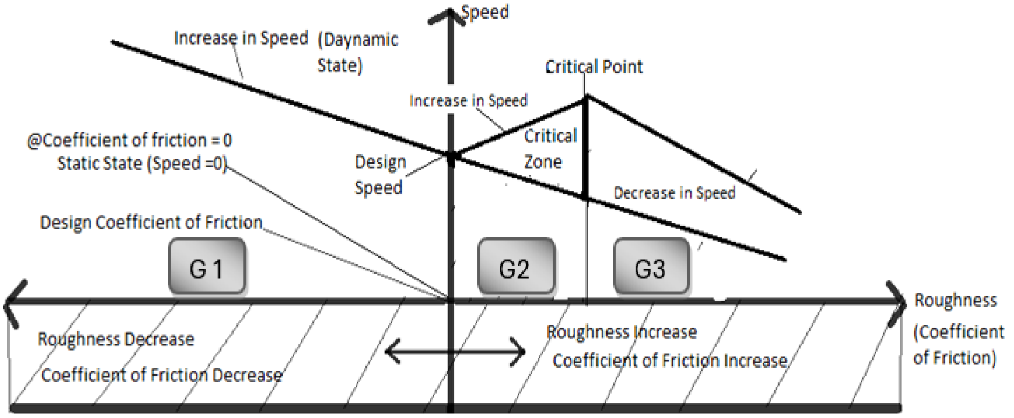

Figure 5. Conceptual frame of vehicular speed vs. road surface roughness ($f_{max}$)

Figure 5 indicated above showed how the roughness of the road surface affects the speed of the vehicle by creating variation of side friction factor. It shows that a decrease in coefficient of friction (side friction factor) below design requirement would increase the speed of the vehicle ultimately at maximum superelevation. Meanwhile, the increase in roughness of the road surface by some extent defines the maximum desired operating speed that remain the same to design speed up to critical point. After a critical point the speed starts to decline gradually.

Based on Figure 3, speed of the vehicle has direct relationship with side friction. In line with AASHTO recommendation and other scientific findings, Figure 3 and Equation 1 cannot define properly the relationship between speed and side friction factor at horizontal curved road across the design period. This study clearly indicated and empirically models the relationship between speed and side friction factor considering Appendix B, Figure B21 above through grouping the outcome and their relation in the following three condition as shown in Figure 5.

Based on the nature of the data, AASHTO recommendation and other scientific finding depicted in Table 28 and Figure 4 side friction factor gradually changed due to the change in roughness of the road surface and tire block..

$$D_S = \frac{1}{2}\sqrt{254}\sqrt{R_{\min}\left(\left(\frac{1-f_{\max}}{1+f_{\max}}\right)-0.05e_{\max}\right)} \qquad \text{Equ. 34}$$

Equations 34 basically used to calculate desired operating speed ($D_S$) at which radius, and superelevation remains constant across design period of the road with variation of side friction factor. To address the aim of this analysis the following condition were in consideration.

**Condition 1 (G1) -** at this condition Equations 34 is functional at which the following is fulfilled: when the vehicular situation is at dynamic state and the coefficient of side friction is decreasing; the speed of the vehicle increases. Under this condition no skid resistance. This implies that $f_{max} \sim 0$, $D_S \sim$ maximum. For further analysis of this condition the study considered the movement of a vehicle is at static state. As a result, this study recommends that desired operating speed at zero side friction factor is unreliable.

**Condition 2 (G2) -** a critical zone at which coefficient of side friction gradually increases with a condition where desired operating speed increases and ultimately maximum at critical point and start to decline.

**Condition 3 (G3) -** at which coefficient of side friction gradually increases with a condition where desired operating speed gradually decreases.

To check the significancy of the above conditions and Figure 6 point out the desired operating speed at $e_{max}$ = 8%, recommended minimum radius, and $f_{max}$ varies with 0.05.

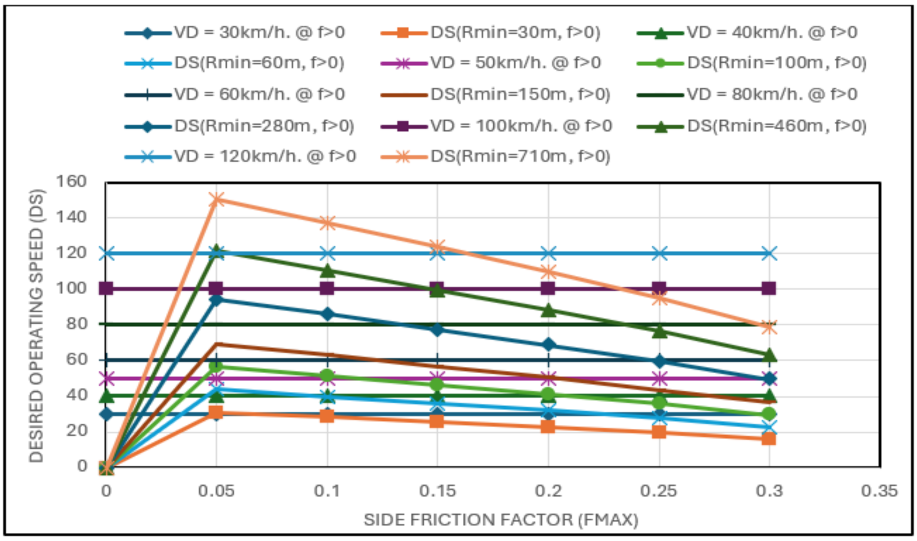

Figure 6. Effects of change of $f_{max}$ on speed at recommended $R_{min}$, and $e_{max}$ = 8%

Figure 6 indicated that as the coefficient of side friction increases desired operating speed decreases. Even if the coefficient of friction gradually increases starting from critical point the desired operating speed progressively declines. This implied; as side friction factor approach to maximum the desired operating speed approach to minimum. Reference to design side friction factors: the speed of a vehicle gradually decreases as side friction factor increases except at critical zones across the design period of the road.

### 5.4. Discussion

Researchers and certainty behind the relationship between desired operating speed and side friction factor contradict the correlation between variable in Equation 1 to determine the desired operating speed across the design period of the road. Equation 1 is appropriate at a predefined maximum superelevation and constant side friction factor. But, due to different factors, the surface of the road and tire block can vary conditionally across the design period. The friction between tire and road surface would be static friction when the wheels are not moving, rolling friction when they are, kinetic friction during a skid on dry pavement, and fluid friction in a skid on wet pavement. So, variation in the surface condition of the road results in variation in the coefficient of friction (f). As a result, this study develops an empirical model that is used to explore desired operating speed across the design (serviceability) period of the road that resulted from the variation of the side friction factor at the same minimum radius and maximum superelevation at the horizontal curvature of the road.

Figure 6 above illustrated that Equation 34 developed for stated conditions properly defines the desired operating speed ($D_S$) as side friction factor increases or decreases in reference to design (assumed) speed ($V_D$) across the design period of the road. So, under this circumstance this study indicated that the speed of the vehicle increases or decrease across the design period of the road with variation of side friction factor ($f_{max}$). Even though this indicates the recommendation of AASHTO and other manual on side friction factor and the empirical model result support each other, the equation that depict to analysis minimum radius contradict with the new model used to analysis desired operating speed.

This study recommends the newly defined Equation 34 that is used to analysis desired operating speed across the design period of the road by defining the side friction factor (coefficient of friction) of the existing road and tire surface other than the recommended side friction factor. So, by defining the desired operating speed on a horizontal curved (bent) road, the probability of traffic crashes will be reduced due to restricted management of traffic maneuver speed across the design period of the road. As a result, due to the empirical equation formulated in this study, the tendency of traffic crash occurrences and their outcome severity will be reduced dramatically. In case it is advisable to use this model in order to define the desired operating speed to minimize the occurrences of traffic crashes and their outcome severity across the design period of the road.

**Thesis Point 4**

I affirm a newly empirical model that is used to analysis desired operating speed at a bend (horizontal curved) road. The impacts of pavement surface roughness on desired operating speed across the design period of the road were examined. To illustrate the empirical model's applicability, the desired operating speed at a constant minimum radius, constant maximum superelevation, and variation in the maximum side friction factor (coefficient of side friction) was analyzed.

⋆ Related publications to this chapter: [232]

# Chapter 6

## 6. Road Topographic Formation Impacts on Traffic Crash Occurrence

### 6.1. Introduction

In addition to road geometry formation, traffic crash density and proximity level, the change in pavement surface roughness across the design period of the road that led to a change in design speed, the occurrences of road traffic crashes, and their outcomes are concatenated with topographic formation. Starting from route selection, topography is one of the parameters used for the design and construction of a safe road in a given area. As a result, even if other parameters have their own impact on the occurrence of traffic crashes and their outcome, the topography of the road also plays a significant role. So, road traffic crashes are defined as incidents involving at least one moving vehicle and that result in personal death, injury, or property damage in a region meant for transportation [233] [234] [235]. This region is defined based on its topographic formation. Searching the truthful reason of a traffic crash, a dangerous area on the road network, and the appropriate response to it are critical and difficult issues in road traffic crash study. The road's location and surrounding environment constituted an interaction factor in traffic crashes [236] [237] [238]. This illustrated how the prevalence of road traffic crash is correlated with physical features of the earth and their measurements, such as height disparity between locations or points, slope variation across locations or points, and terrain development.

Geographic information systems (GIS) use spatial elements to represent traffic crashes because these events are random and continuous in nature. Continuous, non-discrete surfaces are known as spatial features, and they are commonly represented in GISs by uniform grids [239]. Continuous surfaces can be represented in a GIS system in a number of ways. Since this study used point coordinates, the elevation values can be represented in vector form as either points with coordinate pairs or as contours with the nodes that make up these lines saved as coordinate pairs. As an alternative, continuous surfaces are also represented by a raster grid, in which a single value is represented by each cell. Using a triangular irregular network (TIN) is another method of portraying a continuous surface [240]. For more information refer Appendix B, Figure B22 (A, B, C, D) below for additional details [240]. This study used triangular irregular network (TIN) for further analysis elevation difference, slope variation and terrain formation [241] [242] [243] [244] [245].

In terms of particular surface details, the triangular irregular network (TIN) is more dependable than alternative formats [56]. Triangles that are next to one another do not overlap make up the surface of TIN. TINs are often generated using the triangulation of a point coordinate (x, y, z). The fact that the points are distributed differently depending on an algorithm that ascertains which points are most essential to produce an accurate representation is one benefit of utilizing a TIN. Flexible data entry means fewer points need to be kept [246]. Furthermore, the TIN model, which is insensitive to changing data scales, use continuous data to represent discontinuities in the surface. TINs enable the simulated surface's level of detail to be adjusted as needed. Also, it’s efficient in terms of data storage [247].

Different researchers in GIS were perplexed by the term "elevation" and "altitude." In particular, elevation describes the height above mean sea level of a point on the surface of the globe or the location of a crash [248]. On the other hand, altitude is the vertical distance of a point, crash site, or object above a reference level, which, depending on the situation, may be mean sea level or ground level [249]. The study's context was unaffected by the usage of elevation or altitude in this instance because mean sea level was employed as the data's reference. Despite the fact that the term "elevation" was frequently used in this study.

Any elevation shift carries the risk of being hazardous because it might be challenging to recognize the incline or decline and cause the user to trip or fall [250]. A Qinghai-Tibetan plateau experiment study revealed that the driver's level of weariness increased with elevation [251]. This suggested that a high elevation area had a higher likelihood of traffic crashes occurring as a result of tired drivers. According to a Chinese study, the national rate of traffic crashes was lower at high elevations [252].

Studies indicated that there is a considerable correlation between the position and slope of a traffic crash and its outcome, in addition to the elevation of the crash site. According to a study conducted by Huiying Wen et al. in 2023, the combination of curve and slope has a significant impact on the severity of truck injuries [253]. According to the findings of another researcher, driving recklessly down a slope can quickly result in collisions with other cars or pedestrians [254]. The occurrence of traffic crashes was highly correlated with the slope length [255]. The road's longitudinal slope was a high-frequency site of traffic accidents [256]. The slope might be changed from 1:2 to 1:7 to reduce rollover crashes by 27% [257]. The researcher did not address the slope trend between traffic crashes or points, despite the fact that the incidence of traffic crashes was connected to the slope of the road segment.

This paper also looked into the origin of terrain and road traffic crashes. According to a 2017 study by Hui Zhao et al., the frequency of crashes at plateau areas rose quickly and gradually [258]. On the other hand, there was a relatively high rate of traffic crashes on roadways that descended in mountains [259]. Compared to level or flat ground, mountainous topography accounts for 30% more accidents [260]. Highway sections with undulating terrain typically have higher collision rates [261]. India federal highways showed the frequency of traffic crashes was high in hilly regions" [262]. The information above suggested that there are a significant association between the formation of the landscape and road traffic crashes.

As revealed above, researchers showed that there is a general overview and correlation between the trends of traffic crashes and the variations in elevation, slope, and terrain formation between the road network location. However, the alarming issues were the elevation difference, the slope variation, and the terrain development between the locations or point of traffic crashes and its scrutiny. This would provide a precise definition of the unsafe zone on the existing road network. To assesses and simulate traffic crashes and determine the risky zone of the road network, this study demonstrated a newly triangular irregular network (TIN) approach using ArcGIS tool. This method is applicable to any form and location of the road network that is affected by traffic crashes and related factors at the macroscopic level. Furthermore, because the city of Budapest was used as a data source for this investigation, the study would identify problematic zones of the road network and provide alternate methods for analyzing traffic crash scenes. Based on the above-stated research gap, and data nature, the main purpose of this study was investigating dangerous road network using triangular irregular network (TIN).

## 6.2. Methodology

The study employed intersection zone road traffic crash data of the city of Budapest in order to comprehend and visualize this research work and its methodology. The study examined 5-year (from 2017–2021) data. This study utilized a triangular irregular network (TIN) using ArcGIS tool. The data features that are randomly distributed, so characterizing the method's significance and locating the study area's dangerous road section depend heavily on defining the elevation difference between the traffic crash location or point, the slope variation between traffic crash location or point, and the terrain formation between the traffic crash location.

Triangulation is the art of subtly or overtly manipulating others by starting and sustaining disputes [263]. In GIS refers to the process of identifying locations on the surface of the earth utilizing the idea that if the dimensions of one side and each of a triangle's two adjacent angles are known [264] [265]. A triangulated irregular network, which is mostly utilized as a discontinuous global grid in primary elevation modeling, is a GIS representation of a continuous surface made up completely of triangular facets [266]. The study employed geometrical interval categorization in relation to this concept. The classification scheme for geometrical intervals class intervals with a geometric series are the basis for the creation of geometric interval class breaks [267].

The other parameter that comes from TINs is slope. Usually, these parameters are derived in a facet-oriented manner, which means that each facet is evaluated separately [268]. The angle of inclination between a surface and a horizontal plane is called the slope [241], which the following Equations 32 & 33 can be used to analyze. Slope expressed in percent (%) or degrees. Since the modeling in the study was done using ArcGIS, degree ($^0$) used as measurement. The study's slope, expressed in degrees (0-90) [269].

$$Slope = \arctan\sqrt{b_1^2 + b_2^2} \qquad \text{Equ. 35}$$

The fundamental idea behind determining a line's slope at two points in a line is provided by [270].

$$Slope = \frac{rise}{run} = \frac{(z_2 - z_1)}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} = \frac{z_2 - z_1}{\sqrt{x_2^2 - 2x_2x_1 + x_1^2 + y_2^2 - 2y_2y_1 + y_1^2}} \qquad \text{Equ. 36}$$

The points within the line are $\left(x_1,y_1,z_1\right)$ and $(x_2,y_2,z_2)$ such that $z_2 > z_1$. Slope was categorized differently in different studies: 1–3$^0$ mildly inclined plain/extremely gentle, 3–50 gentle/inclined plains, 5-7$^0$ sloppy, 7–10$^0$ sloping, 10-15$^0$ strongly sloping, 15-20$^0$ sharp, 20–40$^0$ very sleep, and >40$^0$ steeper slope [271, 272]. Consequently, the classification approach was employed in this work to define the slope variation.

A digital elevation model (DEM) is a term commonly used to describe a triangulation irregular network (TIN) used to represent topography [273]. A DEM is a topographic representation of the naked earth that does not include any buildings, trees, or other surface items [274]. Based on similarities in topographical qualities, geomorphological characteristics, geological characteristics, morphometric properties, soil characteristics, etc., those model divides the earth's surface into units or sub-units. In order to identify the risky area of the road network, this study attempted the morphometric feature of contour to define terrain formation.

Morphometrics is a term used to describe the quantitative study of form. It is the measurement and mathematical analysis of the landform's dimensions, shape, and arrangement on Earth's surface using features that tend to total length (TL) or standard length (SL) [275, 276, 277]. Using a measurable trait—like standard length that can be measured as a length or ratio of other measurements, it analyzes the size and shape. Using a measuring tape, parameters are measured directly in conventional morphometric measurements. In this investigation, the contour is used as a measurement tool.

This study acknowledges that the number of points shown in the contour and the distance between them can be used to find the road network's risky zones using all available topography features [278]. A topographic map's contour lines show the terrain's height at regular intervals. In order to effectively depict the form of the land surface on a map, contour lines display elevation and the contours of the terrain [279]. The distance between lines is commonly expressed in feet or meters, with each line encircling a region of equal elevation [280].

### 6.2.1. Point set triangulation irregular network (TIN)

Point set triangulation was the focus of the study in order to fulfill the stated purpose because the data used in this investigation are three-dimensional (x, y, and z) point data. A set of points in the space that encloses the convex hull of a point and whose vertices are part of the point is known as a point set triangulation [281]. TINs are helpful for the description and study of generic horizontal (x, y) distributions and relationships. They are related to three-dimensional (x, y, z) data. A triangular tessellation, or TIN, is made up of a triangular network of vertices, or mass points, connected by edges and corresponding coordinates in three dimensions. Rendering triangular facets makes it easy to generate three-dimensional representations. The points may be widely apart in locations with little fluctuation in surface height, while the point density is higher in areas with more intensive variation in height.

A TIN's facet is its triangular face [282]. The geometry properties of each triangle facet correspond to that region of the surface. This is equivalent to a planar triangle with a particular inclination. In other words, a plane represents each point on the facet [283]. Thus, the Equation 37, which is displayed below, is a TIN facet of a plane, with Z (x, y) standing for the elevation.

$$Z(x,y) = b_0 + b_1 x + b_2 y \qquad \text{Equ. 37}$$

By using the coordinates of the three nodes of a facet (x, y, and z) to solve a system of equations, the coefficients $b_0$, $b_1$, and $b_2$ are obtained. Where the surface is complicated, the smaller facet displays TIN in greater depth.

### 6.2.2. Triangulation irregular network (TIN) model quality control

Thin triangles, which can introduce mistakes into the triangulation process, can be prevented through quality control and measurement. Due to a higher spatial resolution, smaller triangles may be linked to better quality TINs, so in a way, this is also a measure of compactness. Multi-resolution TINs were introduced to address the trade-off between integrity and efficiency in data processing. Depending on the needs of the phenomena under study, terrains can be represented at different resolutions thanks to this integrated TIN model with adjustable resolutions [268]. In addition to resolution the quality of TIN measured by elevation difference (z-factor) between input TIN surface and interpolated output surface [57].

#### a. Elevation difference (Z-factor)

The z-values of the input surface are multiplied by the z-factor when calculating the z-values of the output surface. Where z-value is the elevation value or vertical distance. If the difference between z-values is zero, that means the z-factor is 1. In this study, based on this concept, the z-values of the crash location (input surface) and the z-value of the interpolated output surface remain the same. This shows the interpolation of the input TIN surface occurs at regular intervals with no loss of information.

## 6.3. Result

The developing relationship between the road network's elevation, slope, and terrain formation, and the distribution of traffic crashes was portrayed. The distribution of intersection zone traffic crashes in the city of Budapest from 2017-2021 was illustrated. Of the total traffic crash distribution around 5250 were registered at intersection segments of the road network. For more information see Appendix B, Figure B2.

Traffic crashes occur frequently and randomly. The formation of road traffic crash incidents and its interaction with elevation was depicted in Appendix B, Figure B23 below, which were created from ArcGIS using triangular irregular network (TIN). Based on geometry interval categorization the outcome the study attempted to classify the zone of elevation difference into five classes. Zones 1, 2, 3, 4 and 5 have a range of 96–110 meter, 110–114 meter, 114–127 meter, 127–185 meter, and 185–432 meter, respectively. Based on the nature of data and elevation difference, zone 1 of the research areas of the road network is a risky zone.

The nature of traffic crash incidents and their interactive relationship with slope were depicted in Appendix B, Figure B24. The slope illustrates how locational differences in height and distance from one place contribute to the likelihood of traffic crashes. This research attempted to categorize slope variation into five zones using the geometrical interval classification approach. Zones 1, 2, 3, 4 and 5 had a range of 89.98 to 90 degrees, 89.8 to 89.98 degree, 88.43 to 89.8 degree, 78.11 to 88.43 degree, and 0 to 78.11 degree, respectively.

Based on the above slope variation this study indicated that the majority of traffic crashes were reported in locations with a higher slope between the crash location or point. This showed that the vertical distance (elevation difference) between traffic crash location or point was higher than horizontal distance between traffic crash location or point. Therefore, there was a higher likelihood of crashes occurring at locations with steeper or cliff slopes where the slope approaches verticality. The study's conclusions demonstrated that the study area's slope varies from 78 to 90 degrees between the traffic crash location or point. Zone 1 and 2 of the intersection zones of the road network had a slope between the crash location or pointes to 90 degrees, with higher concentration of traffic crashes of the study area. Those intersection road segment of the research area's road networks were classified as risky regions. This suggested that the slope between the locations of the traffic crashes, and their relevance were corelated.

In addition to elevation difference and slope variation road traffic crashes are sensitive to structure of the topography. Along with slope variation and elevation difference, there was a substantial association between the site of traffic crashes and the terrain formation. Therefore, the formation of the terrain was one of the other likely reasons for traffic crashes that characterize the dangerous area of the road network. The interaction between terrain formation and road traffic crash occurrences is depicted in Appendix B, Figure B25.

The study used an indexed contour factor of 5m and a contour interval of 10m in order to produce telling outcomes. This study categorized topography according to the number of contours and their index using the geometrical interval classification method. This study found that the majority of traffic crashes occurred in flat terrain, based on the elevation, and created contour between the incident locations. This suggested that the majority of crashes were reported in locations with relatively little elevation difference between the riskiest zone and the study area's road network, which is flat terrain.

### 6.4. Discussion

Most road traffic crashes occur in locations with lower elevations and their minimum differences of the study area. Accordingly zone 1 of the research area's road network is a risky zone, as seen in Appendix B, Figure B23. This suggested that the frequency of traffic crashes and their significance were correlated with the road network's elevation. Zone 5 is a location/point where there have been traffic crashes; greater elevations have resulted in lesser numbers of crashes. The results of this investigation contradicted with a study conducted in the Qinghai-Tibet Plateau, which demonstrated that driver weariness increases with elevation [251]. It also contradicts with Chinese research that found, relative to the national rate, the number of traffic crashes at high elevations remained high [252]. The results of the study indicated that the rate, frequency, and distribution of traffic crashes were high at lower elevations.

The elevation of the road network, as shown, along with other contributing elements, plays a significant role in the occurrence of traffic crashes. The gradient between the site and location of traffic crash is directly correlated with the elevation difference. This suggested that the road network's dangerous zone was triggered by the elevation and slope between traffic crash location or point, which resulted in a substantial number of casualties.

Even though zones 1 and 2 may had relatively high slopes and traffic crash frequencies, the remaining zone slope exceeded 78 degrees, that indicates the elevation difference and horizontal distance between traffic crashes remained the same. On the other hand, in the research area, the rate of traffic crashes was higher at locations where the slope variation between crashes or point was large.

Slope between the locations of the traffic crashes, and their relevance were corelated. The results of this study validate the findings of Huiying Wen et al.'s 2023 study, which found that the combination of curve and slope significantly affects the severity of truck crashes [253]. It also concurred with the study that showed reckless driving on a slope can quickly result in collisions with other cars or pedestrians [254]. Additionally, this study maintains that the incidence of traffic crashes was substantially correlated with the slope length [255]. It also supports the study done by Song et al. 2011, that longitudinal slope section of the road was high frequency location of traffic crashes [256]. Furthermore, this study supported the idea that changing the slope from 1:2 to 1:7 could minimize rollover crashes by 27% [257]. According to this study, there was a higher distribution of traffic crashes at locations with steeper or cliff-slope between traffic crash location or point.

Terrain formation contradict with those of a 2017 study by Hui Zhao et al., which showed that the frequency of unintentional crashes in plateau regions rose quickly and progressively [258]. However, this data runs counter to a 2011 study by Rui Fu et al. that found a high rate of traffic crashes on routes that descend steep mountains [259]. Additionally, the results of this study, which indicated that hilly terrains cause 30% more collisions than level or flat terrains, are not supported by investigations conducted by MD Hasibul Islam et al. in 2019 [260]. Unlike other research, this study confirms the findings of Reg Soulyerette et al. (2001) that highway stretches with rolling and level terrain have greater crash rates [261]. Along with the aforementioned research, this document also disputes the findings of a 2016 study by Ravi Pradas regarding to national highways of India that traffic crash was high in hilly areas [262]. Overall, the study's findings demonstrated that in the study area flat terrain had a high in rate, distribution, and frequency of traffic crashes.

**Thesis Point 5**

I present a newly triangular irregular network (TIN) approach that is used to analysis center of the traffic crash attraction zone based on the topographic formation of the earth. Based on the concept of triangular irregular network (TIN), the impacts of the topographic formation of the earth on the occurrences of traffic crashes were analyzed at the macroscopic level of the road network. To define the center of the traffic crash attraction zone elevation difference, slope variation, and terrain formation between the traffic crash location/point was examined.

⋆ Related publications to this chapter: [284]

# Chapter 7

## 7. Micromobility Accidents Contributing Factors and Other Mishaps

### 7.1. Introduction

Transportation is the way a person is moved from one place to another using different mode and means [285, 286]. This study basically emphasis on land mode of transportation particularly on micromobility vehicles. Micromobility refer to a form of transport where lightweight vehicles can be owned for short-range travel intracity and operate at speeds typically below 25 km/h and driven by users personally [287, 288, 289]. It can use human power or electric power as an energy source. Human powered micromobility is active transportation such as biking, walking, or rolling [290, 291]. At the same time electric micromobility vehicles classified with a mass of no more than 350 kg and can't travel over 45 km/h [292, 293, 294]. Electric micromobility vehicles are electric-bikes, electric-scooters, electric skateboards, electric unicycle, one wheel electric-powered conveyances etc. [295, 296].

The sleek of micromobility is to make the city more accessible and allow people to explore their cities [297, 298, 299]. It offers new and powerful ways to help people meet their transportation needs [300, 301, 302]. In the past few years micromobility vehicles have become globally popular due to their efficiency and effective means of transport in terms of cost, emission and congestion reduction, accessibility, time savings, flexibility, reliability, parking relief and etc. [303, 304]. At most micromobility has potential to disrupt private vehicle [305].

Micromobility enhances transportation sustainability and assists in fulfilling the United Nations Sustainable Development Goals (SDGs). The SDGs report showed that micromobility could play a major role in achieving the SDGs through creating good health and well-being by lowering toxic gas emissions (greenhouse gases). Moreover, it plays a significant role by reducing projected traffic accidents [306].

Even though using micromobility had a lot of benefit, still it accounts for a higher proportion of injuries [307, 308, 309]. Like road transportation and its related accidents depicted in the above chapters of the dissertation, different factors cause traffic crashes. Like other means of land transportation, micromobility vehicles also play a significant role in the occurrences of accidents. The occurrence of accidents due to micromobility vehicles has its own causes and factors. The risk of injury for riders, pedestrians, and other vehicles on the road is a primary concern [310, 311, 312]. Even if studies showed that micromobility has a role in reducing projected traffic accidents, still micromobility-related accidents attract publicity [306, 313].

The detailed review of this paper was screening the global trend of micromobility related accidents and their causes, and concerned demography, examining market and service trend, and proposing remedial action. To undertake this review, the study used an explanatory review [28, 29]. Explanatory review is a research method that explores why something occurs when limited information is available [31]. A technique used to gain a deeper understanding of the underlying reasons for, causes of, and relationships behind a particular issues [32]. Exploratory research design can be defined as research conducted to investigate an undefined/unclear problem. It is carried out to gain a better understanding of the current problem [33, 34].

The exploratory research design focuses on collecting secondary or primary data in an unstructured format and interpreting it using informal procedures [314]. The primary research methods include survey/poll, interview, focus group, and observation. Whereas the secondary research methods contain online research, literature research and case study research [315]. This study basically emphasizes on secondary data accentuated on literature and case study.

Literature research is one of the most cost-effective methods due to information's available in libraries, online sources, and even commercial databases, newspapers, magazines, library books, documents from government agencies, specific topic related articles, literature, annual reports, published statistics from research organizations, and so on [33, 34]. The file extracted for the for this types of study were examined using content analysis [315]. Whereas case study research can assist a researcher in gathering more information by carefully analyzing existing cases that have encountered a similar problem [316].

### 7.2. Methodology

This study utilized exploratory research design and was reliant on secondary data gathered from various publications, journals, textbooks, and internet sources that focused on micromobility factors contributing to accidents, market and service trends, and related mishaps. Since this study emphasizes on secondary information accentuated on literature and case studies. Information available in open libraries, online sources, commercial databases, newspapers, magazines, documents from government agencies, specific topic-related articles, annual reports, and published data from research organizations were used as data sources. The files extracted for this study were examined content-wise and utilized accordingly.

To address the purpose of this review, both qualitative and quantitative literature data were used. Based on the convenience and content of documents, this review used enormous data sources to define micromobility accidents and related causes, micromobility vehicle market and service trends, micromobility accident-related demography, socio-economic, behavioral, and cultural factors that affect micromobility usage, and proposed remedial action. In addition to that, to support the overall concern of this study also tried to incorporate a case study that deals with trends of selected micromobility types and accidents, regional population size and micromobility market share, and facilities for micromobility and development.

### 7.3. Result

The global micromobility market is expected to be $340 billion by 2030 [317]. The global micromobility market accounted for USD 4.47 billion in 2024 and is expected to reach $15.17 billion by 2034 [318]. Other report indicated that the global micromobility market would be expected to be $186.2 billion in 2030. Reference to the base year of 2021 the growth rate of micromobility market would be 378.3% [319]. Asia-Pacific micromobility market value gathered more than $22.2 billion in 2021. In North America micromobility market growth will record more than 16% from 2022 to 2030 [320]. The African micromobility share market has experienced remarkable growth in recent years [321]. The increased focus on sustainability is a popular micromobility market trend that drives the industry demand [320].

In terms of service, in Europe micromobility increased in 2022 with 39% uptake compared to 2021 [322]. In US according to a recent National Association of City Transportation Officials (NACTO) report, users took 136 million trips in 2019 on shared micromobility systems, a 60% increase from 2018 [323]. In Asia-Pacific are growing rapidly because of the demand in countries such as China, India, and Japan [324]. Due to local urban and economic context in 2020 Africa is quite left behind shared micromobility development [325]. According to Kersten Heineke et al. 2020 consumer survey, the use of micromobility will increase by 9% for private micromobility and by 12% for shared micromobility compared to precrisis levels [326].

In US micromobility related injuries have trended upward average annual 23% since 2017 [327]. The study by University of California, Los Angeles (UCLA) shows ultimately 1,354 electric scooter-related injuries were found, accounting for 115 injuries per 1 million rides [328]. In Washington DC the report by the US Consumer Product Safety Commission (CPSC), injuries using e-scooters and e-bikes have jumped 70% over the past four years (2017-2020) [329]. Report in the US showed due to e-scooters, hoverboards and e-bikes emergency departments are treating an increase in injuries nationwide up 127% between 2017 and 2021. Particularly due to e-scooter injuries which increased by more than 500% from 2014 to 2021 [330, 331]. In 2022 in US e-scooters injuries continue to increase by 22% compared to 2021.

Fractures, followed by contusions/abrasions, are the two most common injuries that happen on the upper and lower limbs, as well as the head and neck of injured body [332, 333, 334].

In 2022 in Washington DC by US CPSC, around 41 fatalities associated with micromobility were reported in 2019. From stated death, majorities (26) occurred due to motor vehicle and 7 due to loss of user control [335]. In US in 2021, from total traffic fatality amounting to around 13.4% accounted for 985 deaths were related to bicyclists that was up 5% from deaths in 2020 [336]. The study done in New York city showed that in reference to 2018, in 2019 pedestrian and cyclist death increase by 7.9% and 180% accounted for 219 and 28 [337].

In Europe in 2022, the rate of e-scooter injuries fell by nearly 20% compared to 2021. At the same time the risk of fatality has decreased by 17.7% [322, 338]. From stated severe casualties over 80% of e-scooter rider deaths and 50% of trauma patients' injuries resulted from crashes with motor vehicle [339]. Since 2019 the risk of shared e-scooter incidents that require medical treatment has decreased by 60% in two years [340]. The study done in six (6) European country police-report accidents involving personal injuries in the average month increased by around 8.2% after shared e-scooters were introduced [341]. The study done in French in 2022, mortality associated with e-scooter crashes was 9.2%, compared with 10% for bicycles and 5.2% for motorbikes [342]. In some country like Norway, micromobility effects was negligible. In Oslo, in 2019 without a single cyclist or pedestrian fatality [337].

Micromobility injuries and mortality in China, India, Japan, and US overall upward trend. A higher risk of micromobility-related injuries was witnessed in China and the US in 2015-2019 [343]. In Australia for the 2017-18 financial year there were 177 pedestrian deaths and 45 cyclist deaths [337]. In Singapore, Khoo Teck Puat Hospital, micromobility related injuries increased yearly by 20%-30% [344]. In the Middle East, the United Arab Emirates (UAE) has become an epicenter and a high number of micromobility-related injuries [345].

### 7.3.1. Trends of selected micromobility type and accident

The study considers the two mostly affected continents by micromobility accidents (Europe and North America). Based on the maximum population size, usage of micromobility, and income level, the study tried to consider Germany and the United States (USA) for further review. From different types of micromobility, this study tried to visualize the most commonly used and type that causes accidents. Particularly, e-scooters and e-bikes were considered.

Table 30. E-scooter and e-bike accident in Germany and USA from 2021-2023

| | | | E-scooter | | | E-bike | | |
|---|---|---|---|---|---|---|---|---|
| **Country** | **Year** | **Population Size (Million)** | **Fatality** | **Injury** | **Total** | **Fatality** | **Injury** | **Total** |
| Germany | 2021 | 83.2 | 5 | 4882 | 4887 | 131 | 20000 | 20131 |
| | 2022 | 83.8 | 11 | 8700 | 8711 | 208 | 23600 | 23808 |
| | 2023 | 84.48 | 22 | 8400 | 8422 | 188 | 23900 | 24088 |
| USA | 2021 | 332 | 40 | 42200 | 42240 | 35 | 11800 | 11835 |
| | 2022 | 333.3 | 36 | 51700 | 51736 | 53 | 24400 | 24453 |
| | 2023 | 334.9 | 41 | 40400 | 40441 | 76 | 34200 | 34276 |

*Source:*[346, 347, 348, 349, 350, 351, 352, 353, 354][355, 356, 357]

As shown in Table 30, in the past three (3) years, both in the USA and Germany, the maximum number of fatalities registered due to e-scooters in 2023. Where is the maximum number of injuries registered in 2022. At the same time, the maximum number of fatalities was registered due to e-bikes in 2022.

Table 31. Population, e-scooters and e-bikes accident ratio of USA to Germany (2021-2023)

| | | USA / Germany Ratio | | | |
|---|---|---|---|---|---|
| | | **E-scooters** | | **E-bikes** | |
| **Year** | **Population** | **Fatality** | **Injury** | **Fatality** | **Injury** |
| 2021 | 3.990 | 8.000 | 8.644 | 0.267 | 0.590 |
| 2022 | 3.977 | 3.273 | 5.943 | 0.255 | 1.034 |
| 2023 | 3.990 | 1.864 | 4.810 | 0.404 | 1.431 |

Table 31 indicated that the population ratio between the USA and Germany was approximately four (4). From 2021-2023 the ratio of fatality due to e-scooters was approximately 8, 4, and 2. While, the ratio of injuries due to e-scooters was approximately 9, 6, and 5, respectively. On the contrary, in the past three (3) years from 2021-2023, the ratio of fatalities due to e-bikes was approximately 0.3, 0.3, and 0.5. At the same time, the ratio of injuries due to e-bikes was approximately 0.6, 1 and 1.5, respectively. This implied that in 2021 the number of injuries in the USA due to e-bikes was two times lower than injuries due to e-bikes in Germany. At the same time, the number of injuries in the USA due to e-bikes in 2022 was approximately equal to injuries due to e-bikes in Germany. In 2023, the number of injuries in the USA due to e-bikes was 50% higher than injuries due to e-bikes in Germany.

### 7.3.2. Micromobility vehicles related to accident causes and demography

In U.S the micromobility vehicles become safety hazards for many reasons, such as when they obstruct sidewalks, when parked, used by unexperienced rider, distracted, and when colliding with cars or pedestrians [358]. The study in Washington D.C showed that fires was a significant hazard across all micromobility devices [359, 360]. In addition to this, many of accidents occur due to the silent nature of e-scooters [361, 362]. Many micromobility riders do not wear helmet [363, 364] s. Lastly, many of these accidents occurred due to excessive speeding [365, 366]. Collisions with motor vehicles were the leading cause of death associated with e-bikes, accounting for 27 of the 53 reported deaths [330, 367]. Crashing into other fixed objects, struck pedestrians, brake issues, product-related issues were some of the defects that causes fatality in e-bike [330, 368]. According to US CPSC report more than 21% of victims due to micromobility related to visibility [358]. According to the study in Network city bike lanes, fewer than 2% were observed using a phone while moving, fewer than 9% of City Bike users were wearing a helmet [369]. Study done by Cakici 2022 experiencing falling from the e-scooter type of accidents, riding at nights, and riding shared e-scooters on sidewalks or bike lanes was found to be significant for affecting the severity level shared e-scooter crashes [370].

The study in Europe showed that a large proportion of users admit that they often ride on the pavement, even when this is not allowed [339]. Micromobility vehicle accident mostly registered during summer [341]. French National Trauma Registry, in 2022 from total 88 registered patients, 36.7% of e-scooter users had a blood alcohol content higher than the legal threshold (n = 84) and 22.5% wore a protective helmet (n = 32) [342]. The study in Singapore that recorded in hospital from November 2014 to October 2017 showed that most patients were injured from falling off their devices (83.4%, 83.7%, and 79.5% in the consecutive years), followed by collisions [344]. In Metropolitan area of Turkey most of the e-scooter-related accidents happen on weekdays and non-collision type [371].

According to the micromobility market forecast, the 35-54 age group is expected to hold the largest share from 2022 to 2030 [372]. That suggest a shared micromobility market with a split of 59% male and 40% female rider [373]. The study in Zurich, Switzerland suggested that shared micromobility users tend to be young male [374]. Neuron research suggests a higher proportion of women (60%) aged 16–34 years worldwide are now actively choosing to ride e-scooters compared to the same-aged male (52%) [373]. Nikolaus Lang et al. 2022 in Boston showed that young people (ages 16–29) and middle-aged people (ages 30–49) are the biggest users of micromobility and young males are the biggest users of e-scooters and e-mopeds [375].

Incidence related to micromobility in Europe faced population with an age of ≥14[376, 377]. Yudi Zhao et al. 2022 showed that people older than 45 years has higher risk of mortality in China, India, and the US in 2015-2019 [378]. Children less than 14 years of age make up 18% of the U.S. population but accounted for 36% of micromobility injuries [379, 380]. French trauma system shows regarding individuals using e-scooters admitted to major trauma centers, 83% were men, and the median age was 33 (IQR, 25-46) years. This was similar to motorbike users, whose median age was 31 (IQR, 23-44) years, while bicycle users were significantly older, with a median age of 48 (IQR, 30-61) years [342]. The study in Singapore that recorded in hospital from November 2014 to October 2017 showed that the mean age of patients increased from 28 (range, 5-89 old) in year 1 to 33 (range, 4-83 years). Most patients were males (61.8% in year 1, 76.8% in year 2, and 73.3% in year 3) [381]. The same study in Chinese (55.4% in year 1, 62.7% in year 2, and 65.5% in year 3), followed by Malays, Indians [344].

The study in Metropolitan area of Turkey showed that the majority of the micromobility victims were university students and male gender was slightly higher, and the mean age was 25.3±13.0 years [371]. The transport research board (TRB) report stated that experienced riders crashed less frequently than first time riders [358]. This implied not only age or sex, but experience is also mattering the occurrences of accident.

### 7.3.3. Micromobility accident related to socio-economic, behavioral, and cultural factors

Like other modes of transport, micromobility accidents are related to the socio-economic, behavioral, and cultural characteristics of micromobility users. Along with the increased usage of micromobility vehicles, vehicle-related accidents have also become an emerging global public health concern [382]. Social acceptance of micromobility vehicles, little knowledge about micromobility vehicles and usage, lack of proper infrastructure and regulation, poor vehicular design, and lack of understanding techniques and technologies are some of the common problems that intensify the micromobility accident [383] [384] [385, 386].

In line with the geometry factor, left-turn users often have higher tendencies to violate dedicated lanes, posing collision risks [387]. The speed analysis underscores potential conflicts and reduced handling capabilities for users breaching lane boundaries. Studie showed most micromobility accidents registered in urban areas with intersections or at cycle lanes with bad pavement conditions [388]. For instance, e-scooter-related injury crashes were more likely to occur riding on sidewalks and non-paved surfaces more frequently [382] [389].

In addition to violating lane usage, speed, pavement selection, and improper use of sidewalks, not wearing a helmet and riding for leisure, had the potential to result in severe outcomes [388]. Micromobility users are more often associated with risky and aberrant riding [390]. Micromobility users feel safer and comfortable riding on pavements away from parked or moving motorized traffic and on protected bicycle tracks [391]. Injuries soar among kids without helmets and drunken adults in a nation ill-suited for the surge in micromobility [392].

### 7.3.4. Remedial action to mitigate micromobility vehicles related accident

The severity of accident in micromobility related crashes depend on its causes [393, 394]. The study done in Washington D.C., US by CPSC stated to overcome micromobility fire related accident urged that consumer only use products that have been designed, manufactured, and certified for compliance with the applicable consensus safety standards and apply manufacturer’s instructions. The studies in the same area stated that collusion between micromobility and motor vehicle was hazards causes of accident [395, 396, 397]. To prevent this problem, it was advisable that always wear a bicycle helmet when riding to protect your head in a fall, slow down (speed) and stay aware of your surroundings, use the bell to alert others, always keep both hands on the e-scooter handlebars and keep items off the handlebars, never ride under the influence of drugs, only one person per scooter [395, 398].

In addition to that, the existing infrastructure was another cause of micromobility accident [399, 400]. To overcome infrastructure related causes, integrate micromobility system into the pre-existing infrastructure that reduce accident, emissions, congestion, and other factors [401, 402]. At the same time, the same goes to bike lanes, designing cycle superhighways for longer distances and higher speeds, providing safer routes for commuters [403, 404]. The other remedial action proposed by researcher to overcome micromobility accident is providing geofencing (No-Go) technology that enables cities to control where micromobility vehicles operate [405, 406, 407]. By setting boundaries, cities can enforce regulations and protect pedestrian areas by disabling/limiting the speed of micromobility devices in prohibited zones [408, 409]. The other option is introducing car free strategy [410, 411]. In addition to that, providing data-sharing platforms and application that generates real-time information other alternative used to minimize micro mobility traffic accident [412, 413].

### 7.3.5. Regional population size and micromobility market share

To visualize the global share micromobility, the study used 2023, the most recent data, as an input. Studies showed that the maximum level of micromobility was practiced in North America and the lowest was in Africa. North America is currently considered the leading micromobility market place globally, followed by Europe [306] [414]. Africa is quite left behind to shared micromobility development [415].

As shown in Appendix B, Figure B26, in 2023 the global population and the micromobility market share were not proportional. To clarify the above statement, this review tried to visualize the ratio of the micromobility market to the population size of regions, as shown in Appendix B, Figure B27.The ratio of micromobility market share to population size was high in North America (3.462), while the lowest was registered in Africa (0.054). Most developing nations with higher population sizes used a low level of micromobility. This is directly related to the income of the nation and infrastructure development used for micromobility operations.

### 7.3.6. Factors affect micromobility usage

Cost and culture of micromobility usage for lower-income residents are typically less inclined to use micromobility [417]. Income influences the usage of micromobility [418]. A study in Malaysia showed that only a small portion of the lower income users utilize micromobility [419]. In addition to that, lack of accessibility of micromobility for low-income society is another concern [420]. The spatial accessibility of disadvantaged communities, such as racial and ethnic minorities, low-income populations, and transit-dependent populations, showed that extreme inequity in access to micromobility services [421]. Even if shared micromobility is meeting low-income people's basic mobility needs, they are not being subsidized [422].

The cost of riding a micromobility continues to rise in numerous cities, posing a threat to affordability [423, 424]. Lack of infrastructure and poor quality is another factor affecting micromobility usage [425]. Environmental factors, such as temperature and precipitation, and demographic characteristics, including age and resident status, are also another issue [426]. The other factor of micromobility is asset regulation; it’s an issue of where to park the vehicles [427]. The above studies outcome is supported by the reports done by [306] [414] [415].

## 7.4. Discussion

Globally, compared to the number of automotive growth rates (3.01%), the micromobility growth rate was 5.4 times that of automobiles [441]. This showed that the market growth rate of micromobility vehicles is the most dominant in the automotive industry. So, since the usage of micromobility vehicles is in a frightening condition, in the near future, micromobility will be the most universal, attractive means of transportation. Even if the rate of micromobility growth is in an alarming, the number of accidents registered annually was a disgusting issue.

Even if the population size of the US is relatively high, micromobility users died due to e-scooters was also high. While compared with Germany's population, the gross number of injuries both due to e-scooters and e-bikes in the US was higher than in Germany; in 2021, 2022, and 2023, the number of fatalities in the US due to e-scooters was 8, 3, and 2 times more than fatalities in Germany. At the same time, the number of injuries in the US due to e-scooters was 9, 6, and 5 times more than injuries due to e-scooters in Germany. Meanwhile, the number of fatalities in the US due to e-bikes was 3, 3, and 2 times lower than fatalities due to e-bikes in Germany. Even though the above discussion doesn’t represent micromobility accidents happening due to e-scooters and e-bikes in the two (2) different regions. The above analysis shows how different types of micromobility vehicles have different impacts on the occurrences of accidents in different countries/regions.

The trend of micromobility accidents and their causes are unidentified in developing countries. In most developed countries, accidents happen due to micromobility vehicles caused by technical problems that cause fire, riders not using helmets, collisions with other vehicles, pedestrians, and fixed objects, the nature of the vehicles by themselves, visibility, and seasonal variation. Unlike other modes of transportation, speed has little bearing on the causes of micromobility accidents. Even if the preference for micromobility gradually increases as a means of transportation, the age and sex of micromobility users contest, and that causes the occurrence of accidents. Still, the population with an age less than 14 suffered from a micromobility accident. Particularly, male riders suffer micromobility accidents due to different factors. For instance, male' riders often valued speed and handling, and most women prioritized safety to a greater extent and were unwilling to negotiate traffic [373] [442].

Even if the rate of injuries for men is comparatively high due to micromobility vehicles, women also suffer from the same problem at a younger age. The older population, aged 45 and above, mostly experienced fatality. This illustrates that, like other forms of transportation, particularly males and the population in a productive age group, suffer accidents due to micromobility vehicles. To overcome this problem using designed, manufactured, and certified micromobility devices, wearing a helmet, slowing down while riding, being aware of the surroundings, using an alert bell, keeping hands in positions, never riding under the influence of drugs, integrating a micromobility system into the pre-existing infrastructure, constructing cycling superhighways, providing a safer route, geofencing, setting boundaries, data-sharing platforms and applications, and a car-free strategy were common attributes.

In different places, micromobility was used in different amounts, types, and sizes, except in Antarctica. The coverage of micromobility as a means of transport in those regions varies accordingly. Of those highly populated regions, there was a low level of micromobility market share and service trend. This illustrates that the region with a high population size has a low possibility of using micromobility that basically depends on the income. Income level, accessibility, infrastructure, environment, etc., are some of the common challenges that affect the usage of micromobility. The region with high income had a higher possibility of using micromobility. At most, the price of micromobility vehicles is related to the income of society. The level of services is also related to the infrastructure quality, accessibility, income, etc. This is directly or indirectly related to the occurrences of accident.

**Thesis 6**

I assessed the global market and service trend of micromobility. I present a micromobility-related accident and its causes. Factors affecting micromobility usage are also illustrated. The demography of the global population affected by micromobility vehicles is explored. The impacts of income on micromobility usage and related issues were examined. To avoid micromobility accidents, remedial action based on the causes was indicated. In addition to that, micromobility vehicles-related socio-economic, behavioral, and cultural factors also reflected.

⋆ Related publications to this chapter: [443]

# Chapter 8

## 8. Application of Scientific Outcomes and Limitation

### 8.1. The application of the scientific findings

The significance of long-term effects in policymaking and applications of each thesis point findings are presented as shown in the following subsections. The finding of each thesis point had a benefit to policymakers, road geometry designers, and stakeholders in developing strategies that are used to minimize road traffic crash occurrences.

#### a. The applications of the findings of Thesis Point 1

The findings of this thesis point provide insights into the impacts of road geometric formation on traffic crash occurrences. It confirmed that traffic crash occurrence was deliberately related to the geometry formation of the road. Particularly, this thesis points forward to an emphasis on motorways, straight alignment, two-way road formation and its carriageways, and a flawless one-lane that encourages the occurrence of traffic crashes and their outcomes that bring traffic safety by minimizing traffic crashes and accidents.

In the study area, even though a large number of traffic crashes were registered on the straight segment of the road network, the severity level was high at the horizontal curved segment of the road network. Researchers, policymakers, and stakeholders must emphasize the curved road geometry formation of the road network to minimize the number of traffic accidents. At most, the finding indicated that horizontally curved roads have a positive and strong relationship with road traffic fatalities. The primary reasons for the occurrences of a road traffic crash at an intersection, horizontal curve, and straight road geometry formation were the improper use of traffic signs, pavement condition, and stopping sight distance problems, respectively. The regression model indicated that light conditions, collision type, road geometry, and speed had a significant effect on traffic accidents.

This above finding had a strong remark on the impacts of road geometry formation that used to manage traffic crash occurrences that forced the stakeholders to develop and implement traffic crash policies concerning design and manuals, traffic safety rule and regulation standards, and policy. In the future, the trend of traffic crash occurrences and their outcomes (accidents) will be minimized by undertaking proper remedial action concerning the design, construction, and maintenance of road infrastructure, particularly the geometry formation of the road network. Road geometry designers can get data on their traffic safety concern on the reduction of traffic crashes and outcomes, which advances road safety.

#### b. The applications of the findings of Thesis Point 2

This thesis is used to identify dangerous sections of road segments used to identify proper causes and minimize road traffic crash occurrences. As the findings in point 1 prevailed, road geometry had an impact on traffic crash occurrences. It confirmed that traffic crash occurrence was deliberately related to the intersection segment (crossroad) of the road geometry.

Mostly the density of traffic crashes defines the black spot location of the road network. Point density estimation, kernel density estimation, and multipoint-to-multipoint distance proximity are used to identify dangerous road sections by identifying the dense location and proximity between traffic crashes at a macroscopic level. In comparison, density estimation highly recommended to the stakeholders to identify blackspot location.

Based on this density estimation approach, this study discovered that intersection zones with an enormous number of legs are more likely to experience high traffic crashes. In addition to that, multipoint-to-multipoint distance proximity plays a significant role in identifying the sever road segment based on the mean and skewness, mode, and mean-mode variation. So, road segments with multiple legs had a positive and strong impact on the occurrences of traffic crashes. The newly approached multipoint-to-multipoint had decisive power in identifying the road section highly severed based on the distance proximity between traffic crashes.

In the study area, even though a large number of traffic crashes were registered on the intersection part of the road network, the severity level was high at the road segment with ≥ four legs and above. Researchers, policymakers, and stakeholders must emphasize the point density estimation approach to analyze the black spot location of the road network at a macroscopic level that is used to identify highly dangerous road sections used to minimize traffic crashes by identifying the proper causes and factors.

This above finding had a strong remark on road geometry formation and its severity level that was used to manage traffic crash occurrences by motivating the stakeholders to develop and implement traffic crash control mechanisms and policies. In the future, the trend of traffic crash occurrences and their outcomes (accidents) will be minimized by undertaking proper mechanisms used to identify dangerous road segments. By implementing the stated approach, the safety management team plays significant roles in the reduction of traffic crashes.

### c. The applications of the findings of Thesis Point 3

This thesis point used to analyze the severity level of road segments based on the number of traffic crashes, traffic accidents, crash costs, and other determinant factors. Based on the existing severity level analysis approach, this thesis points to a newly alternative approach that incorporates the number of traffic crashes, traffic accidents, and crash costs, plus other determinant factors that use combined parameters utilizing relative percentage share. Based on the geometric formation of the study area road network, the findings of this thesis revealed that the road geometry had a correlation with the traffic crash occurrences. Based on the existing and an alternative severity indexing approach, even though the Bend road was a severe segment, greater than 60% of traffic crashes were registered on the straight road.

Compared to the existing severity level analysis approach, utilizing the relative percentage share of road traffic crashes, accidents, and crash costs in a combined approach had a significant impact on defining the severity level. It confirmed that traffic crash occurrence was deliberately related to the formation of the road segments. So, stakeholders must utilize the stated alternative approaches to analyze road segment severity level.

Even though the weight of the severity level of the road segment varies between the existing and an alternative approach, this study discovered that the bend road had a higher severity level for both approaches. As a result, stakeholders must emphasize the bend in the road to minimize the severity level of the road segments. In comparison to the existing and an alternative approach, the severity level analysis way, an alternative approach showed that the severity level of straight roads was higher than cross roads, and the severity value of cross roads was reduced.

In the study area, due to traffic crashes, the country lost on average around 0.2% of GDP annually. Researchers, policymakers, and stakeholders must emphasize the bend road segment to minimize traffic crashes, related accidents, and economic losses.

The above finding revealed that an alternative approach had a strong remark on road segment severity level analysis that was used to manage traffic crash occurrences. In the future, the trend of traffic crash occurrences and their outcomes (accidents) will be minimized by undertaking proper mechanisms/methods used to assess the severity level of the road segment. By implementing the stated approaches, the road safety management team would play significant roles in the reduction of traffic crashes and outcomes.

### d. The applications of the findings of Thesis Point 4

This thesis point used to analyze the severity level of road segments. Based on the thesis indicated above, the higher severity level was registered on the bend road due to the high speed and roughness of the road pavement. The theoretical concept and the practical analysis of speed across the design period of the road varied. As a result, based on the theoretical background of design speed, the desired speed across the design period for the bend road was analyzed using a novel empirical model derived from the existing design speed formula. Traffic crash occurrences are deliberately related to the existing vehicles maneuver speed.

The newly developed empirical model for desired speed analysis is used to analyze speed as the roughness of the bend road varies across the design period of the road. Even though the existing concept of speed is defined based on the minimum radius of curvature, maximum super elevation, and friction factor of the pavement, that design speed remains constant across the design period of the road. This conceptual framework of seep was not fictional due to the variation in roughness of the road that causes a change in the friction factor. As a result, the newly developed formula is used to analyze the speed.

To overcome traffic crash-related problems that happen due to the speed of maneuvers, this thesis point will bring significant outcomes in minimizing traffic crashes. The newly introduced empirical model will improve the safety of the road by optimizing speed usage according to the existing condition of the road pavement roughness. Compared to the existing conceptual framework in speed analysis, the newly introduced empirical model has a significant impact on defining operating speed based on the design period of the road, except at the opening phase of the project. So, stakeholders must utilize the stated alternative approaches to analysis vehicles maneuver speed that minimize the occurrences of traffic crashes.

The above finding revealed that a novel speed analysis approach had a strong remark on road segment severity level analysis that was used to manage or minimize traffic crash occurrences. In the future, the trend of traffic crash occurrences and their outcomes (accidents) will be minimized by undertaking proper mechanisms/methods used to analyze the operating speed based on the current condition of the road pavement roughness. By implementing the stated empirical formula, the road safety supervision team/stakeholders would play significant roles in the reduction of traffic crashes and outcomes.

### e. The applications of the findings of Thesis Point 5

The output of this thesis point had a benefit to traffic safety policymakers in developing strategies that consider the topographic formation and the occurrences of road traffic crashes. In most dangerous road section analysis approaches, the topographic formation of the earth was not considered in the occurrences of traffic crashes. Based on the thesis indicated above, the triangular irregular network (TIN) is more powerful to detect dangerous road sections based on the elevation difference, slope variation, and terrain formation between crash locations.

Even though a triangular irregular network was used to analyze spatial data using GIS techniques, the application of this approach is also applicable as a mechanism to analyze dangerous zones of the road network that lead to more traffic crash occurrences. As a result, this approach was used as a novel method to analyze black spot locations of the road network based on the topographic formation of the road based on elevation difference, slope variation, and terrain formation of the road network. The applicability of this method basically depends on spatial data formation that uses vector data (x, y, z).

Based on the analysis and the outcome of the study, traffic crash occurrences are deliberately related to the existing topographic formation of the earth. As indicated above, even though road geometry formation had a significant impact on the occurrence of traffic crashes, topographic formation of the road had a significant influence on the occurrences of traffic crashes. To detect the black spot location and severity level of the road segment using a triangular irregular network (TIN) plays a significant role at the macroscopic level of the road network.

To overcome traffic crash-related problems that happen due to elevation differences, slope variations, and terrain formations, this thesis point will bring significant outcomes in minimizing traffic crash occurrences and their outcomes. The newly introduced approach will improve the safety of roads by optimizing topographic formation and its usage. So, stakeholders must utilize the stated substitute approaches to analyze blackspot locations that are used to overcome the occurrences of traffic crashes. By implementing the triangular irregular network (TIN), it is easy for stakeholders to identify locations highly affected by traffic crashes and use it to undertake remedial action to minimize traffic crash occurrences.

### f. The applications of the findings of Thesis Point 6

The finding of this thesis point had a benefit to traffic safety policymakers in developing strategies that consider the abrupt growth of micromobility vehicles and related accidents. In most policy and strategy markets, the service trend of micromobility vehicles and related problems was not in consideration, particularly in highly populated and developing regions. Based on this thesis point, the concerned body will understand the market and service trend of micromobility vehicles, factors that deter the accessibility of micromobility vehicles and their causes for accidents that minimize losses of life and injuries, and economic costs.

Based on the analysis and the outcome of the study, micromobility accidents are deliberately associated with technical problems of micromobility vehicles that cause fires, riders not using helmets, collisions with other vehicles, pedestrians, and fixed objects, the nature of the vehicles by themselves, visibility, and seasonal variation. Identifying the cause of micromobility accidents is one step towards minimizing related problems. If the group concerned emphasizes the stated problem and undertakes proper action, the situation will degrade.

The reviewed information and the remedial action assessed will improve the safety of micromobility vehicles. So, stakeholders must understand the probable factors that cause micromobility accidents that are helpful in strategy and policy implementation that maximizes traffic safety. By understanding the ultimate growth of micromobility and its accidents, the stakeholder must use this review finding as an input to commence a solution that minimizes micromobility accidents.

## 8.2. Limitation

In **thesis point 1**, the study only focuses on road geometry formation, particularly the road alignment (straight road, horizontal curved road, and crossroad). Other geometry formation parameters, pavement structures, and other related infrastructure formation impacts on traffic crashes were not analyzed. Besides, the study uses data that covers the city of Budapest as a sample to define the impacts. Rather than analyzing the impacts of road geometry formation, the remedial actions were not proposed.

In case of **thesis point 2**: even though different types and approaches used to analysis blackspot at based on density of traffic crashes the study only focuses on point density estimation (PDE) and kernel density estimation (KDE) approach and their comparative implication in identifying center of crash attraction. Besides, the study uses data that covers the city of Budapest as a sample to define the comparative implication of point density estimation and kernel density estimation in defining the black spot location of the road network. At most, the study only focuses on traffic crash data registered at the intersection zone (crossroad) to define the comparative implication of the stated density estimation approach. Based on the concept of minimum spacing between intersections of the road network, the study used the minimum spacing between intersections to define the radius of the output cell size (0.001093 degrees) and its neighborhood radius (0.002 degrees). Even though a rectangular sampling approach was recommended due to overlapping delinquency between raster data cells, the study considered a square data sampling approach to overcome this problem. In addition to that, even though a different approach was used to analyze the distance between points, this study uses the Pythagorean distance (Euclidean distance) formula to measure the proximity between traffic crash locations.

In **thesis point 3**, the study considered the combined effects of traffic crashes, traffic accidents, and crash costs to analyze severity levels. Even though different other determinant factors are used to analyze the severity level of road segments, this study only focuses on the impacts of traffic crashes, traffic accidents, and crash costs in analyzing the severity level of road segments. The stated alternative approach basically emphasizes the relative percentage share of traffic crashes, accidents, and crash costs, apart from the number or amount or the monetary value. The relative percentage share of traffic crashes, accidents, and crash costs was different except in the condition where the traffic accident type was single and property damage only (PDO) across the data review period of the road segment. An alternative severity level analysis approach works for road segments that are affected by any traffic crashes except segments with single traffic crashes that resulted in a single traffic accident (property damage only) for a given data review period.

In the case of **thesis point 4**, the study considered the variation in roughness of the road pavement considered as a cause in the variation of speed that leads to traffic crashes. To define the desired operating speed across the design period of the road, the study proposed that the side friction factor has significant impacts. Based on the nature of the data, even though AASHTO recommendations and other scientific findings and manuals define the design speed, the side friction factor gradually changed due to the change in roughness of the road surface and tire block. Based on the mathematical model of minimum radius analysis, circumstance design speed and side friction factor are inversely related. But, in practice, the desired speed and design speed remain constant across the design period of the road. To overcome this problem, the study frames a new empirical model that is used to analyze desired speed with the following limitations. Limitation 1: When the vehicle is in a dynamic state and the coefficient of side friction is decreasing, the speed of the vehicle increases. Under this condition, there is no skid resistance. This implies that fmax ~ 0, DS ~ maximum. For further analysis of this condition, the study considered the movement of a vehicle in a static state. As a result, this study recommends that the desired operating speed at a zero-side friction factor is unreliable. Limitation 2: a critical zone at which the coefficient of side friction gradually increases with a condition where desired operating speed increases and ultimately reaches a maximum at a critical point and starts to decline. Limitation 3: at which coefficient of side friction gradually increases with a condition where desired operating speed gradually decreases.

In **thesis point 5**, the study used triangular irregular networks (TINs) that were often generated using the triangulation of a point coordinate (x, y, z). Spatial data was used to analyze traffic crash redundancy and its topographic formations. It used intersection zone data that covers the city of Budapest as a sample to define the impact of topographic formation on traffic crash occurrences. Furthermore, the TIN model is insensitive to changing data scales; use continuous data to represent discontinuities in a surface. Like other blackspot analysis approaches, assessing and simulating traffic crashes and determining the level, zone of the road network at a macroscopic level a triangular irregular network (TIN) is a more appropriate method using an approach using GIS techniques.

In **thesis point 6**, Due to insufficient data and information on micromobility vehicle accidents, the study used secondary/literature-reviewed data as a means. The reliability and quality of data and information used in this thesis point were not examined. The result of this study is not an accurate sign of micromobility vehicles-related accidents, service and market trends, and other related mishaps. Because of insufficient data, studies, and information about micromobility vehicles, the study prefers an explanatory review to collect thoughtful evidence and summarize the outcome. Like other modes of transportation, micromobility vehicles-related issues need emphasis by stakeholders to have reliable data and information.

# Chapter 9

## 9. Scope of Future Works and Conclusion

### 9.1. Scope of future works

In thesis point 1, the impact of road geometry formation on traffic crashes postulated that most road traffic crashes happen due to the improper use of road traffic signs. In the near future if the stakeholders particularly, driver is well trained on how to use road traffic control devices and respect rules and regulations the tendency of traffic crash occurrences unconditionally reduced. In addition to that, to overcome this problem, further investigation is needed to understand the reason behind why road users were not properly using traffic control devices, and the stakeholders must emphasize on determinant factors to mitigate the problem. Since the study depicted that intersection road geometry formation has a strong and positive impact on the occurrences of fatal road traffic accidents in the near future, it needs spatial concern in defining the probable cause and factors related to the intersection zone of the study area.

In case of thesis point 2, comparatively using point density estimation (PDE) is a highly recommended approach to analysis black spot locations that consider the spacing between traffic crash points and the number of traffic crash points. Since this study has used 2D vector data to analysis black spot location. It is advisable to use a distance proximity approach that accounts for vector data (x, y, z) and will consider the 3D version that is used to visualize both horizontal and vertical distance proximity between traffic crash locations (points). Further investigation of factors accounted for the occurrences of traffic crashes for defined black spot locations having a significant impact on the reduction of traffic crashes. So, it is advisable to consider the black spot location of the road network and its severity level both in space and number that utilize horizontal and vertical proximity levels. To minimize the road traffic crashes, it is advisable to check their performance of the locations and propose remedial action. In addition to that, it is better to analyze the severity level of those locations for betterment.

In thesis point 3, based on an alternative approach, even though the number of traffic crashes, traffic accidents, and crash cost indicators of severity level have a significant effect in defining the severity level of road segments/networks, incorporating other determinant factors has a significant impact in defining the severity level of road networks. Having more traffic crashes/accidents/crash costs doesn't describe the severity level unless the compiled effects, and other determinant factors are incorporated to analyze the severity level. At most, the severity level is advanced to monetary value.

In the case of thesis point 4 in the study area, the quality of the road and speed were the most related causes for the occurrences of traffic crashes and related outcomes. Checking the performance of pavement surfaces annually is used to define the desired speed that minimizes traffic crash occurrences. Since the data was collected from literature review to have a better empirical model and result in sight, data from other simulating software is preferable. Since the study considered a horizontal curved road, it is better to consider the gradual variation of road surface roughness across the design period of the road to define the desired speed at the straight and crossroad of the road network. To check the significance of the novel empirical model that was used to analysis desired speed, the maximum superelevation of 8% and recommended minimum radius of curvature and various side friction factors depicted were used. It's better to change the maximum superelevation for better understanding and development of other empirical models of desired speed.

In thesis point 5 the application of triangular irregular network (TIN) plays a significant role in defining dangerous road section based on the elevation difference, slope variation and terrain formation between traffic crash locations. In addition to the topographic formation of the road, it's better to incorporate the road geometry formation, pavement condition, and other related parameters to define the dangerous road section using triangular irregular networks. This research suggests that the triangular irregular network (TIN) is the most effective substitute for defining the dangerous zone of the road network at the site of a traffic crash at a macroscopic level, where the data set includes the proper vector data (coordinates (x, y, z)).

In thesis point 6, the significance of micromobility vehicle usage, its accidents, and related mishaps was apprehended by the researcher in a condensed way to create common understanding and deep investigation in developing and highly dense population regions. Since the growth rate and its market and service trend are alarming, it is a technical area for researchers to have scientific evidence that is used to minimize the number of micromobility vehicle accidents and severity levels. Even though there is a shortage of information and a research gap, it's a marked area that the geometry formation, pavement condition, and other infrastructure used for micromobility maneuver will be counseled as an area of future study. This review suggested that even though using micromobility vehicles is a means of transport in most urban areas, the level of accidents and mostly injuries was the most unpredictable concern. So, this review envisages that further study is needed to overcome this problem.

## 9.2. Conclusion

The overall conclusion is drawn by incorporating the findings of the six (6) thesis points. The research aims to address the impacts of road geometry and topographic formation effects on traffic crash center of attraction, severity level, and economic losses. In addition to that, micromobility vehicle accidents and related mishaps were reviewed. In the impacts of road geometry formation, **Thesis point 1** revealed road geometry formation has an impact on the occurrences of road traffic crashes. To further analyze the study, it used the city of Budapest's source of data. For further investigation, multicollinearity tests, p-value, and overdispersion were undertaken to analyze the significance of the data. This study considers a variable that had a correlation coefficient less than 80%. The maximum variable similarity was observed between light conditions and hourly distribution with a value of 28.9%. As a result, all variables were used for analysis and modeling.

Both dependent and independent variables for model selection were undertaken with an overdispersion test by comparing the mean and variance. The analysis indicated that more than 80% of the data was not over dispersed. As a result, multinomial logistic regression was selected for the analysis of the determinant factor. In addition, the p-value was used to determine the level of accuracy. The variable used for model development was considered with a p-value of 0.05. This means the accuracy level of the analysis was more than 95%.

To check the significance of the Multilayer Perceptron Artificial Neural Network analysis (MNPANN), the percentage of incorrect predictions both for testing and training was analyzed. The analysis indicated that the percentage of incorrect predictions was less than 25%, which shows the accuracy level of the model was 75% and above. So, the model was a good fit. The higher frequency of road traffic crashes are observed in straight road geometry formations that account for around 63.7%. Higher severity was observed on bend road geometry formation.

The Multinomial Logistic (MNL) Regression model output indicated that light conditions, collision type, alcohol consumption, speed limit, and road geometry formation have significant impacts on the occurrences of road traffic crashes. In terms of collisions, a high number of road traffic deaths and injuries were registered due to collisions between vehicles and vehicles with pedestrians. Vehicle collisions (especially rear-end collisions) play an important role in the occurrence of road traffic crashes at straight and intersection parts of the road geometry.

According to the Multilayer Perceptron Artificial Neural Network (MLP-ANN), road horizontal curved geometry has a positive and significant relationship with road traffic fatalities. The intersection and horizontal curve had positive interactions and a strong impact on the occurrences of slight injuries. Concomitantly, the one-lane road has positive and strong interaction with road traffic and causes serious and slight injuries. Meanwhile, two-lane roads had a positive and strong interaction with road traffic and slight injuries. In this case, one-lane and three-lane roads have a positive impact on the number of fatalities on the road.

A high number of road traffic crashes were registered due to the improper use of traffic control devices. The primary reasons for the occurrences of a road traffic crash at an intersection, horizontal curve, and straight road geometry formation were the improper use of road traffic signs, pavement condition, and stopping sight distance problems, respectively. This implied that in a given road network, the occurrences of road traffic crashes depend on the geometry formation. In this study, the driver played a vital role in the occurrences of traffic crashes, accounting for more than 82.6%. This shows that at most the driver was responsible for the occurrences of road traffic crashes in all of the road geometry formations.

**Thesis Point 1**

I developed an accident prediction model utilizing multinomial logistic regression (MNLR). Using multilayer perceptron-artificial neural network (MLP-ANN), the relationship between road geometry formation and traffic crash occurrences was analyzed. In addition to that, the impacts of road geometry formation on traffic crash occurrences and other determinant factors were identified.

Since relative to other forms of road geometry, intersections have positive and strong impacts on the occurrences of slight injuries, and the maximum number of road traffic accidents registered in the study area was slight injuries. **Thesis point 2** was initiated to investigate an alternative density estimation and black spot identification approach at the macroscopic level of a road network. This study rasterizes road traffic crash scenes using point density estimation (PDE) and kernel density estimation (KDE) to identify intersection zone road network blackspot locations at the macroscopic level using the ArcGIS tool.

Based on the above-stated parameter, five blackspot locations were identified at intersection zones of the road network in Budapest as depicted in Appendix B, Figure B17. In the stated intersection zone with a high number of legs, there is a concordance with a high number of road traffic crashes and their outcomes. This depicts that road geometric formation has its own significant influence on the occurrences of traffic crashes and their severity level.

From the stated density estimation approach, point density estimation was preferable for identifying highly dense black spot locations in a specified road network. As a result, it is highly recommended that a point density estimation approach be used to identify the location of extremely high road traffic crashes for a given road network.

**Thesis Point 2**

I deliberated the proper method used to analysis center of traffic crash attraction comparatively using point and kernel density estimation. I proposed a new concept used to define the raster data cell to analysis traffic crashes at the center of attraction based on the minimum spacing between the intersection zone to outline the bandwidth/radius of the raster cell size. To figure it out, the density-based blackspot location of the intersection zone of the road network was analyzed for the study area. Using a multipoint-to-multipoint distance proximity approach as a new tactic that exploited to analysis traffic crashes in the attraction zone using mean, mode, mean-mode variation, and skewness at the macroscopic level of the road network. Based on the distance proximity concept between the traffic crash location/point, a highly severe road geometry formation was analyzed.

Ther tendency of slight injury was high at the intersection road, the severity level of the road segment basically depends on the number of fatalities in a given road segment. **Thesis point 3** deals with the road geometry formation provisionally correlated with the occurrence of a traffic crash and its severity level. To implement the analysis, this study initiated an alternative that was used to analyze severity level based on the combined approach between the severity level indicator variables using relative percentage share principle in comparative inference with the existing severity indexing approach. As an input, the study used 5-year (2017–2021) Budapest city road network traffic crash data, the annual inflation rate, and the GDP of Hungary.

In the study area, most traffic crashes, traffic accidents, and traffic crash costs were recorded on straight segments of the road network. But, based on equations in Table 1 above, the higher severity level indicated on the bend road (a curved road) is more severe than other road segments. This depicts that having a high number of traffic crashes, accidents, or crash costs doesn't outline the maximum severity level, and vice versa.

In the study area, due to traffic crashes in the past 5 years, around 1.4 billion dollars were lost. Annually, approximately 0.3 billion dollars were lost. This depicted that Hungary lost on average, around 0.2% of its GDP annually due to traffic crashes registered in Budapest. In terms of geometry formation, the maximum crash cost was registered due to an accident recorded on a straight road segment of the road network. Of the total crash costs, around 0.9 billion dollars were lost due to traffic crashes that happened in straight road segments.

Even though different approaches were used to analyze the severity level, most of the analysis approaches depend on the number of traffic crashes and accidents, crash costs, traffic volume, etc. This study identified that using numbers (amount) and costs in monetary value with limited variables had uncertainty in defining the severity level. As a result, this study used the relative percentage share of traffic crashes, accidents, and crash costs to analyze the severity level of a given road segment as a basic severity level demonstrating variables.

Based on the overall assumption, Equations 27, 28, 30 & 31 were proposed as an alternative to analyze the severity level of the road segments based on the existing Equations A1 & A2 depicted in Table 1. Even though alternative approaches agreed with this result, the consequence of combined effects had a significant change in severity value and level. Based on this, an alternative approach for Equation A1 of Table 1 showed that a straight road was more severe than a crossroad. In addition to that, in all an alternative approach, the severity value and severity score of crossroads significantly reduced when compared to bend road and straight road segments.

Based on multipoint-to-multipoint distance proximity result indicated that the severity level of crossroad, straight road, bend road and cross road was high based on mean, mode, mean-mode variation and skewness respectively.

In general, having a higher traffic crash, traffic accident, and traffic crash cost doesn't describe the severity level of the road segment, and vice versa. Therefore, analyzing and considering the combined effects had significant implications for defining the severity level of the road segment. In this study, the consequence of poor pavement quality and over speeding makes the bend road more severe.

**Thesis Point 3**

I established a newly empirical model that was used to analysis road network severity level based on the traffic crashes, traffic accidents, crash costs, other determinant factors, and their combined effect. The comparative implication of the newly and existing severity level analysis approach was properly examined. Based on the newly and existing approach of the severity value of the road network, its severity level was analyzed based on the geometry formation.

In addition to the severity level of road segment pavement quality and design speed, it was enabled under **Thesis point 4**, which emphasizes defining the speed across the design period of the road. Road surface roughness, type, block, and condition of tire as a basis in defining the side friction factor that determines the comfort of road users and vehicular movement. The empirical model used to analysis minimum radius of horizontal curved road geometry used by engineers shown in Equation 32 above basically considers the constant maximum side friction factor, maximum superelevation, and design speed as basic inputs across the design period. This equation developed by the American Association of State Highway and Transportation Officials (AASHTO) assumes that the side friction factor of the road remains constant and the same as the opening phase of the road across the design period. In addition to that, the empirical model depicted in Equation 1 above showed that vehicular speed has a direct relation to the side friction factor. This assumption has its own drawback in defining the desired operating speed across the design period of the road.

In general, this study directed that the desired operating speed of a vehicle depends on the side friction factor (coefficient of friction) across the design period of the road. Equation 34 stated above is functional at a maximum superelevation, minimum radius of curvature with a referenced side friction factor, which gradually changed across the design period at the horizontal curvature of the road, except at the opening phase of the road.

**Thesis Point 4**

I affirm a newly empirical model that is used to analysis desired operating speed at a bend (horizontal curved) road. The impacts of pavement surface roughness on desired operating speed across the design period of the road were examined. To illustrate the empirical model's applicability, the desired operating speed at a constant minimum radius, constant maximum superelevation, and variation in the maximum side friction factor (coefficient of side friction) was analyzed.

In addition to the geometric formation of the road other aspect also contributes to the creation of a risky zone on the road network, there is the location of traffic crashes. The aim of **Thesis point 5** was investigating dangerous road networks and their topographic formation that was affected by traffic crashes using a triangular irregular network (TIN). In order to address these objectives, the study sought to examine the interactive effects of elevation and its difference, slope variation, and terrain formation between traffic crash locations of the road network. The distribution and frequency of traffic crashes were related to the existing formation of the earth structure (topographic formation). Elevation difference, slope variation, and terrain formation significantly correlated with road traffic crashes and their causation. In the study area, the majority of traffic crashes were reported in locations or points with lower elevation and their difference, steeper or cliff slopes, and flat terrain formations. Therefore, the study suggests that the formation of the road network and its location have an interaction with the occurrence of road traffic crashes and their causality.

**Thesis Point 5**

I present a newly triangular irregular network (TIN) approach that is used to analysis center of the traffic crash attraction zone based on the topographic formation of the earth. Based on the concept of triangular irregular network (TIN), the impacts of the topographic formation of the earth on the occurrences of traffic crashes were analyzed at the macroscopic level of the road network. To define the center of the traffic crash attraction zone elevation difference, slope variation, and terrain formation between the traffic crash location/point was examined.

Like other mode of transportation micromobility is one of land mode of transportation that causes accident on users. A micromobility is a form of transport where lightweight vehicles can be owned for short-range intracity travel. Micromobility vehicles have been globally popular due to their efficiency and effectiveness. Even though using micromobility has a benefit, it’s still accountable for a higher proportion of accidents. Due to the threats of micromobility, the aim of **Thesis point 6** was assess micromobility factors contributing to accidents and related mishaps. To address the purpose, the study undertakes an explanatory review approach.

Information available in open libraries, online sources, commercial databases, newspapers, magazines, documents from government agencies, specific topic-related articles, annual reports, and published data from research organizations were used as data sources. Based on the convenience and content of the extracted document, this review used to define micromobility accident and related causes, micromobility vehicle market and service trend, micromobility accident-related demography, socio-economic, behavioral, and cultural factors, and other factors that affect micromobility usage, and proposed remedial action.

Global infrastructure limitation for micromobility like lack of charging stations and parking spaces. Micromobility market and service gradually increased due to urbanization. Most developing nations with higher population sizes used a low level of micromobility. This is directly related to the income of the nation and infrastructure development. The average annual global number of people dying and injured due to micromobility is soaring and demonstrates the alarming nature. Most micromobility accidents are caused by device technical problem the causes fire, riders not using helmets that aggravate the risk level, collisions with other (vehicles, pedestrians, and fixed objects), the nature of the vehicles by themselves, visibility, and seasonal variation.

From the global population young people of the age of 14 and above suffer enormous physical injury due to micromobility. Particularly, men are highly risky. Even if the rate of injuries for men is comparatively high, young women also suffer the same problem. The older population used micromobility with an age of 45 and above, mostly experiencing fatality. To minimize the micromobility-related accident, using designed, manufactured, and certified devices, wearing a helmet, slowing down speed, being aware of the surroundings, using an alert bell, keeping hands in positions, never riding under the influence of drugs, integrating a micromobility system into the pre-existing infrastructure, contract cycling superhighways, providing a safer route, geofencing, setting boundaries, data-sharing platforms, and a car-free strategy were the most common attributes.

At the end, micromobility helps to create a more environmentally friendly transport future. It's crucial for users to understand that, despite certain drawbacks, micromobility can still be an advantageous and sustainable form of transportation if safety, upkeep, legal requirements, and storage options are provided. As a result, stakeholders must undertake proper remedial action to overcome micromobility problem. Unless and otherwise, in proportion with the service and market growth in the coming few years, micromobility will become one of the leading causes for death and injury.

**Thesis Point 6**

I assessed the global market and service trend of micromobility. I present a micromobility-related accident and its causes. Factors affecting micromobility usage are also illustrated. The demography of the global population affected by micromobility vehicles is explored. The impacts of income on micromobility usage and related issues were examined. To avoid micromobility accidents, remedial action based on the causes was indicated. In addition to that, micromobility vehicles-related socio-economic, behavioral, and cultural factors also reflected.

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# Appendices

## Appendix A

Table A 1. Road traffic crash district distribution

| Traffic Crash Distribution | | |
|---|---|---|
| **Budapest District** | **Frequency** | **Percent** |
| District I | 435 | 2.6 |
| District II | 819 | 4.8 |
| District III | 903 | 5.3 |
| District IV | 592 | 3.5 |
| District V | 553 | 3.3 |
| District VI | 578 | 3.4 |
| District VII | 583 | 3.4 |
| District VIII | 987 | 5.8 |
| District IX | 861 | 5.1 |
| District X | 1089 | 6.4 |
| District XI | 1312 | 7.7 |
| District XII | 401 | 2.4 |
| District XIII | 1353 | 8.0 |
| District XIV | 1442 | 8.5 |
| District XV | 694 | 4.1 |
| District XVI | 456 | 2.7 |
| District XVII | 669 | 3.9 |
| District XVIII | 701 | 4.1 |
| District XIX | 516 | 3.0 |
| District XX | 581 | 3.4 |
| District XXI | 583 | 3.4 |
| District XXII | 434 | 2.6 |
| District XXIII | 329 | 1.9 |
| Unknown | 135 | 0.8 |
| Total | 17,006 | 100.0 |

Table A 2. Cross-tab. of hourly distribution of road traffic crash and geometry formation

| | | **Road Geometry Formation** | | | | **Total** |
|---|---|---|---|---|---|---|
| | | **Intersection** | **Horizontal Curve** | **Straight Road** | **Others** | |
| 1-hour Distribution | 0:00–1:00 | 37 | 21 | 126 | 1 | 185 |
| | 1:01–2:00 | 25 | 19 | 84 | 6 | 134 |
| | 2:01–3:00 | 26 | 7 | 72 | 2 | 107 |
| | 3:01–4:00 | 30 | 16 | 64 | 0 | 110 |
| | 4:01–5:00 | 25 | 11 | 61 | 0 | 97 |
| | 5:01–6:00 | 71 | 13 | 140 | 1 | 225 |
| | 6:01–7:00 | 190 | 23 | 358 | 3 | 574 |
| | 7:01–8:00 | 333 | 30 | 620 | 4 | 987 |
| | 8:01–9:00 | 351 | 27 | 647 | 5 | 1030 |
| | 9:01–10:00 | 320 | 33 | 629 | 6 | 988 |
| | 10:01–11:00 | 351 | 28 | 613 | 6 | 998 |
| | 11:01–12:00 | 311 | 40 | 653 | 3 | 1007 |
| | 12:01–13:00 | 333 | 40 | 619 | 5 | 997 |
| | 13:01–14:00 | 348 | 49 | 653 | 9 | 1059 |
| | 14:01–15:00 | 312 | 32 | 653 | 10 | 1007 |
| | 15:01–16:00 | 362 | 45 | 751 | 9 | 1167 |
| | 16:01–17:00 | 431 | 59 | 950 | 17 | 1457 |
| | 17:01–18:00 | 404 | 49 | 876 | 11 | 1340 |
| | 18:01–19:00 | 339 | 53 | 667 | 13 | 1072 |
| | 19:01–20:00 | 238 | 34 | 549 | 8 | 829 |
| | 20:01–21:00 | 173 | 28 | 360 | 3 | 564 |
| | 21:01–22:00 | 133 | 24 | 301 | 4 | 462 |
| | 22:01–23:00 | 108 | 28 | 247 | 6 | 389 |
| | 23:01–24:00 | 68 | 17 | 132 | 4 | 221 |
| Total | | 5319 | 726 | 10,825 | 136 | 17,006 |

Table A 3.Cross-tab of primary reason for road traffic crash and geometry formation

| | | **Road Geometry Formation** | | | | **Total** |
|---|---|---|---|---|---|---|
| | | **Intersection** | **Horizontal Curve** | **Straight Road** | **Others** | |
| Primary Reason | Failure of Brake | 2 | 2 | 1 | 0 | 5 |
| | Careless Driving | 84 | 31 | 788 | 23 | 926 |
| | Chassis Failure | 1 | 0 | 2 | 0 | 3 |
| | Disruption of Oncoming Vehicle | 4 | 3 | 18 | 0 | 25 |
| | Driver Distraction | 0 | 0 | 3 | 0 | 3 |
| | Road Crossing Disturbing Behaviors | 2 | 0 | 49 | 2 | 53 |
| | Early Starting of Vehicle | 5 | 2 | 26 | 3 | 36 |
| | Engine Failure | 0 | 0 | 2 | 0 | 2 |
| | Entering to the Market | 40 | 7 | 384 | 11 | 442 |
| | Failure to Illuminate Vehicle | 0 | 0 | 1 | 0 | 1 |
| | Glare with Reflector | 0 | 1 | 0 | 0 | 1 |
| | Animal | 1 | 2 | 9 | 0 | 12 |
| | Improper use of Road Sign | 1974 | 27 | 771 | 4 | 2776 |
| | Improper use of Lane | 10 | 8 | 44 | 0 | 62 |
| | In attention during Takeoff and Landing | 0 | 0 | 13 | 0 | 13 |
| | Invisibility at Bend and Bump | 0 | 4 | 0 | 0 | 4 |
| | Irregular Evasion | 2 | 1 | 31 | 0 | 34 |
| | Irregular Lane Change | 49 | 23 | 644 | 1 | 717 |
| | Irregular Reversal | 11 | 3 | 243 | 17 | 274 |
| | Irregular Transport of Passenger and | 1 | 0 | 3 | 0 | 4 |
| | Irregular Turn | 18 | 3 | 143 | 0 | 164 |
| | Jumping in or out of the vehicle | 0 | 0 | 2 | 0 | 2 |
| | Lack of Side Spacing | 2 | 7 | 104 | 0 | 113 |
| | Leaving Child an attended | 1 | 0 | 11 | 0 | 12 |
| | Malaise | 4 | 4 | 32 | 0 | 40 |
| | Obstructing Straight line Traffic | 124 | 23 | 326 | 2 | 475 |
| | Overloading | 61 | 26 | 388 | 11 | 486 |
| | Overtaking another Vehicle | 0 | 0 | 2 | 0 | 2 |
| | Passing in front of Stationery Object | 4 | 4 | 188 | 1 | 197 |
| | Passing through Prohibited Place | 20 | 10 | 256 | 8 | 294 |
| | Non-Priority for Electric Vehicle | 37 | 0 | 37 | 0 | 74 |
| | Non-priority for Pedestrian | 437 | 32 | 1126 | 2 | 1597 |
| | Road Pavement Condition | 103 | 350 | 1428 | 25 | 1906 |
| | Rubber Defect | 0 | 0 | 7 | 0 | 7 |
| | Traffic Signal Failure | 2 | 1 | 6 | 0 | 9 |
| | Traffic Signal Negligence | 734 | 7 | 253 | 0 | 994 |
| | Sleeping | 1 | 6 | 36 | 0 | 43 |
| | Slipperiness | 2 | 1 | 3 | 0 | 6 |
| | Over speed | 7 | 4 | 17 | 0 | 28 |
| | Steering Failure | 0 | 0 | 4 | 0 | 4 |
| | Stopping Sight Distance | 123 | 33 | 1712 | 1 | 1869 |
| | Vehicle Technical Problem | 3 | 2 | 17 | 2 | 24 |
| | Traffic Condition | 41 | 9 | 314 | 1 | 365 |
| | Vehicle using Distractive Sign | 18 | 0 | 23 | 0 | 41 |
| | Violation of Left Turn Rule | 757 | 22 | 522 | 0 | 1301 |
| | Violation of Right Turn Rule | 550 | 4 | 162 | 1 | 717 |
| | Weather and Visibility | 9 | 37 | 134 | 0 | 180 |
| | Others | 75 | 27 | 540 | 21 | 663 |
| Total | | 5319 | 726 | 10,825 | 136 | 17,006 |

Table A 4. Cross-tab of primary reason for road traffic crash and 3-hour distributions

| | | **3-hour Dist.** | | | | | | | | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **0:00-** | **3:01-** | **6:01-** | **9:01-** | **12:01-** | **15:01-** | **18:01-** | **21:01-** | |
| Primary Reason | Failure of Brake | 0 | 0 | 2 | 0 | 1 | 0 | 1 | 1 | 5 |
| | Careless Driving | 25 | 13 | 134 | 147 | 166 | 200 | 169 | 72 | 926 |
| | Chassis Failure | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 3 |
| | Disruption of | 1 | 1 | 6 | 1 | 3 | 3 | 7 | 3 | 25 |
| | Driver Distraction | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 3 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Road Crossing | 4 | 3 | 6 | 5 | 7 | 6 | 15 | 7 | 53 |
| | Early Starting of | 1 | 0 | 6 | 5 | 7 | 13 | 2 | 2 | 36 |
| | Engine Failure | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 2 |
| | Entering to the | 3 | 7 | 80 | 78 | 92 | 113 | 54 | 15 | 442 |
| | Failure to Illuminate | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| | Glare with Reflector | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| | Animal | 1 | 0 | 3 | 2 | 3 | 1 | 1 | 1 | 12 |
| | Improper use of | 56 | 73 | 448 | 467 | 529 | 634 | 381 | 188 | 2776 |
| | Improper use of | 2 | 2 | 9 | 5 | 13 | 16 | 14 | 1 | 62 |
| | In attention during | 1 | 0 | 1 | 1 | 0 | 7 | 3 | 0 | 13 |
| | Invisibility at Bend | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 1 | 4 |
| | Irregular Evasion | 0 | 0 | 11 | 7 | 5 | 7 | 3 | 1 | 34 |
| | Irregular Lane | 9 | 12 | 135 | 139 | 154 | 142 | 96 | 30 | 717 |
| | Irregular Reversal | 2 | 2 | 30 | 85 | 65 | 59 | 26 | 5 | 274 |
| | Irregular Transport | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 4 |
| | Irregular Turn | 2 | 4 | 30 | 30 | 27 | 41 | 21 | 9 | 164 |
| | Jumping in or out of | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 |
| | Lack of Side | 2 | 2 | 16 | 16 | 25 | 27 | 17 | 8 | 113 |
| | Leaving Child an | 0 | 0 | 1 | 2 | 2 | 7 | 0 | 0 | 12 |
| | Malaise | 0 | 0 | 5 | 18 | 10 | 5 | 0 | 2 | 40 |
| | Obstructing Straight | 6 | 3 | 72 | 87 | 96 | 124 | 62 | 25 | 475 |
| | Overloading | 10 | 8 | 55 | 102 | 100 | 121 | 59 | 31 | 486 |
| | Overtaking another | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 2 |
| | Passing in front of | 6 | 1 | 41 | 27 | 33 | 53 | 33 | 3 | 197 |
| | Passing through | 5 | 8 | 52 | 44 | 43 | 59 | 57 | 26 | 294 |
| | Non-Priority for | 1 | 0 | 10 | 17 | 15 | 16 | 10 | 5 | 74 |
| | Non-priority for | 18 | 35 | 299 | 274 | 195 | 436 | 268 | 72 | 1597 |
| | Road Pavement | 172 | 113 | 208 | 233 | 302 | 353 | 297 | 228 | 1906 |
| | Rubber Defect | 0 | 0 | 1 | 0 | 3 | 2 | 1 | 0 | 7 |
| | Traffic Signal | 0 | 0 | 0 | 2 | 4 | 1 | 1 | 1 | 9 |
| | Traffic Signal | 26 | 43 | 135 | 166 | 181 | 212 | 158 | 73 | 994 |
| | Sleeping | 6 | 11 | 4 | 3 | 3 | 11 | 5 | 0 | 43 |
| | Slipperiness | 0 | 0 | 1 | 2 | 1 | 1 | 0 | 1 | 6 |
| | Over speed | 2 | 0 | 4 | 4 | 5 | 8 | 1 | 4 | 28 |
| | Steering Failure | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 4 |
| | Stopping Sight | 14 | 24 | 262 | 404 | 363 | 506 | 227 | 69 | 1869 |
| | Vehicle Technical | 0 | 1 | 2 | 4 | 10 | 5 | 2 | 0 | 24 |
| | Traffic Condition | 6 | 12 | 41 | 82 | 71 | 95 | 44 | 14 | 365 |
| | Vehicle using | 0 | 1 | 3 | 11 | 10 | 8 | 4 | 4 | 41 |
| | Violation of Left | 6 | 22 | 208 | 257 | 228 | 308 | 204 | 68 | 1301 |
| | Violation of Right | 4 | 7 | 142 | 133 | 142 | 167 | 99 | 23 | 717 |
| | Weather and | 8 | 9 | 35 | 24 | 25 | 27 | 26 | 26 | 180 |
| | Others | 27 | 15 | 88 | 106 | 119 | 166 | 92 | 50 | 663 |
| Total | | 426 | 432 | 2591 | 2993 | 3063 | 3964 | 2465 | 1072 | 17006 |

Table A 5. Cross-tab of road traffic crash outcome and its primary reason

| | | Crash Outcome | | | Total |
|---|---|---|---|---|---|
| | | Fatality | Serious Injuries | Slight Injuries | |
| Primary Reason | Failure of Brake | 0 | 3 | 2 | 5 |
| | Careless Driving | 26 | 298 | 602 | 926 |
| | Chassis Failure | 0 | 0 | 3 | 3 |
| | Disruption of Oncoming Vehicle | 2 | 8 | 15 | 25 |
| | Driver Distraction | 0 | 3 | 0 | 3 |
| | Road Crossing Disturbing Behaviors | 3 | 17 | 33 | 53 |
| | Early Starting of Vehicle | 0 | 6 | 30 | 36 |
| | Engine Failure | 0 | 0 | 2 | 2 |
| | Entering to the Market | 5 | 95 | 342 | 442 |
| | Failure to Illuminate Vehicle | 0 | 0 | 1 | 1 |
| | Glare with Reflector | 0 | 0 | 1 | 1 |
| | Animal | 0 | 5 | 7 | 12 |
| | Improper use of Road Sign | 38 | 589 | 2149 | 2776 |

| | | | | |
|---|---|---|---|---|
| Improper use of Lane | 0 | 20 | 42 | 62 |
| In attention during Takeoff and Landing | 0 | 2 | 11 | 13 |
| Invisibility at Bend and Bump | 0 | 2 | 2 | 4 |
| Irregular Evasion | 1 | 5 | 28 | 34 |
| Irregular Lane Change | 6 | 141 | 570 | 717 |
| Irregular Reversal | 4 | 79 | 191 | 274 |
| Irregular Transport of Passenger and | 0 | 1 | 3 | 4 |
| Irregular Turn | 3 | 48 | 113 | 164 |
| Jumping in or out of the vehicle | 0 | 1 | 1 | 2 |
| Lack of Side Spacing | 0 | 30 | 83 | 113 |
| Leaving Child an attended | 0 | 0 | 12 | 12 |
| Malaise | 3 | 6 | 31 | 40 |
| Obstructing Straight line Traffic | 3 | 118 | 354 | 475 |
| Overloading | 0 | 145 | 341 | 486 |
| Overtaking another Vehicle | 0 | 0 | 2 | 2 |
| Passing in front of Stationery Object | 2 | 62 | 133 | 197 |
| Passing through Prohibited Place | 17 | 102 | 175 | 294 |
| Non-Priority for Electric Vehicle | 0 | 19 | 55 | 74 |
| Non-priority for Pedestrian | 23 | 529 | 1045 | 1597 |
| Road Pavement Condition | 20 | 550 | 1336 | 1906 |
| Rubber Defect | 0 | 2 | 5 | 7 |
| Traffic Signal Failure | 0 | 0 | 9 | 9 |
| Traffic Signal Negligence | 16 | 194 | 784 | 994 |
| Sleeping | 0 | 8 | 35 | 43 |
| Slipperiness | 0 | 1 | 5 | 6 |
| Over speed | 5 | 6 | 17 | 28 |
| Steering Failure | 0 | 0 | 4 | 4 |
| Stopping Sight Distance | 6 | 188 | 1675 | 1869 |
| Vehicle Technical Problem | 0 | 9 | 15 | 24 |
| Traffic Condition | 2 | 85 | 278 | 365 |
| Vehicle using Distractive Sign | 0 | 6 | 35 | 41 |
| Violation of Left Turn Rule | 11 | 286 | 1004 | 1301 |
| Violation of Right Turn Rule | 2 | 116 | 599 | 717 |
| Weather and Visibility | 1 | 31 | 148 | 180 |
| Others | 17 | 183 | 463 | 663 |
| Total | 216 | 3999 | 12,791 | 17,006 |

Table A 6. Traffic crash and accident percentage frequency distribution and severity index

| Geometry Type | Number of Accident | Perc (%) | Number of Crash | Perc (%) | Severity Index |
|---|---|---|---|---|---|
| Straight Route | 13006 | 62.3 | 10961 | 64.5 | 1.19 |
| Cross Road | 6926 | 33.1 | 5319 | 31.3 | 1.30 |
| Road Bend | 952 | 4.6 | 726 | 4.3 | 1.31 |
| Total | 20884 | 100.0 | 17006 | 100.0 | |

Table A 7. Accident number and crash frequency

| Accident Type | Number of Accident | Crash Frequency | Perc (%) | Accident Frequency | Perc (%) |
|---|---|---|---|---|---|
| Fatality | 0 | 16790 | 98.7 | 0 | 0.0 |
| | 1 | 209 | 1.2 | 209 | 93.3 |
| | 2 | 6 | .0 | 12 | 5.4 |
| | 3 | 1 | .0 | 3 | 1.3 |
| | Total | 17006 | 100.0 | 224 | 100.0 |
| Serious Injuries | 0 | 12987 | 76.4 | 0 | 0.0 |
| | 1 | 3893 | 22.9 | 3893 | 93.1 |
| | 2 | 99 | .6 | 198 | 4.7 |
| | 3 | 22 | .1 | 66 | 1.6 |
| | 4 | 4 | .0 | 16 | 0.4 |
| | 7 | 1 | .0 | 7 | 0.2 |
| | Total | 17006 | 100.0 | 4180 | 100.0 |
| | 0 | 3608 | 21.2 | 0 | 0.0 |
| | 1 | 11218 | 66.0 | 11218 | 68.1 |
| | 2 | 1576 | 9.3 | 3152 | 19.1 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Slight Injuries | 3 | 432 | 2.5 | 1296 | 7.9 |
|  | 4 | 114 | .7 | 456 | 2.8 |
|  | 5 | 33 | .2 | 165 | 1 |
|  | 6 | 11 | .1 | 66 | 0.4 |
|  | 7 | 7 | .0 | 49 | 0.3 |
|  | 8 | 2 | .0 | 16 | 0.1 |
|  | 9 | 1 | .0 | 9 | 0.05 |
|  | 10 | 1 | .0 | 10 | 0.05 |
|  | 11 | 1 | .0 | 11 | 0.05 |
|  | 12 | 1 | .0 | 12 | 0.05 |
|  | 20 | 1 | .0 | 20 | 0.1 |
| Total |  | 17006 | 100.0 | 16480 | 100.0 |

Table A 8. Annual crash severity index

| **Year** | **Accident Type** |  |  | **Total Number of Accident** | **Total Number of Crash** |
|---|---|---|---|---|---|
|  | **Fatality** | **Serious Injury** | **Slight Injury** |  |  |
| 2017 |  |  |  |  |  |
| Accident Number | 41 | 813 | 2895 | 3749 | 3016 |
| Annual Severity Index (SI) | 0.014 | 0.270 | 0.960 |  |  |
| 2018 |  |  |  |  |  |
| Accident Number | 40 | 680 | 2874 | 3594 | 2910 |
| Annual Severity Index (SI) | 0.014 | 0.234 | 0.988 |  |  |
| 2019 |  |  |  |  |  |
| Accident Number | 46 | 798 | 2992 | 3836 | 3117 |
| Annual Severity Index (SI) | 0.015 | 0.256 | 0.960 |  |  |
| 2020 |  |  |  |  |  |
| Accident Number | 61 | 1314 | 5318 | 6693 | 5505 |
| Annual Severity Index (SI) | 0.011 | 0.239 | 0.966 |  |  |
| 2021 |  |  |  |  |  |
| Accident Number | 36 | 575 | 2401 | 3012 | 2458 |
| Annual Severity Index (SI) | 0.015 | 0.234 | 0.977 |  |  |
| Total |  |  |  | 20884 | 17006 |

Table A 9. Annual crash severity index

| **Road Geometry** | **Total Number of Accident** | **Accident > 3** |  |
|---|---|---|---|
|  |  | **Number of Accident** | **Perc (%)** |
| Straight Route | 13006 | 1401 | 10.77 |
| Cross Road | 6926 | 1193 | 17.22 |
| Road Bend | 952 | 165 | 17.33 |
| Total | 20884 | 2759 | **13.21** |

Table A 10. Road geometry and crash severity index analysis of accident ≥ 3

| **Road Geometry** | **Fatality ≥ 3** |  |  |  |
|---|---|---|---|---|
|  | **Number of Crash** | **Number of Accident** | **Percentage** | **Severity Index** |
| Straight Route | 1 | 3 | 100 | 3 |
| Cross Road | 0 | 0 | 0 | NA |
| Road Bend | 0 | 0 | 0 | NA |
|  | **Serious Injury ≥ 3** |  |  |  |
|  | **Number of Crash** | **Number of Accident** | **Percentage** | **Severity Index** |
| Straight Route | 17 | 51 | 63 | 3 |
| Cross Road | 8 | 25 | 29.6 | 3.12 |
| Road Bend | 2 | 7 | 7.4 | 3.50 |
|  | **Slight Injury ≥ 3** |  |  |  |
|  | **Number of Crash** | **Number of Accident** | **Percentage** | **Severity Index** |
| Straight Route | 300 | 900 | 49.6 | 3 |
| Cross Road | 276 | 947 | 45.8 | 3.44 |
| Road Bend | 28 | 97 | 4.6 | 3.46 |

Table A 11. Road geometry and annual crash severity index

| **Year** | **Road Geometry** | **Number of Crashes** | **Number of Accident** | **Severity Index (SI)** |
|---|---|---|---|---|
|  | Straight Route | 1624 | 1467 | 0.90 |

| | | | | |
|---|---|---|---|---|
| 2017 | Cross Road | 1247 | 1592 | 1.28 |
| | Road Bend | 145 | 208 | 1.43 |
| 2018 | Straight Route | 1820 | 2187 | 1.20 |
| | Cross Road | 972 | 1256 | 1.29 |
| | Road Bend | 118 | 151 | 1.28 |
| 2019 | Straight Route | 2225 | 2637 | 1.19 |
| | Cross Road | 761 | 1036 | 1.36 |
| | Road Bend | 131 | 163 | 1.24 |
| 2020 | Straight Route | 3670 | 4300 | 1.17 |
| | Cross Road | 1606 | 2106 | 1.31 |
| | Road Bend | 229 | 287 | 1.25 |
| 2021 | Straight Route | 1622 | 1933 | 1.19 |
| | Cross Road | 733 | 936 | 1.28 |
| | Road Bend | 103 | 143 | 1.39 |

Table A 12. Annual crash severity index

| Year | Accident Type | Number of Crash | Number of Accident | Severity Index (SI) |
|---|---|---|---|---|
| 2017 | Fatality | 3016 | 41 | 0.014 |
| | Serious Injury | | 813 | 0.27 |
| | Slight Injury | | 2895 | 0.96 |
| 2018 | Fatality | 2910 | 40 | 0.014 |
| | Serious Injury | | 680 | 0.234 |
| | Slight Injury | | 2874 | 0.99 |
| 2019 | Fatality | 3117 | 46 | 0.015 |
| | Serious Injury | | 798 | 0.26 |
| | Slight Injury | | 2992 | 0.96 |
| 2020 | Fatality | 5505 | 61 | 0.011 |
| | Serious Injury | | 1314 | 0.24 |
| | Slight Injury | | 5318 | 0.97 |
| 2021 | Fatality | 2458 | 36 | 0.015 |
| | Serious Injury | | 575 | 0.23 |
| | Slight Injury | | 2401 | 0.98 |
| Total | | 17006 | 20884 | |

Table A 13. Traffic accident road geometry annual crash severity index

| Year | Accident Type | Road Geometry | Number of Crash | Number of Accident | Severity Index (SI) |
|---|---|---|---|---|---|
| 2017 | Fatality | Straight Route | 38 | 25 | 0.66 |
| | | Cross Road | | 10 | 0.26 |
| | | Road Bend | | 6 | 0.16 |
| | Serious Injury | Straight Route | 777 | 457 | 0.59 |
| | | Cross Road | | 311 | 0.40 |
| | | Road Bend | | 45 | 0.06 |
| | Slight Injuries | Straight Route | 2322 | 1467 | 0.63 |
| | | Cross Road | | 1271 | 0.55 |
| | | Road Bend | | 157 | 0.07 |
| 2018 | Fatality | Straight Route | 39 | 23 | 0.59 |
| | | Cross Road | | 13 | 0.33 |
| | | Road Bend | | 4 | 0.10 |
| | Serious Injury | Straight Route | 639 | 450 | 0.70 |
| | | Cross Road | | 200 | 0.31 |
| | | Road Bend | | 30 | 0.05 |
| | Slight Injuries | Straight Route | 2342 | 1714 | 0.73 |
| | | Cross Road | | 1043 | 0.45 |
| | | Road Bend | | 117 | 0.05 |
| 2019 | Fatality | Straight Route | 45 | 31 | 0.69 |
| | | Cross Road | | 10 | 0.22 |
| | | Road Bend | | 5 | 0.11 |
| | Serious Injury | Straight Route | 766 | 583 | 0.76 |
| | | Cross Road | | 180 | 0.23 |
| | | Road Bend | | 35 | 0.05 |

| | | | | | |
|---|---|---|---|---|---|
| | Slight Injuries | Straight Route | 2422 | 2023 | 0.84 |
| | | Cross Road | | 846 | 0.35 |
| | | Road Bend | | 123 | 0.05 |
| 2020 | Fatality | Straight Route | 61 | 47 | 0.77 |
| | | Cross Road | | 11 | 0.18 |
| | | Road Bend | | 3 | 0.05 |
| | Serious Injury | Straight Route | 1267 | 937 | 0.74 |
| | | Cross Road | | 314 | 0.25 |
| | | Road Bend | | 63 | 0.05 |
| | Slight Injuries | Straight Route | 4370 | 3316 | 0.76 |
| | | Cross Road | | 1781 | 0.41 |
| | | Road Bend | | 221 | 0.05 |
| 2021 | Fatality | Straight Route | 33 | 27 | 0.82 |
| | | Cross Road | | 3 | 0.09 |
| | | Road Bend | | 6 | 0.18 |
| | Serious Injury | Straight Route | 570 | 422 | 0.74 |
| | | Cross Road | | 129 | 0.23 |
| | | Road Bend | | 24 | 0.04 |
| | Slight Injuries | Straight Route | 1942 | 1484 | 0.76 |
| | | Cross Road | | 804 | 0.41 |
| | | Road Bend | | 113 | 0.06 |

Table A 14. Accident distribution and annual crash cost

| Year | Accident Type | Number of Accident | Total Accident Cost (bill. Euro) | Sum (bill. Euro) |
|---|---|---|---|---|
| 2017 | Fatality | 41 | 0.03 | 0.21 |
| | Serious Injury | 813 | 0.13 | |
| | Slight Injury | 2895 | 0.04 | |
| 2018 | Fatality | 40 | 0.03 | 0.19 |
| | Serious Injury | 680 | 0.12 | |
| | Slight Injury | 2874 | 0.04 | |
| 2019 | Fatality | 46 | 0.03 | 0.22 |
| | Serious Injury | 798 | 0.14 | |
| | Slight Injury | 2992 | 0.05 | |
| 2020 | Fatality | 61 | 0.05 | 0.36 |
| | Serious Injury | 1314 | 0.23 | |
| | Slight Injury | 5318 | 0.09 | |
| 2021 | Fatality | 36 | 0.03 | 0.17 |
| | Serious Injury | 575 | 0.11 | |
| | Slight Injury | 2401 | 0.04 | |
| Total | | 20884 | 1.15 | 1.15 |

Table A 15. Road geometry accident distribution and annual crash cost

| | | **Straight Route** | | |
|---|---|---|---|---|
| **Year** | **Accident Type** | **Number of Accident** | **Accident Cost (bill. Euro)** | **Sum (bill. Euro)** |
| 2017 | Fatality | 25 | 0.017 | 0.114 |
| | Serious Injury | 457 | 0.076 | |
| | Slight Injury | 1467 | 0.022 | |
| 2018 | Fatality | 23 | 0.016 | 0.119 |
| | Serious Injury | 450 | 0.077 | |
| | Slight Injury | 1714 | 0.026 | |
| 2019 | Fatality | 31 | 0.022 | 0.157 |
| | Serious Injury | 583 | 0.103 | |
| | Slight Injury | 2023 | 0.032 | |
| 2020 | Fatality | 47 | 0.035 | 0.254 |
| | Serious Injury | 937 | 0.165 | |
| | Slight Injury | 3316 | 0.054 | |
| 2021 | Fatality | 27 | 0.021 | 0.125 |
| | Serious Injury | 422 | 0.078 | |
| | Slight Injury | 1484 | 0.025 | |
| Total | | 13006 | 0.769 | 0.769 |
| | | **Cross Road** | | |

| Year | Accident Type | Number of Accident | Accident Cost (bill. Euro) | Sum (bill. Euro) |
|---|---|---|---|---|
| 2017 | Fatality | 10 | 0.007 | 0.077 |
| | Serious Injury | 311 | 0.052 | |
| | Slight Injury | 1271 | 0.019 | |
| 2018 | Fatality | 13 | 0.009 | 0.059 |
| | Serious Injury | 200 | 0.034 | |
| | Slight Injury | 1043 | 0.016 | |
| 2019 | Fatality | 10 | 0.007 | 0.052 |
| | Serious Injury | 180 | 0.032 | |
| | Slight Injury | 846 | 0.013 | |
| 2020 | Fatality | 11 | 0.008 | 0.092 |
| | Serious Injury | 314 | 0.055 | |
| | Slight Injury | 1781 | 0.029 | |
| 2021 | Fatality | 3 | 0.002 | 0.040 |
| | Serious Injury | 129 | 0.024 | |
| | Slight Injury | 804 | 0.014 | |
| Total | | 6926 | 0.321 | 0.321 |

**Bend Road**

| Year | Accident Type | Number of Accident | Accident Cost (bill. Euro) | Sum (bill. Euro) |
|---|---|---|---|---|
| 2017 | Fatality | 6 | 0.004 | 0.014 |
| | Serious Injury | 45 | 0.007 | |
| | Slight Injury | 157 | 0.002 | |
| 2018 | Fatality | 4 | 0.003 | 0.010 |
| | Serious Injury | 30 | 0.005 | |
| | Slight Injury | 117 | 0.002 | |
| 2019 | Fatality | 5 | 0.004 | 0.012 |
| | Serious Injury | 35 | 0.006 | |
| | Slight Injury | 123 | 0.002 | |
| 2020 | Fatality | 3 | 0.002 | 0.017 |
| | Serious Injury | 63 | 0.011 | |
| | Slight Injury | 221 | 0.004 | |
| 2021 | Fatality | 6 | 0.005 | 0.011 |
| | Serious Injury | 24 | 0.004 | |
| | Slight Injury | 113 | 0.002 | |
| Total | | 952 | 0.064 | 0.064 |

Table A 16. Accident distribution and crash cost

| Accident Type | Number of Accident | Perc (%) | Accident Cost (bill. Euro) | Perc (%) |
|---|---|---|---|---|
| Fatality | 224 | 1.07 | 0.16 | 14.06 |
| Serious Injury | 4180 | 20.02 | 0.73 | 63.38 |
| Slight Injury | 16480 | 78.91 | 0.26 | 22.56 |
| Total | 20884 | 100 | 1.15 | 100 |

Table A 17. Accident distribution and economic losses

| Year | Number of Accident | Total Accident Cost (bill. Euro) | Average Exchange Rate | Total Accident Cost (bill $) | GDP (bill $) | Lost Perc (%) |
|---|---|---|---|---|---|---|
| 2017 | 3749 | 0.205 | 1.1304 | 0.232 | 143.1 | 0.162 |
| 2018 | 3594 | 0.187 | 1.1800 | 0.221 | 160.57 | 0.138 |
| 2019 | 3836 | 0.221 | 1.1199 | 0.247 | 164.01 | 0.151 |
| 2020 | 6693 | 0.363 | 1.1420 | 0.415 | 157.23 | 0.264 |
| 2021 | 3012 | 0.176 | 1.1830 | 0.208 | 182.28 | 0.114 |
| Total | 20884 | 1.153 | | 1.323 | 807.19 | 0.164 |
| Average | | | 1.15106 | 0.265 | 161.438 | 0.164 |

Table A 18. Road geometry and accident cost distribution

| Road Geometry | Accident Type | Number of Accident | Accident Cost (bill. Euro) | Perc (%) |
|---|---|---|---|---|
| Straight Route | Fatality | 153 | 0.11 | 14.47 |
| | Serious Injury | 2849 | 0.50 | 64.95 |
| | Slight Injury | 10004 | 0.16 | 20.58 |
| **Sum** | | **13006** | **0.77** | **100** |
| Cross Road | Fatality | 47 | 0.03 | 10.45 |
| | Serious Injury | 1134 | 0.20 | 61.39 |
| | Slight Injury | 5745 | 0.09 | 28.16 |
| **Sum** | | **6926** | **0.32** | **100** |
| Road Bend | Fatality | 24 | 0.02 | 27.44 |
| | Serious Injury | 197 | 0.03 | 54.34 |
| | Slight Injury | 731 | 0.01 | 18.22 |
| **Sum** | | **952** | **0.06** | **100** |

Table A 19. Road geometry and traffic accident distribution

| Road Geometry | Fatality | Perc (%) | Serious Injury | Perc (%) | Slight Injury | Perc (%) | Total | Perc (%) |
|---|---|---|---|---|---|---|---|---|
| Straight Route | 153 | 68.30 | 2849 | 68.16 | 10004 | 60.70 | 13006 | 62.28 |
| Cross Road | 47 | 20.98 | 1134 | 27.13 | 5745 | 34.86 | 6926 | 33.16 |
| Road Bend | 24 | 10.72 | 197 | 4.71 | 731 | 4.44 | 952 | 4.56 |
| **Total** | **224** | **100** | **4180** | **100** | **16480** | **100** | **20884** | **100** |

Table A 20. Road geometry and traffic accident distribution

| Year | Number of Crash | Crash Distribution (%) | Number of Accident | Accident Distribution (%) | Total Crash Cost (bill $) | Crash Cost Distribution (%) |
|---|---|---|---|---|---|---|
| 2017 | 3016 | 17.735 | 3749 | 17.952 | 0.232 | 17.8 |
| 2018 | 2910 | 17.112 | 3594 | 17.209 | 0.221 | 16.3 |
| 2019 | 3117 | 18.329 | 3836 | 18.368 | 0.247 | 19.2 |
| 2020 | 5505 | 32.371 | 6693 | 32.048 | 0.415 | 31.5 |
| 2021 | 2458 | 14.454 | 3012 | 14.423 | 0.208 | 15.2 |
| **Total** | **17006** | **100** | **20884** | **100** | **1.323** | **100** |

Table A 21. Annual number of traffic accident distribution

| Year | Fatality | Serious Injury | Slight Injury |
|---|---|---|---|
| 2017 | 41 | 813 | 2895 |
| 2018 | 40 | 680 | 2874 |
| 2019 | 46 | 798 | 2992 |
| 2020 | 61 | 1314 | 5318 |
| 2021 | 36 | 575 | 2401 |
| Total | 224 | 4180 | 16480 |
| Average | 45 | 836 | 3296 |

Table A 22. Cross tab. of collision type and road geometry formation

| Collusion Types | Intersection | Horizontal Curve | Straight Road | Others | Total |
|---|---|---|---|---|---|
| Collision with Animals | 1 | 2 | 10 | 0 | 13 |
| Collision with Pedestrian | 668 | 81 | 3258 | 83 | 4090 |
| Pileup Collision | 112 | 41 | 1485 | 1 | 1639 |
| Collision with Object | 21 | 52 | 332 | 7 | 412 |
| Head on Collision | 925 | 141 | 850 | 6 | 1922 |
| Side Swipe Collision | 6 | 4 | 49 | 0 | 59 |
| Side Impact Collision | 1011 | 18 | 438 | 3 | 1470 |
| Rear End Collision | 2575 | 387 | 4403 | 36 | 7401 |

Table A 23. Cross tab. of number of lane and road traffic crash outcome

| Crash Outcomes | Number of Lane | | | | |
|---|---|---|---|---|---|
| | One Lane | Two Lane | ≥ Three Lane | Others | Total |
| Fatality | 95 | 65 | 48 | 8 | 216 |
| Serious Injuries | 2281 | 999 | 624 | 95 | 3999 |
| Slight Injuries | 7107 | 3395 | 2119 | 170 | 12,791 |

Table A 24. Cross tab. of responsible body and road traffic crash outcome

| Responsible body | Fatality | Serious Injuries | Slight Injuries | Total |
|---|---|---|---|---|
| Vehicular Failure | 16 | 202 | 838 | 1056 |
| Failure of Traffic Control Devices | 0 | 1 | 9 | 10 |
| Pedestrian | 87 | 621 | 1095 | 1803 |
| Passenger | 0 | 29 | 47 | 76 |
| Driver | 113 | 3139 | 10,789 | 14,041 |
| Others | 0 | 7 | 13 | 20 |

Table A 25. Mean and variance of variables

| Variable | | Number | Mean | Variances |
|---|---|---|---|---|
| Dependent | Crash Outcome | 17,006 | 2.74 | 0.218 |
| Independent | Light Condition | 17,006 | 1.27 | 0.233 |
| | Collision Type | 17,006 | 3.94 | 9.204 |
| | Road Geometry | 17,006 | 2.35 | 0.900 |
| | Reason | 17,006 | 4.62 | 9.821 |
| | Pavement Surface | 17,006 | 1.06 | 0.119 |
| | Weather Condition | 17,006 | 2.66 | 0.821 |
| | Alcohol Consumption | 17,006 | 5.05 | 0.512 |
| | Speed Limit | 17,006 | 2.11 | 0.218 |

Table A 26. Cross-tab. of road geometry formation and 3-hour distribution of traffic crashes

| 3-hour Distribution | Intersection | Horizontal Curve | Straight Road | Others | Total |
|---|---|---|---|---|---|
| 0:00–3:00 | 88 | 47 | 282 | 9 | 426 |
| 3:01–6:00 | 126 | 40 | 265 | 1 | 432 |
| 6:01–9:00 | 874 | 80 | 1625 | 12 | 2591 |
| 9:01–12:00 | 982 | 101 | 1895 | 15 | 2993 |
| 12:01–15:00 | 993 | 121 | 1925 | 24 | 3063 |
| 15:01–18:00 | 1197 | 153 | 2577 | 37 | 3964 |
| 18:01–21:00 | 750 | 115 | 1576 | 24 | 2465 |
| 21:01–24:00 | 309 | 69 | 680 | 14 | 1072 |

Table A 27. Integration of Determinant factor and Accident Relationship

| Variables | Classification | Determinant factor | Relationship | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Fatality | | | Serious injury | | | Slight injury | | |
| | | | High | Medium | Low | High | Medium | Low | High | Medium | Low |
| Number of lanes | 1 | No | | * | | * | | | * | | |
| | 2 | | | * | | | | * | * | | |
| | ≥3 | | | * | | * | | | | | * |
| Road Geometry | Straight road | Yes | | | * | | | * | | | * |
| | Cross road | | | | * | | * | | * | | |
| | Bend road | | * | | | | * | | * | | |

Table A 28. Cross tab. between collusion type and road traffic crash outcome

| Collusion Type | Crash Outcome | | | |
|---|---|---|---|---|
| | Fatality | Serious Injuries | Slight Injuries | Total |
| Collision with Animals | 0 | 5 | 8 | 13 |
| Collision with Pedestrian | 122 | 1394 | 2574 | 4090 |
| Pileup Collision | 6 | 177 | 1456 | 1639 |
| Collision with Object | 7 | 114 | 291 | 412 |
| Head on Collision | 27 | 427 | 1468 | 1922 |
| Side Swipe Collision | 1 | 12 | 46 | 59 |
| Side Impact Collision | 4 | 302 | 1164 | 1470 |
| Rear End Collision | 49 | 1568 | 5784 | 7401 |

Table A 29. Determinant factor of road traffic crash and its outcome

| **Parameter Estimates** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Crash Outcome** | | **β** | **Std. Error** | **Wald** | **df** | **Sig.** | **Exp(β)** | **95% Confidence Interval for Exp(β)** | |
| | | | | | | | | **Lower Bound** | **Upper Bound** |
| Fatality | Intercept | −14.340 | 0.941 | 232.268 | 1 | 0.000 | | | |
| | WC | 0.169 | 0.076 | 4.917 | 1 | 0.027 | 1.184 | 1.020 | 1.375 |
| | LC | 0.505 | 0.125 | 16.464 | 1 | 0.000 | 1.657 | 1.298 | 2.115 |
| | CT | 0.118 | 0.028 | 17.357 | 1 | 0.000 | 1.125 | 1.064 | 1.189 |
| | RG | –0.038 | 0.085 | 0.202 | 1 | 0.653 | 0.963 | 0.816 | 1.136 |
| | AC | 1.216 | 0.176 | 47.942 | 1 | 0.000 | 3.374 | 2.391 | 4.760 |
| | R | 0.064 | 0.026 | 6.006 | 1 | 0.014 | 1.066 | 1.013 | 1.122 |
| | PS | 0.262 | 0.139 | 3.559 | 1 | 0.059 | 1.299 | 0.990 | 1.705 |
| | VL | 0.727 | 0.090 | 65.023 | 1 | 0.000 | 2.069 | 1.734 | 2.469 |
| Serious Injuries | Intercept | −2.367 | 0.187 | 159.628 | 1 | 0.000 | | | |
| | WC | 0.008 | 0.020 | 0.147 | 1 | 0.701 | 1.008 | 0.969 | 1.048 |
| | LC | 0.126 | 0.038 | 11.251 | 1 | 0.001 | 1.135 | 1.054 | 1.222 |
| | CT | 0.039 | 0.007 | 35.082 | 1 | 0.000 | 1.039 | 1.026 | 1.053 |
| | RG | 0.104 | 0.020 | 25.784 | 1 | 0.000 | 1.109 | 1.066 | 1.155 |
| | AC | 0.031 | 0.027 | 1.251 | 1 | 0.263 | 1.031 | 0.977 | 1.088 |
| | R | 0.058 | 0.006 | 85.482 | 1 | 0.000 | 1.060 | 1.047 | 1.073 |
| | PS | 0.152 | 0.049 | 9.831 | 1 | 0.002 | 1.164 | 1.059 | 1.281 |
| | VL | 0.013 | 0.040 | 0.098 | 1 | 0.754 | 1.013 | 0.936 | 1.096 |

a. The reference category is: Slight Injuries.

Table A 30. Annual based data reliability checks by analysis of variance

| Year | C(%) | $x_i - \bar{x}$ | $(x_i - \bar{x})^2$ | A(%) | $x_i - \bar{x}$ | $(x_i - \bar{x})^2$ | CC(%) | $x_i - \bar{x}$ | $(x_i - \bar{x})^2$ |
|---|---|---|---|---|---|---|---|---|---|
| 2017 | 17.74 | -2.27 | 5.13 | 17.952 | -2.048 | 4.19 | 17.8 | -2.2 | 4.84 |
| 2018 | 17.11 | -2.89 | 8.34 | 17.209 | -2.791 | 7.79 | 16.3 | -3.7 | 13.69 |
| 2019 | 18.33 | -1.67 | 2.79 | 18.368 | -1.632 | 2.66 | 19.2 | -0.8 | 0.64 |
| 2020 | 32.37 | 12.37 | 153.02 | 32.048 | 12.048 | 145.15 | 31.5 | 11.5 | 132.25 |
| 2021 | 14.45 | -5.55 | 30.76 | 14.423 | -5.577 | 31.10 | 15.2 | -4.8 | 23.04 |
| $\bar{x}$ | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| $n - 1$ | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| $\sum_{i}^{n} (x_i - \bar{x})^2$ | 200.04 | 190.90 | 174.46 | 200.04 | 190.90 | 174.46 | 200.04 | 190.90 | 174.46 |
| $\nu^2$ | 50.01 | 47.73 | 43.62 | 50.01 | 47.73 | 43.62 | 50.01 | 47.73 | 43.62 |
| $\nu$ | 7.07 | 6.91 | 6.60 | 7.07 | 6.91 | 6.60 | 7.07 | 6.91 | 6.60 |

Table A 31. Road segment severity score

| **Severity score (SS)** | **Severity level** |
|---|---|
| $SS \leq 1$ | Minor |
| $1 < SS \leq 2$ | Moderate |
| $2 < SS \leq 3$ | Serious |
| $3 < SS \leq 4$ | Severe |
| $4 < SS \leq 5$ | Critical |
| $5 < SS \leq 6$ | Maximal |
| $SS > 6$ | Unknown |

*Source* : [179]

Table A 32. Traffic crash, accident and crash cost distribution on straight and bend Road

| **Segments** | **$N_C$** | **$N_A$** | **Total $C_C$ (bill. Euro)** | | **F** | **SI** | **SLI** |
|---|---|---|---|---|---|---|---|
| Straight Road | 10961 | 13006 | 0.77 | **Accident Type** | 153 | 2849 | 10004 |
| Bend Road | 726 | 952 | 0.07 | | 24 | 197 | 731 |

Table A 33. Pearson correlation coefficient (matrix)

| Correlation | 3-hour Distribution | Budapest District | Crash Outcome | Weather Condition | Light Condition | Collusion Types | Primary Reason | Road Geometry | Alcohol Consumption | Specific Reason | Pavement Surface | Number of Lane | Speed Limit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3-h Dist. | 1 | −0.008 | −0.003 | −0.031 ** | 0.289 ** | 0.027 ** | −0.006 | 0.013 | 0.031 ** | 0.023 ** | 0.014 | 0.014 | −0.017 * |
| Budapest District | −0.008 | 1 | −0.003 | −0.008 | −0.015 | −0.024 ** | 0.001 | −0.073 ** | −0.040 ** | −0.064 ** | −0.003 | −0.131 ** | 0.142 ** |
| Crash Outcome | −0.003 | −0.003 | 1 | −0.003 | −0.050 ** | −0.105 ** | 0.054 ** | −0.060 ** | −0.071 ** | −0.057 ** | −0.034 ** | −0.011 | −0.017 * |
| Weather Condition | −0.031 ** | −0.008 | −0.003 | 1 | −0.140 ** | −0.009 | 0.018 * | 0.004 | 0.023 ** | 0.002 | 0.009 | 0.003 | 0.012 |
| Light Condition | 0.289 ** | −0.015 | −0.050 ** | −0.140 ** | 1 | 0.069 ** | −0.001 | 0.036 ** | −0.081 ** | 0.050 ** | 0.014 | 0.042 ** | 0.012 |
| Collusion Types | 0.027 ** | −0.024 ** | −0.105 ** | −0.009 | 0.069 ** | 1 | 0.004 | 0.242 ** | 0.245 ** | 0.150 ** | −0.005 | 0.039 ** | −0.026 ** |
| Primary Reason | −0.006 | 0.001 | 0.054 ** | 0.018 * | −0.001 | 0.004 | 1 | 0.026 ** | −0.177 ** | −0.088 ** | 0.002 | 0.054 ** | 0.055 ** |
| Road Geometry | 0.013 | −0.073 ** | −0.060 ** | 0.004 | 0.036 ** | 0.242 ** | 0.026 ** | 1 | 0.053 ** | −0.077 ** | 0.073 ** | 0.171 ** | 0.080 ** |
| Alcohol Consumption | 0.031 ** | −0.040 ** | −0.071 ** | 0.023 ** | −0.081 ** | 0.245 ** | −0.177 ** | 0.053 ** | 1 | 0.218 ** | −0.006 | 0.045 ** | −0.017 * |
| Specific Reason | 0.023 ** | −0.064 ** | −0.057 ** | 0.002 | 0.050 ** | 0.150 ** | −0.088 ** | −0.077 ** | 0.218 ** | 1 | 0.001 | 0.164 ** | −0.039 ** |
| Pavement Surface | 0.014 | −0.003 | −0.034 ** | 0.009 | 0.014 | −0.005 | 0.002 | 0.073 ** | −0.006 | 0.001 | 1 | 0.085 ** | −0.040 ** |
| Number of Lane | 0.014 | −0.131 ** | −0.011 | 0.003 | 0.042 ** | 0.039 ** | 0.054 ** | 0.171 ** | 0.045 ** | 0.164 ** | 0.085 ** | 1 | 0.243 ** |
| Speed limit | −0.017 * | 0.142 ** | −0.017 * | 0.012 | 0.012 | −0.026 ** | 0.055 ** | 0.080 ** | −0.017 * | −0.039 ** | −0.040 ** | 0.243 ** | 1 |

Where, **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

# Appendix B

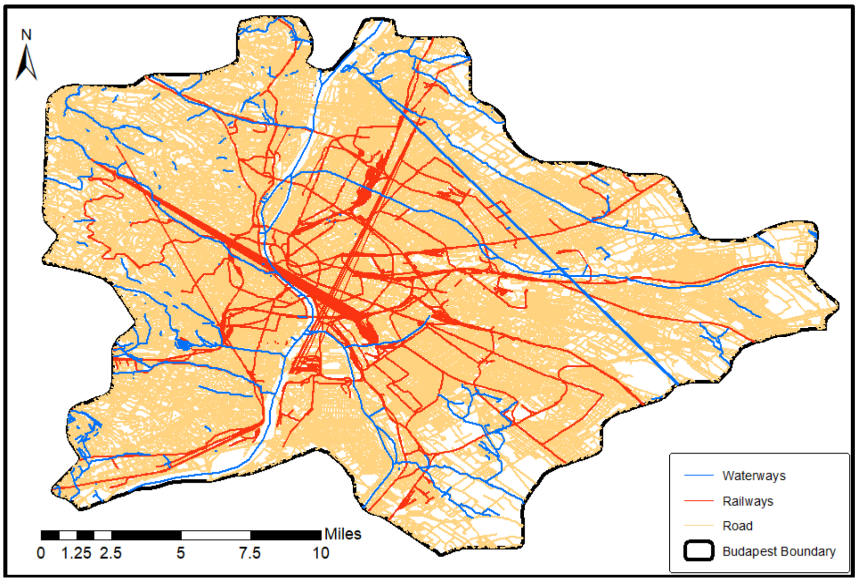


Figure B 1. Budapest city road network and other utility lines

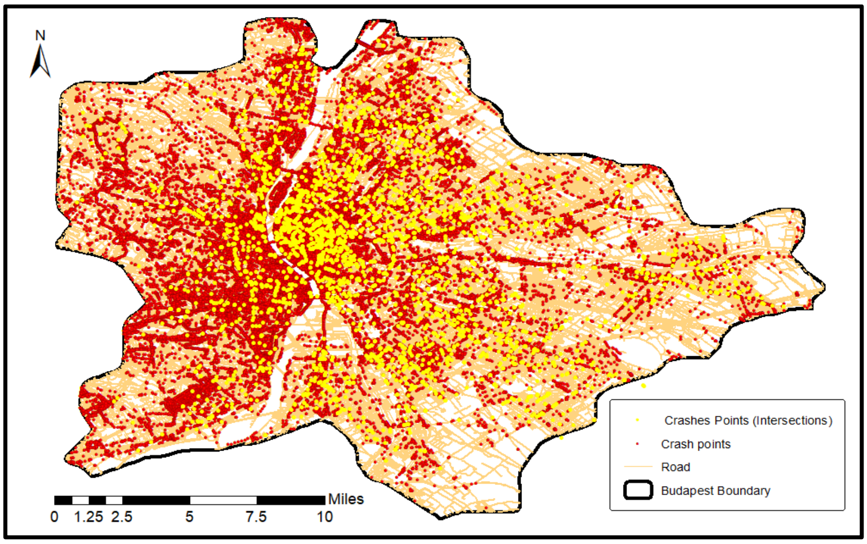


Figure B 2. Road traffic crash distribution of the study area from 2017–2021

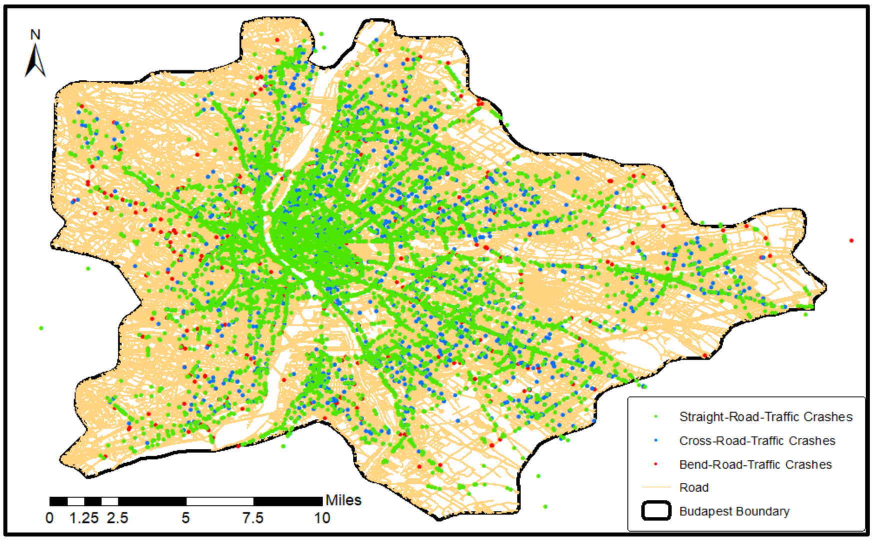


Figure B 3. Road traffic crash distribution based on geometry formation

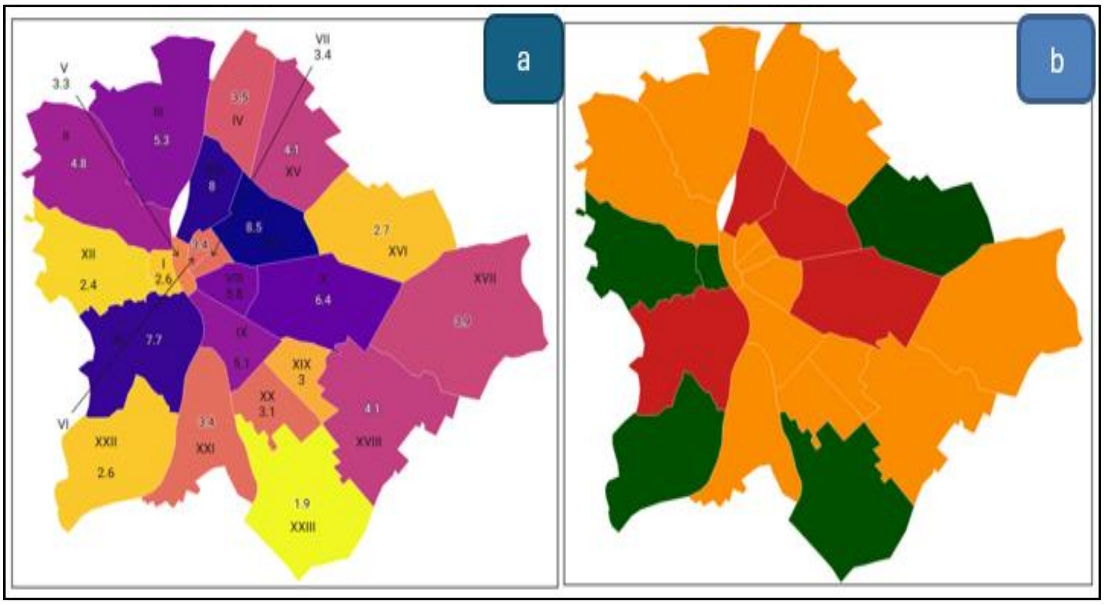


Figure B 4. Road traffic crash district distribution (%)

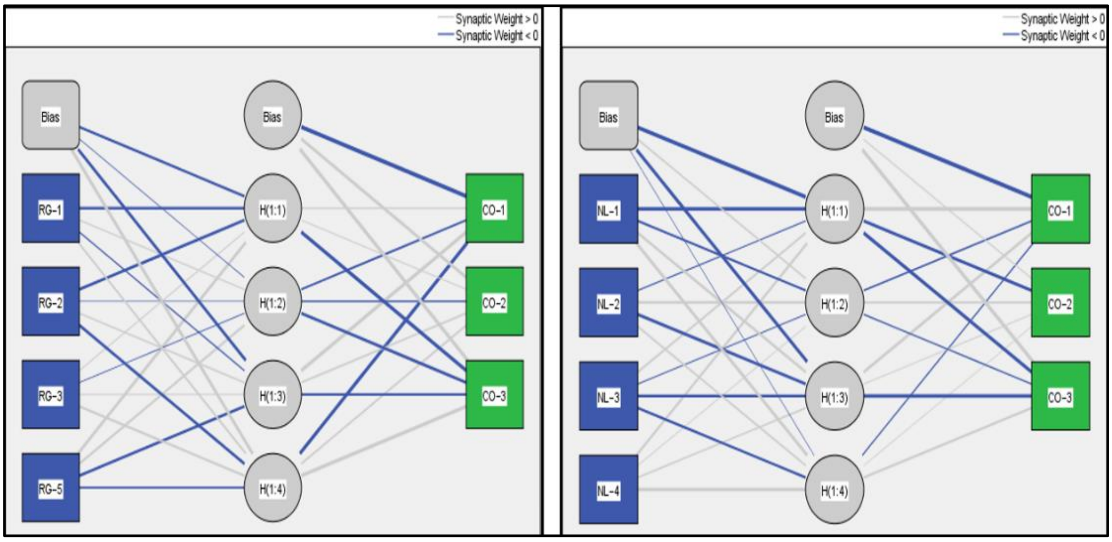


Figure B 5. Road geometry formation and number of lane impact on traffic crash outcome

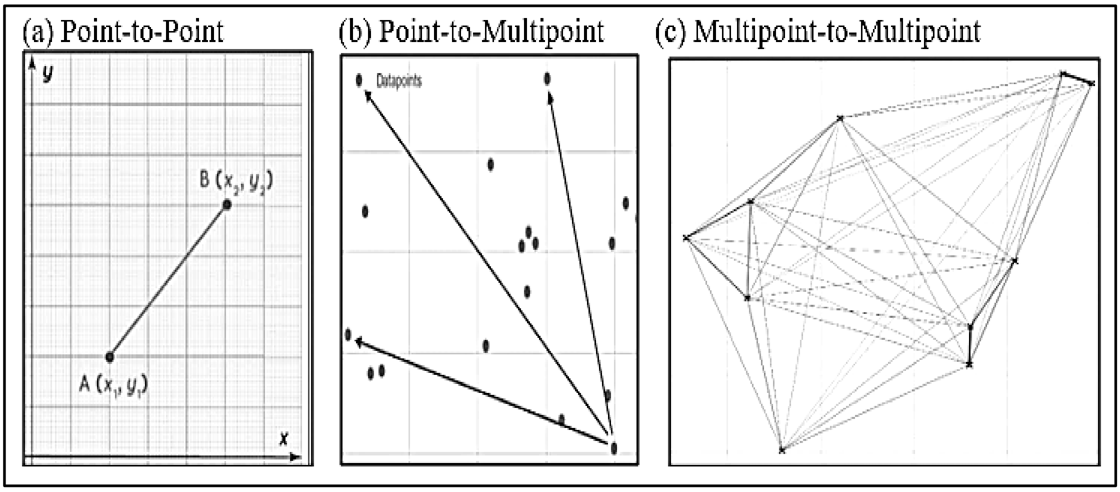
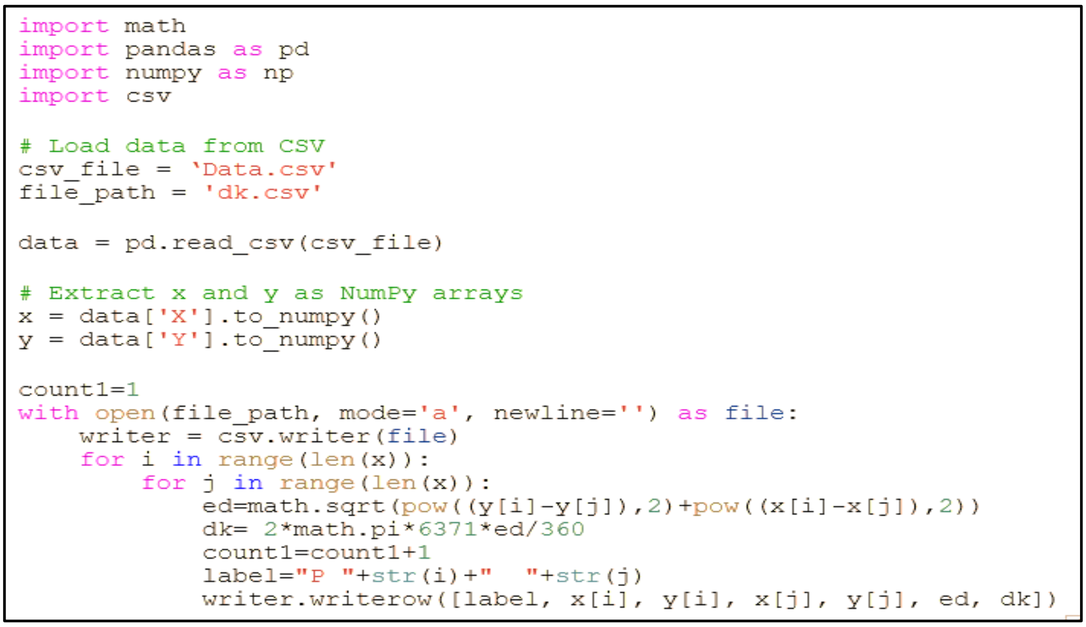


Figure B 6. Type and formation of point distance proximity Source: [136, 137]



```
import math
import pandas as pd
import numpy as np
import csv

# Load data from CSV
csv_file = ‘Data.csv'
file_path = 'dk.csv'

data = pd.read_csv(csv_file)

# Extract x and y as NumPy arrays
x = data['X'].to_numpy()
y = data['Y'].to_numpy()

count1=1
with open(file_path, mode='a', newline='') as file:
    writer = csv.writer(file)
    for i in range(len(x)):
        for j in range(len(x)):
            ed=math.sqrt(pow((y[i]-y[j]),2)+pow((x[i]-x[j]),2))
            dk= 2*math.pi*6371*ed/360
            count1=count1+1
            label="P "+str(i)+"  "+str(j)
            writer.writerow([label, x[i], y[i], x[j], y[j], ed, dk])
```

Figure B 7. Multipoint-to-multipoint distance proximity modeling and unit conversion

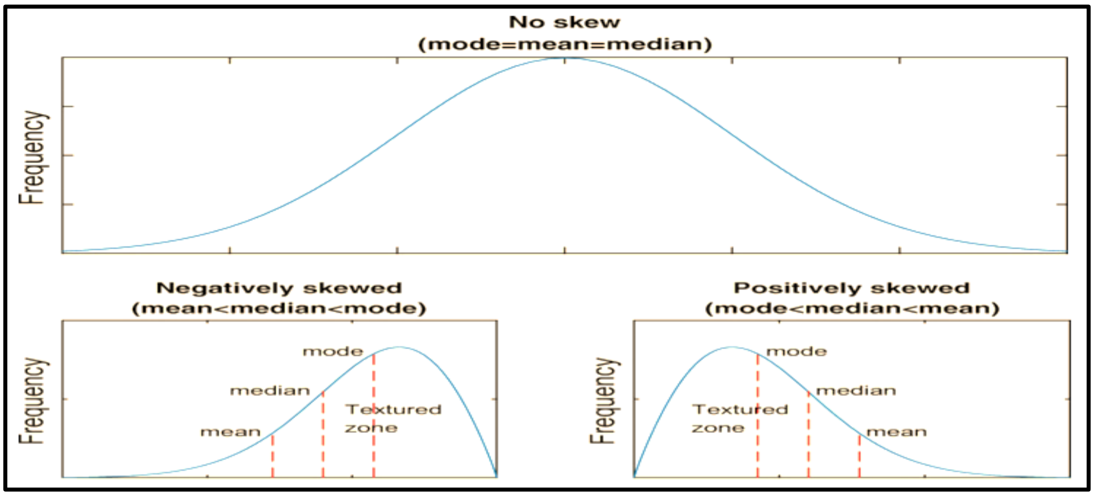


Figure B 8. Skewness Source : [157]

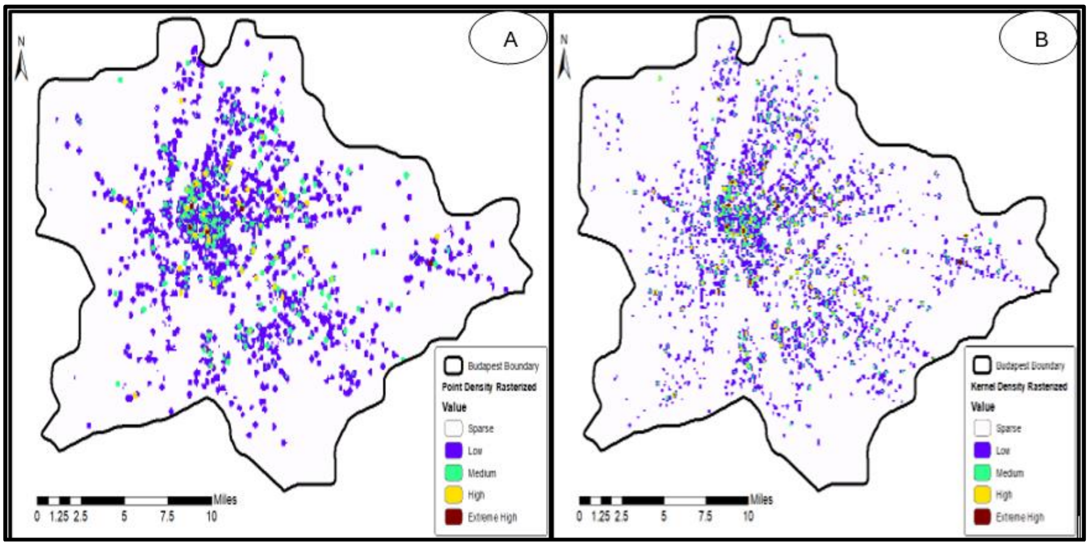


Figure B 9. Crashes distribution pattern by Point Density Estimation (A) and Kernel Density Estimation (B) at neighborhood radius (r) of 0.002 degree

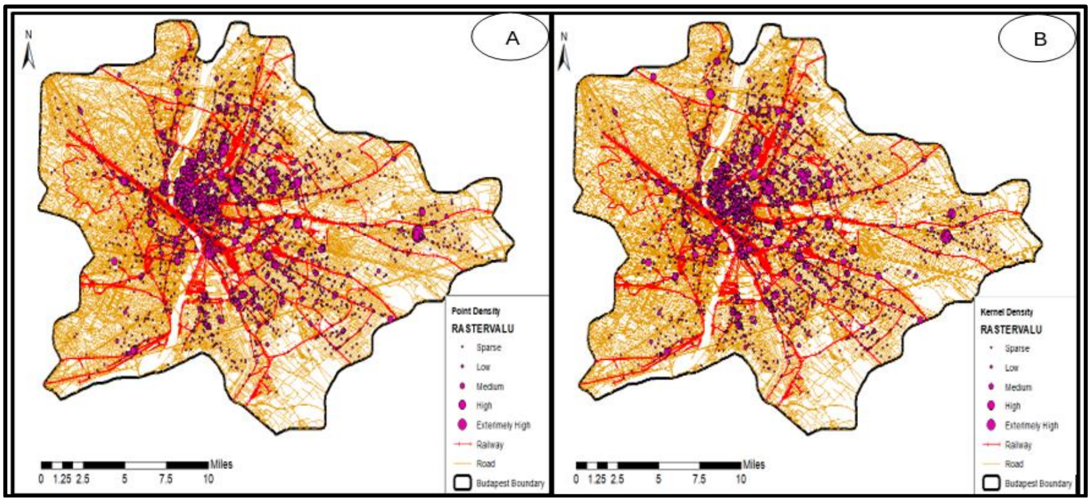
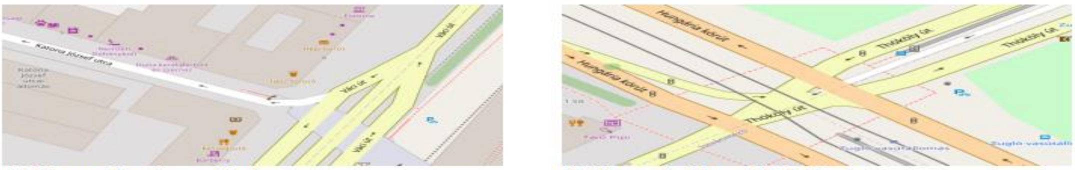


Figure B 10. Crashes distribution pattern by extracting raster to point of Point Density Estimation (A) and Kernel Density Estimation (B) at neighborhood radius (r) of 0.002 degree.

(a) Rakoczi ut -Josef Korut (Blaha Lujza ter aluljaro) (b) Josef Attila utca-Bajcsy Zsilinszky ut-Andrassy ut



(c) Katona Josef utca-Vaci ut (d) Hungaria Korut-Thokoly ut

(e) Pesti ut-Ferihegyi ut

Figure B 11. Blackspot intersection zone of Budapest city road (Source: open street map)

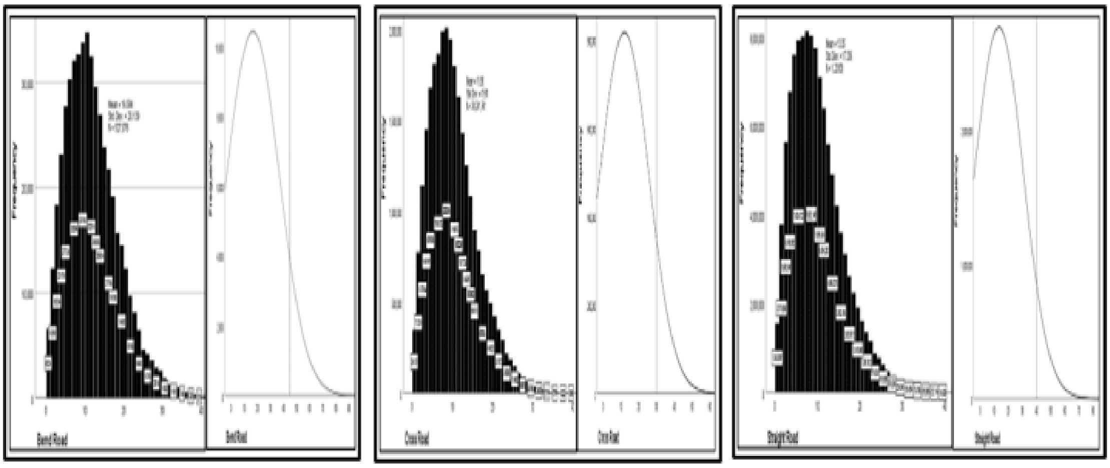


Figure B 12. Bend, Cross and Straight road traffic crash distance proximity distribution respectively

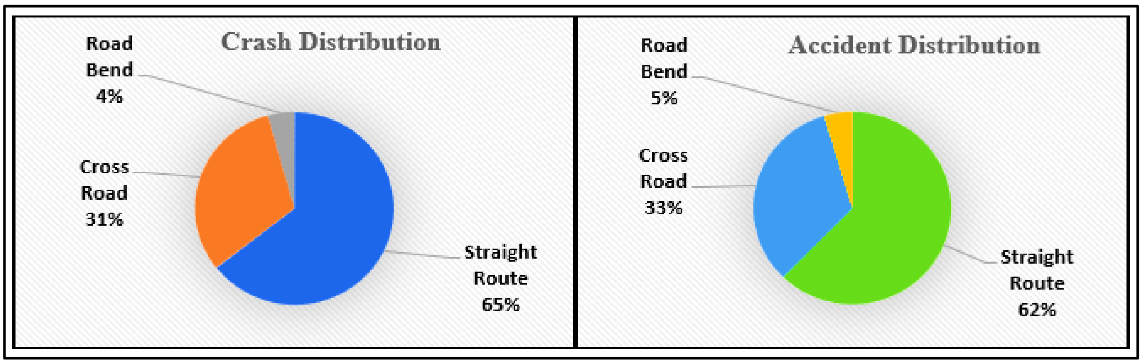


Figure B 13. Road geometry-based relative percentage share of traffic crash and accident

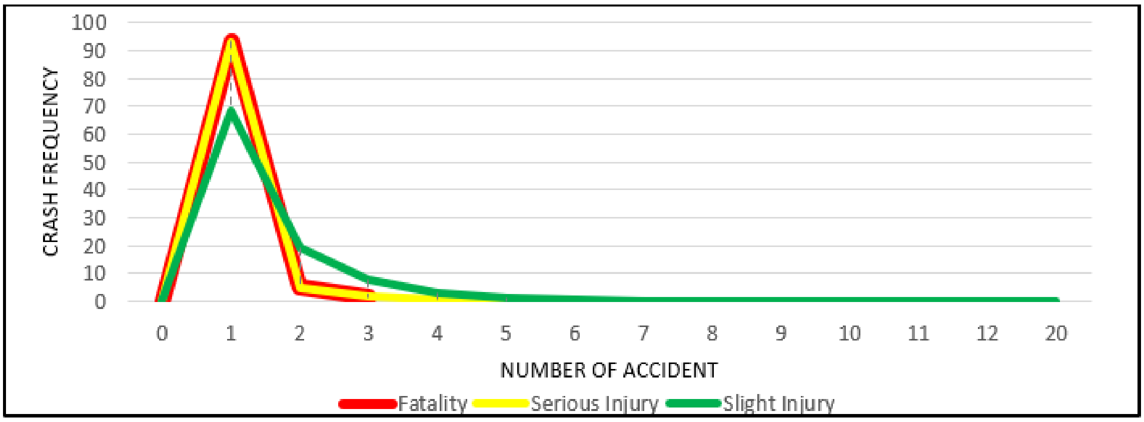
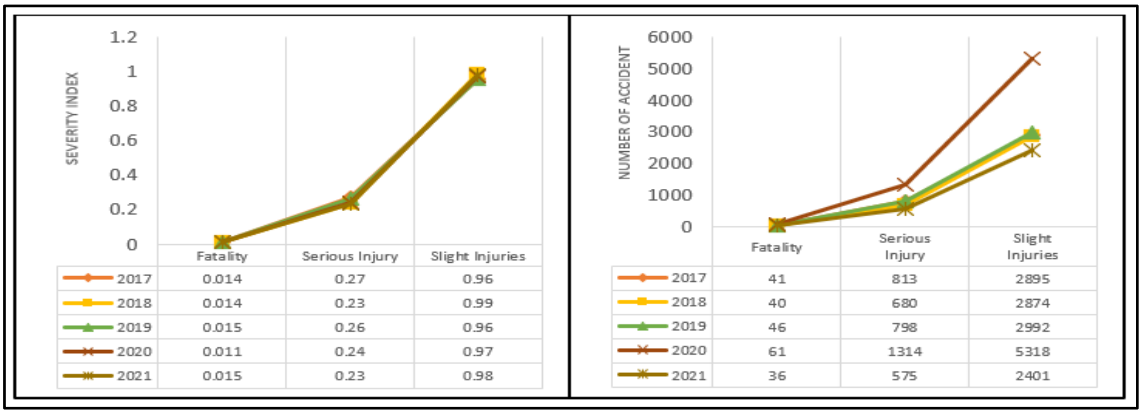


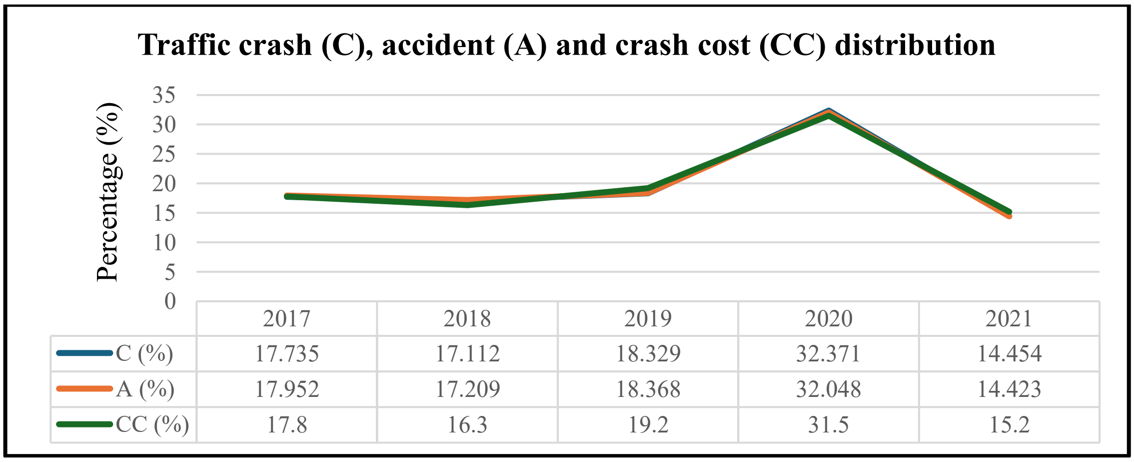
Figure B 14. Number of accident vs. crash frequency



| | Fatality | Serious Injury | Slight Injuries |
|---|---|---|---|
| 2017 | 0.014 | 0.27 | 0.96 |
| 2018 | 0.014 | 0.23 | 0.99 |
| 2019 | 0.015 | 0.26 | 0.96 |
| 2020 | 0.011 | 0.24 | 0.97 |
| 2021 | 0.015 | 0.23 | 0.98 |

| | Fatality | Serious Injury | Slight Injuries |
|---|---|---|---|
| 2017 | 41 | 813 | 2895 |
| 2018 | 40 | 680 | 2874 |
| 2019 | 46 | 798 | 2992 |
| 2020 | 61 | 1314 | 5318 |
| 2021 | 36 | 575 | 2401 |

Figure B 15. Annual traffic accident distribution and severity index



| | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|
| C (%) | 17.735 | 17.112 | 18.329 | 32.371 | 14.454 |
| A (%) | 17.952 | 17.209 | 18.368 | 32.048 | 14.423 |
| CC (%) | 17.8 | 16.3 | 19.2 | 31.5 | 15.2 |

Figure B 16. Relative percentage share of traffic crash, accident and crash cost annually

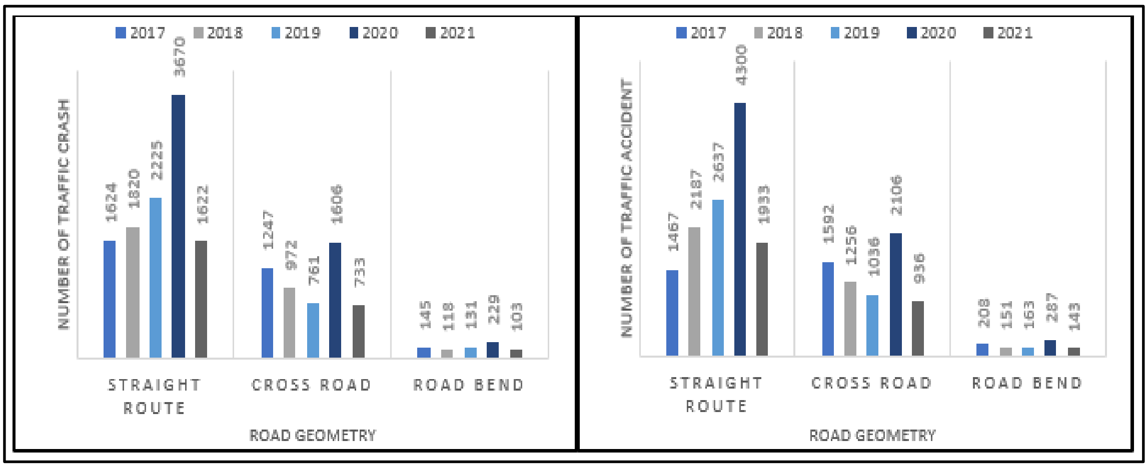


Figure B 17. Road geometry, annul traffic crash and accident distribution.

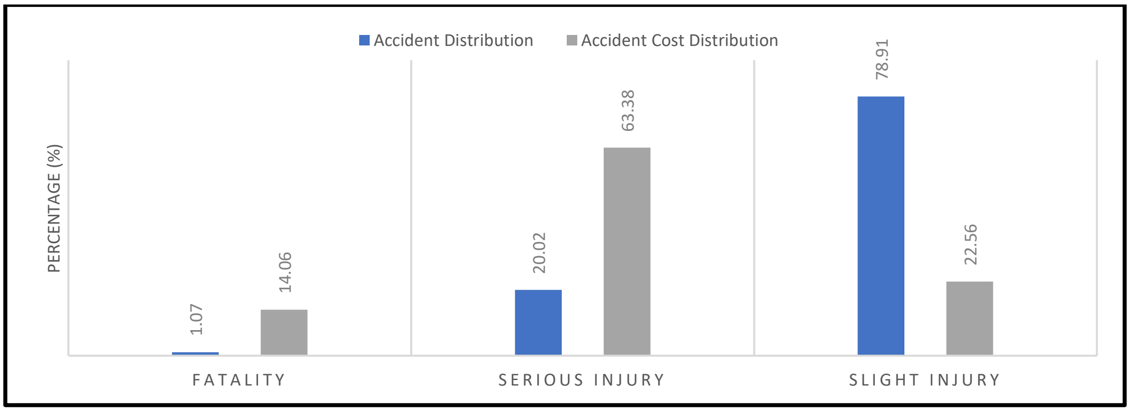
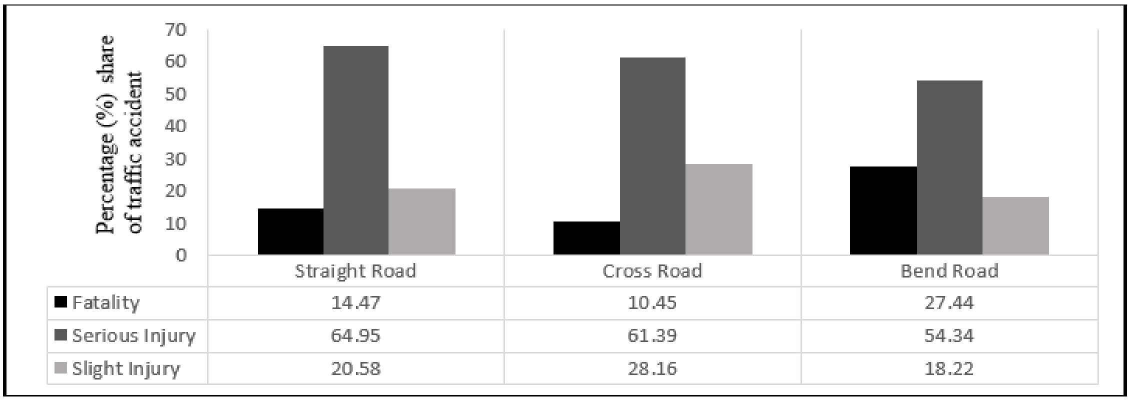
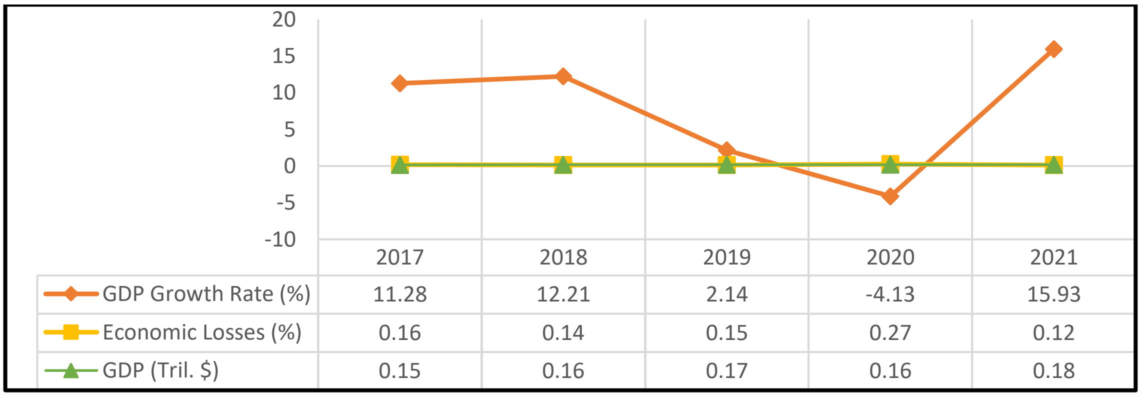


Figure B 18. Traffic crash cost distribution



| | Straight Road | Cross Road | Bend Road |
|---|---|---|---|
| ■ Fatality | 14.47 | 10.45 | 27.44 |
| ■ Serious Injury | 64.95 | 61.39 | 54.34 |
| ■ Slight Injury | 20.58 | 28.16 | 18.22 |

Figure B 19. Road geometry and crash cost distribution



| | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|
| GDP Growth Rate (%) | 11.28 | 12.21 | 2.14 | -4.13 | 15.93 |
| Economic Losses (%) | 0.16 | 0.14 | 0.15 | 0.27 | 0.12 |
| GDP (Tril. $) | 0.15 | 0.16 | 0.17 | 0.16 | 0.18 |

Figure B 20. GDP, annual growth rate and economic losses due to road traffic crash

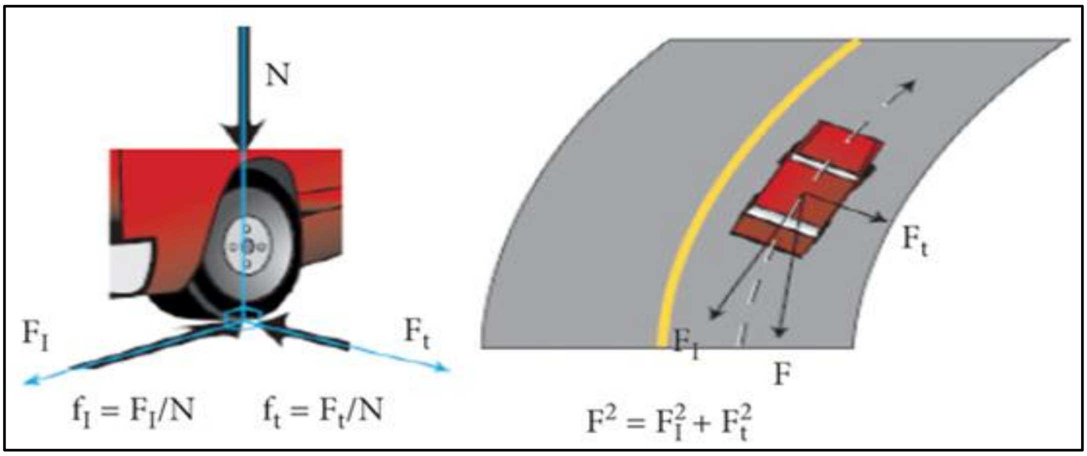


Figure B 21. How the frictional force gets applied on the contact surface of rubber and pavement.   Source: [226]

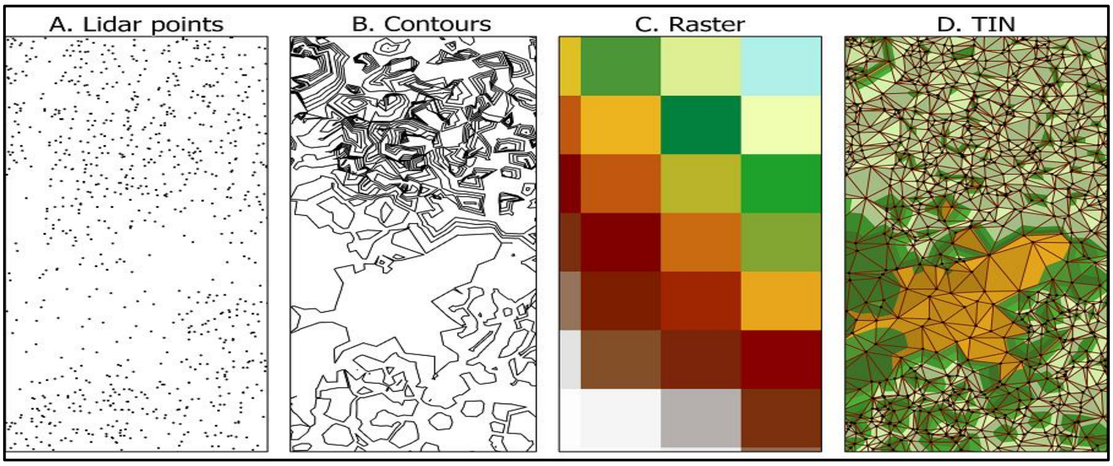


Figure B 22. Various approaches to depicting the same continuous surface in ArcGIS at the same scale and extent   *Source:* U.S. Geological Survey [240].

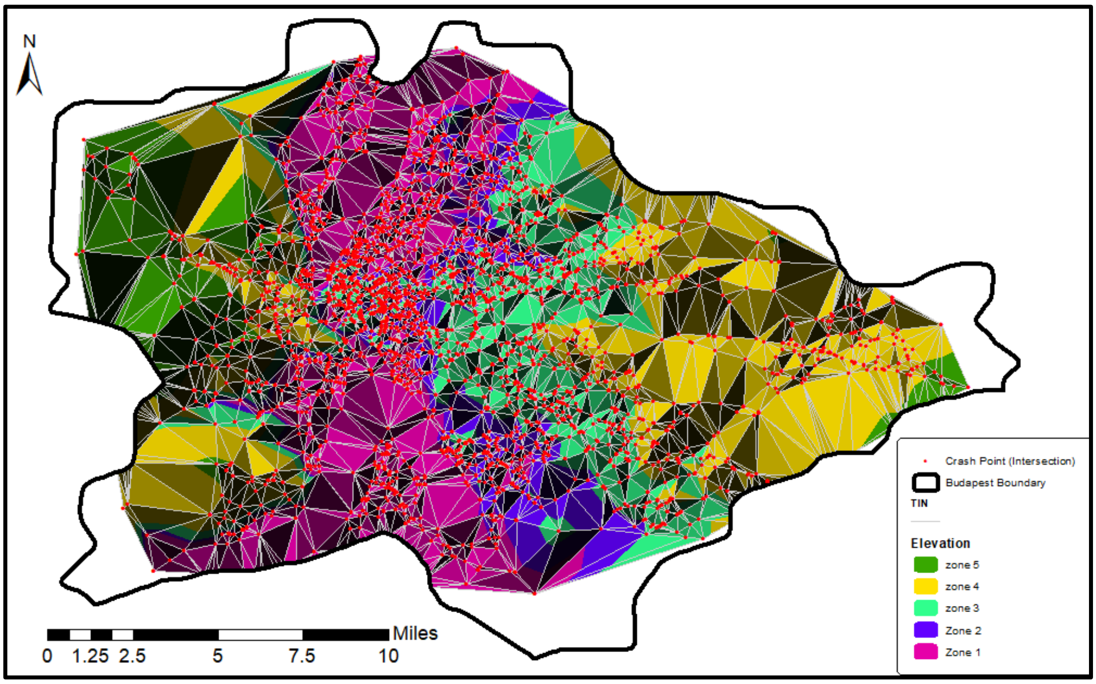


Figure B 23. Triangulation irregular network (TIN) and elevation difference between traffic crash locations or points.

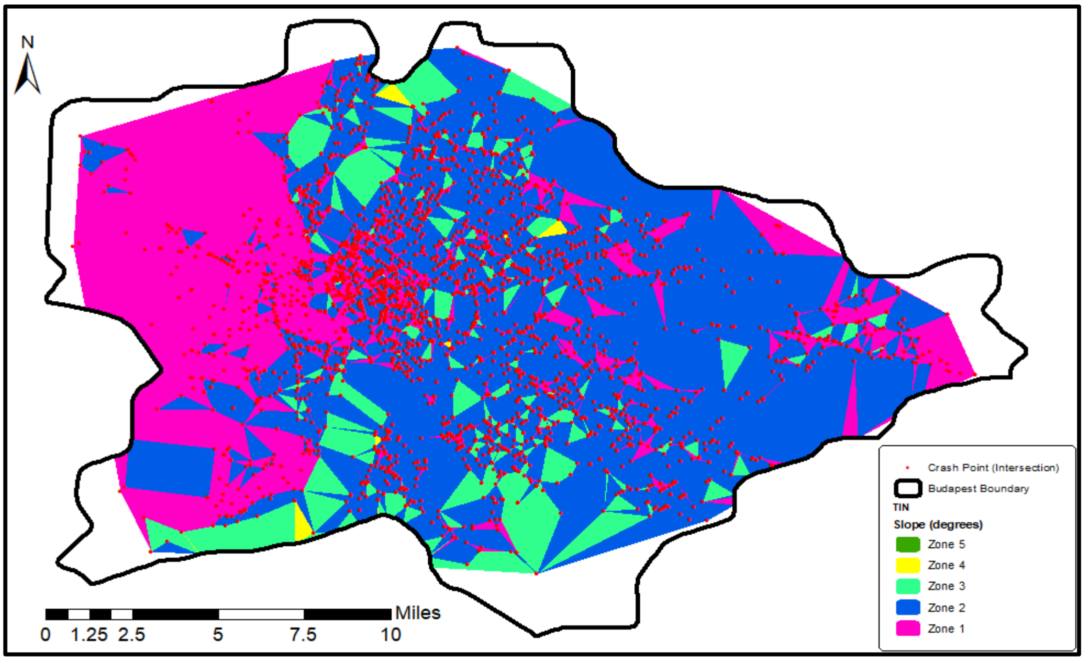


Figure B 24. Slope variation between traffic crash locations or points

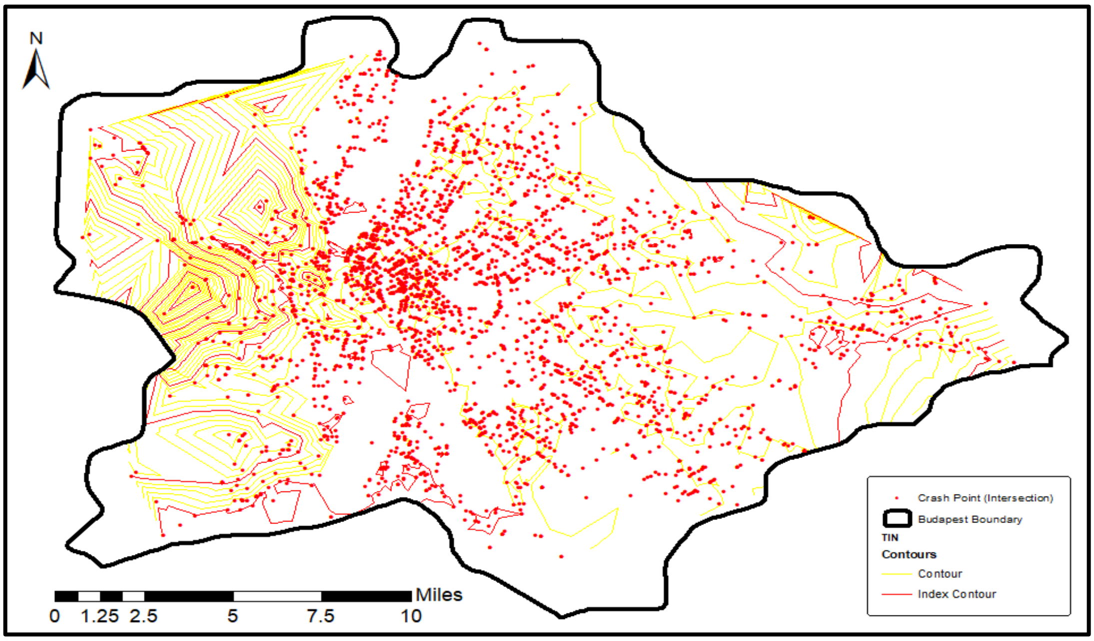


Figure B 25. Contour development and road traffic crash location/point

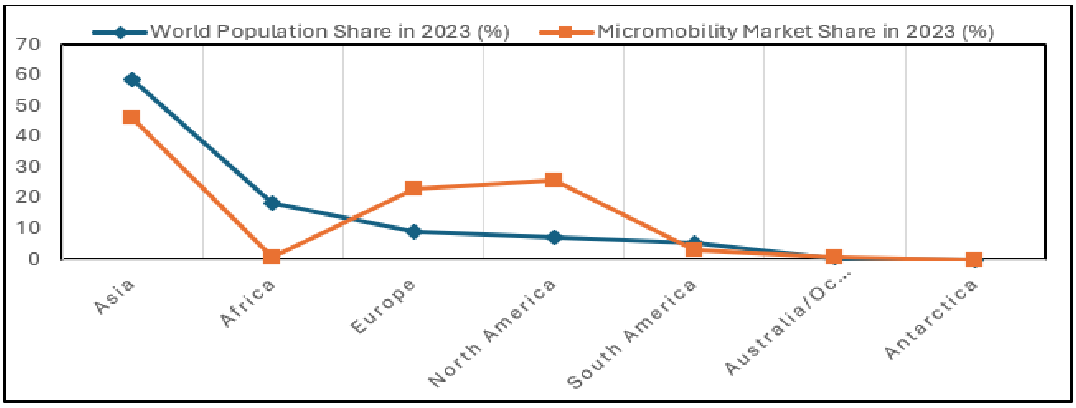


Figure B 26. Global population share vs. micromobility market share *Source*: **[318] [416]**

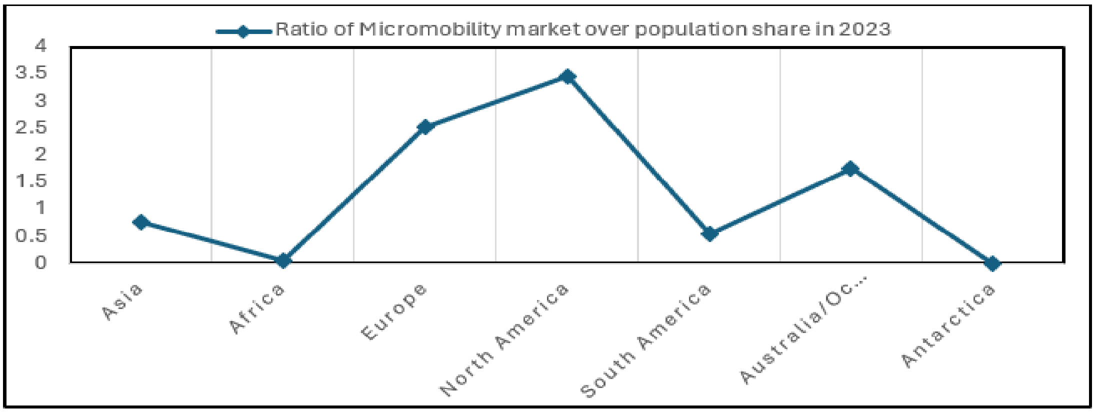


Figure B 27. The ratio of micromobility market share to population size in 2023

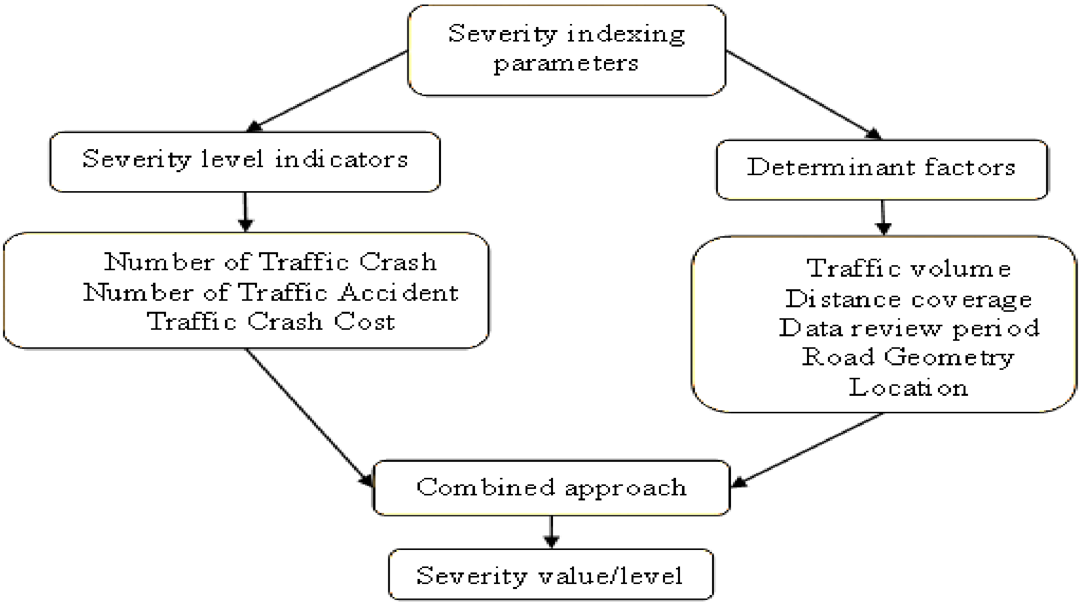


Figure B 28. Pillars and approaches of severity level analysis parameters