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College of Engineering

Civil Engineering Department

Evaluating and Modeling the Sustainability Indicators for Urban Road Network: Karbala City as A Case Study

A Thesis Submitted to the Council of the Faculty of the College of the Engineering/University of Karbala in Partial Fulfillment of the Requirements for the Ph.D in Civil/Infrastructure Engineering

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يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ

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Dedication

I dedicate that work to whom I proudly bear his name: my dear father

To the one who taught me patience and diligence, dear mother. To my darling husband Ali, who helped me all the time with my studies and encouraged me always

To my dear sons, Fatima, Hussain, and Ibrahim

To My Dear Brothers

Finally, to those who gave their lives for us to live: Martyrs of Iraq.

To all of these, I dedicate my scientific thesis.

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Abstract

The study presents a comprehensive, multidisciplinary, and context-sensitive assessment of urban transportation sustainability in Karbala City, Iraq. It aims to address the complex challenges facing urban mobility in rapidly developing cities by formulating a robust and adaptable analytical framework that integrates the environmental, social, and economic pillars of sustainability. In doing so, it bridges critical gaps in existing evaluation models, which often fail to account for the socio-spatial and infrastructural complexities of cities in the Global South.

To achieve its objectives, a multi-method approach was employed, combining the Analytic Hierarchy Process (AHP), Fuzzy Logic, and Geographic Information Systems (GIS). This methodological approach enabled the development of a flexible Multi-Criteria Decision-Making (MCDM) model capable of quantifying the sustainability performance of Karbala's urban road network in both spatial and conceptual dimensions. The work began with an extensive literature review encompassing 197 scholarly sources, from which 33 sustainability indicators were identified and systematically classified under environmental, social, and economic categories.

The case study focused on 18 major intersections and urban corridors within the central region of Karbala, particularly areas linking the Central Business District (CBD) with high-density residential, commercial, and institutional zones. Primary data were collected during peak traffic hours across three consecutive weekdays in October 2023. These data included vehicle counts, travel times, road geometry, accident rates, and environmental measurements such as noise levels and air pollutant

concentrations. Advanced instrumentation, such as the GASMET DX4040 FTIR gas analyzer, was utilized to monitor pollutants including CO_2, NO_2, SO_2, CH_4, NH_3, and benzene, providing real-time and high-accuracy environmental assessments.

Topological and geometrical analysis revealed that the road network, especially within the CBD, exhibits a fragmented, tree-like morphology characterized by low Alpha, Beta, and Gamma indices, as well as poor Relative Neighbourhood Graph (RNG) connectivity. These structural deficiencies result in poor accessibility, weak interconnectivity, and minimal route redundancy, ultimately undermining the resilience and efficiency of the transportation system.

Modal split analysis indicated a significant reliance on private vehicles, which accounted for 73% of peak-hour traffic, whereas buses and minibuses represented only 6% and 21%, respectively. This imbalance exacerbates congestion, increases travel delays, and raises operational and environmental costs. Notably, noise pollution levels in critical corridors such as Al-Tarbiya exceeded 107 dBA, far surpassing internationally accepted thresholds set by the WHO, CPCB, and EPA. Concurrently, air quality analysis demonstrated elevated concentrations of harmful pollutants, posing serious public health risks to residents, particularly in densely populated and poorly ventilated urban zones.

The sustainability evaluation using AHP revealed that environmental indicators held the highest significance, with a weight of 48.95%, followed by social (28.84%) and economic (22.22%) criteria. Overall sustainability scores across the study locations ranged between 29% and 39%, signaling widespread underperformance and the urgent need for targeted interventions.

To assess Karbala's performance against global benchmarks, a comparative analysis was conducted with international sustainability frameworks, including LEED (Leadership in Energy and Environmental Design), Green Star, CASBEE (Comprehensive Assessment System for Built Environment Efficiency), GSAS (Global Sustainability Assessment System), and BREEAM Communities. Except for BREEAM Communities, which showed passing ratings for all selected locations, the city's road network failed to meet the minimum thresholds required by other frameworks. This highlights the necessity for context-sensitive and locally adaptable assessment tools that better align with the conditions of developing cities.

GIS-based spatial modeling played a crucial role in visualizing and analyzing traffic dynamics, congestion hotspots, and environmental stress zones. These spatial outputs also enabled the identification of high-potential corridors for strategic development and sustainable infrastructure investment. However, several practical constraints to implementation were noted, including land tenure conflicts, inadequate municipal funding, institutional inertia, and resistance from local communities.

The research advocates for a paradigm shift in urban transportation planning, moving from fragmented and reactive approaches to integrated, forward-looking strategies grounded in sustainability. It emphasizes the importance of inclusive policy-making, data-driven decision support systems, and long-term planning frameworks that align with both local needs and global development agendas. The proposed framework is tailored to Karbala's urban fabric yet remains scalable and replicable, offering valuable insights for cities across the Global South facing similar developmental and environmental challenges.

In sum, the thesis contributes a novel and holistic sustainability assessment model that integrates scientific rigor with practical relevance. It equips urban planners, engineers, and decision-makers with tools to evaluate, design, and implement sustainable mobility solutions that enhance resilience, equity, and quality of life in complex urban environments.

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List of Abbreviations

Abbreviations	Meaning
ASCE	American Society of Civil Engineers
ASTM	American society for testing and materials
CED	Civil Engineering Department
CNNs	Convolutional neural networks
ECMT	European Conference of Ministers of Transportation
FHA	Federal Housing Administration
ITE	Institute of Transportation Engineers
OECD	Organization for Economic Co-operation and Development
ppb	parts per billion
ppm	parts per million
SSD	Single Shot MultiBox Detector
VMT	vehicle miles travelled
YOLO	You only look once
AHP	Analytic Hierarchy Process
GIS	Geographic Information Systems
RNG	Relative Neighbourhood Graphs
CBD	Central Business District
LEED	Leadership in Energy and Environmental Design
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
GSAS	Global Sustainability Assessment System
BREEAM	Building Research Establishment Environmental Assessment Method
ASCE	American Society of Civil Engineers

ASTM	American Society for Testing and Materials
ECMT	European Conference of Ministers of Transportation
FHA	Federal Housing Administration
ITE	Institute of Transportation Engineers
OECD	Organization for Economic Co-operation and Development
ppb	parts per billion
SSD	Single Shot MultiBox Detector
ppm	parts per million
VMT	Vehicle Miles Travelled

List of Symbols

Symbols	Meaning
A	area of the region
CF	the crossing factor
e	edge number of roads
L	length of road
η	eta index
v	vertex number of road
α	Alpha Index
β	beta index
γ	gamma index
GTP	Global Transportation Performance
TTI	Travel Time Index
PTI	Planning Time Index
LOS	Level of Service
FFS	Free Flow Speed
ATS	Average Travel Speed
CO_2	Carbon Dioxide
dBA	A-weighted Decibel
R, R^2	Correlation and Coefficient of Determination
Std. Error	Standard Error of Estimate
F	F-statistic (ANOVA)
df1, df2	Degrees of Freedom

Chapter One: Introduction

1.1 Introduction

The urban transportation network is an indispensable part of the urban socioeconomic system. Thus, promoting the sustainable development of the urban transportation network must come first to foster sustainable urban development. According to Xing *et al.* (2013), sustainable development should be incorporated into every process stage, including design, building, operation, and management of urban traffic systems. People are moving to cities at an alarming rate worldwide, which has increased the demand for urban housing and transportation. As a crucial component of national and international industrial systems driving profound global change, transportation is a subject that garners considerable attention and consideration from people. It unquestionably plays a crucial part in urban growth by connecting and supplying people with essential services such as education, markets, jobs, recreation, health care, and other vital services that fuel the rise of towns and cities (Sreelekha *et al.*, 2020). The availability of these crucial services drives urban growth. Al-Anbari *et al.* (2020) constructed efficient transportation systems, which, in turn, minimize the negative environmental consequences that the transportation sector has on the environment.

1.2 The problem statement

The city of Karbala is undergoing rapid urban and population growth, resulting in increased pressure on natural resources, public services, and infrastructure (Obaid, 2015). Despite the growing global and local awareness of sustainable development, Karbala lacks clear mechanisms for evaluating the effectiveness of sustainability indicators within its specific local context

(Allawi, 2022). Moreover, there is a noticeable absence of analytical models that capture the interrelationship and mutual influence among environmental, economic, and social factors. This gap limits the ability of policymakers and urban planners to develop evidence-based and effective strategies for sustainable urban development (Ameen *et al.*, 2019, Mohsin *et al.*, 2020, Al-Shebillawy *et al.*, 2024).

In the absence of customized sustainability assessment criteria tailored to the city's unique characteristics, urban planning in Karbala struggles to strike a balance between developmental needs and the preservation of natural resources (Ameen, 2021). Moreover, internationally adopted systems such as LEED and BREEAM may fall short in addressing the specific context of Karbala, resulting in inconsistent application of sustainability standards and a limited ability to accurately measure and analyze sustainable performance (Ameen, 2017).

A review of the literature highlights the existence of several environmental criteria that can be used to assess the impact of metropolitan transit options. However, these criteria have not yet been integrated into a comprehensive multicriteria decision analysis (MCDA) framework to evaluate the sustainability of urban transportation systems. Furthermore, assigning appropriate weights to these criteria remains a significant research challenge, especially given the variability in data availability and reliability across different geographic regions (Camargo Pérez *et al.*, 2015; Oppio *et al.*, 2022).

1.3 Research Hypothesis

By evaluating and modeling the sustainability indicators for the urban road network in Karbala City, the most influential factors in achieving infrastructure sustainability can be identified. In other words, improving the sustainability of the urban road network depends on a set of local indicators that reflect environmental, economic, and social performance. Therefore, developing a model to assess these indicators can contribute to enhancing planning and operational strategies to achieve a more efficient and sustainable urban road network.

1.4 Aim and objectives of the thesis

This study aims to analyze and evaluate the sustainability of the urban transportation and road network in Karbala by developing a comprehensive framework that integrates environmental, economic, and social dimensions. To achieve this aim, the study sets the following specific objectives:

1. Comprehensive Analysis of Urban Sustainability**:** Conduct a detailed analysis of the key sustainability factors in Karbala, considering the environmental, economic, and social aspects of urban development.
2. Application of the Analytic Hierarchy Process (AHP): Employ AHP to assign relative weights to sustainability criteria based on expert input, thereby creating a structured decision-making framework for evaluating urban sustainability.
3. Assessment of Current Sustainability Performance**:** Evaluate the current sustainability performance of Karbala by collecting and analyzing field data, and integrating the results using Fuzzy Logic to develop a composite sustainability index that reflects
4. The overall status of the city.
5. Urban Transportation Network Evaluation: Assess the structure and efficiency of the urban transportation network of Karbala through the

application of topological indicators such as Alpha, Beta, and Gamma indices.

6. Classification and Assessment of Urban Roads: Classify and evaluate the road network of a city using a hierarchical tree-like model that captures road connectivity and functional distribution to better understand its contribution to urban sustainability.
7. Spatial Modeling with Geographic Information Systems (GIS): Utilize GIS technologies to create spatial models that map the most sustainable streets and corridors in Karbala, facilitating the identification of high-priority areas for sustainable urban planning.
8. Benchmarking Against Global Standards: Benchmark the sustainability performance of Karbala against internationally recognized frameworks such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) to determine the level of compliance of the city with global sustainability standards.
9. Evidence-Based Policy Recommendations: Provide data-driven and evidence-based recommendations for enhancing the sustainability of the infrastructure and urban mobility systems in Karbala, based on the outcomes of the analytical models and empirical evaluations conducted in this study. Through these objectives, the study seeks to deliver a comprehensive assessment of Karbala’s urban sustainability and offer practical solutions for future improvements.

1.5 Thesis organization

The Thesis is organized into the following seven chapters:

- Chapter One: Introduction: Provides an overview of the urban transportation network, sustainability indicators, gas emissions in transportation, problem statement, research hypothesis, aims and objectives, and thesis organization.
- Chapter Two: Literature Review: Reviews the concepts and dimensions of sustainable transportation, methods for measuring and evaluating sustainable development, traffic and road network characteristics, sustainability criteria, and analytical approaches such as AHP and fuzzy logic.
- Chapter Three: Sustainable Transportation: Discusses the environmental, economic, and social dimensions of sustainability in urban streets, including traffic noise, gas emissions, public transportation, and sustainability aspects specific to urban road networks.
- Chapter Four: Methodology and Data Collection: Describes the study area, data collection tools, research methodology, and detailed traffic, environmental, and operational data gathered from various locations in Karbala.
- Chapter Five: Results and Discussion: Presents data analysis, including accessibility and network patterns, pollution and noise levels, traffic accidents, level of service, PVCI, AHP, and fuzzy logic evaluations, sustainability comparisons, and GIS-based modeling of the road network.
- Chapter Six: Suggested Sustainable Improvements: Proposes infrastructure and operational enhancements for the Karbala Road network, including ring roads, network gap closure, emission and noise reduction strategies, and public transportation improvements.
- Chapter Seven: Conclusions and Recommendations: Summarizes the main findings, provides recommendations for policy and practice, and suggests directions for future research.

Chapter Two: Literature Review

2.1 Introduction

This chapter examines several concerns about roads, including road sustainability, its dimensions, and principles, since road sustainability is regarded as a crucial and significant subject nowadays. Previously examined sustainability indicators were also recognized, and all indicators were cataloged. A substantial quantity of prior studies was collected, and an extensive array of study publications and their findings were examined. The fundamental sustainability criteria were delineated, including environmental, economic, and social dimensions. Statistical models concerning the weights of sustainability criteria were found, together with the characteristics of street networks, the functional and structural categorization of streets, service levels, congestion, travel time, and flow of streets.

2.2 Sustainable transportation: concepts and dimensions

Before delving into the criteria for sustainable transportation, it is essential first to establish a clear understanding of both “sustainability” and “sustainable transportation”. One of the most widely cited definitions of sustainability originates from the Brundtland Report (Barceló, 2019), which frames it as the ability to meet present needs without compromising the ability of future generations to meet their own (Basiago, 1995). Due to the abstract nature of this definition, scholars have developed more practical interpretations, most of which deconstruct sustainability into three key dimensions: environmental, social, and economic (Purvis *et al.*, 2019). These pillars overlap in areas such as socio-economic equity, environmental-economic efficiency, and social-environmental responsibility (Aldous, 2006). Sustainability is defined as integrating all the described elements

(Sdoukopoulos *et al.*, 2019), and none of the three dimensions must predominate (Kleine *et al.*, 2009). Some researchers argue that the environmental component is particularly critical, as it encompasses the concept of planetary boundaries. The core takeaway is that sustainability represents a balanced and equitable approach that addresses ecological concerns, social well-being, and economic performance simultaneously.

Nonetheless, most definitions continue to incorporate and emphasize social, environmental, and economic goals (Desing *et al.*, 2020). Banister created the most well-known concept (Gillis *et al.*, 2015) to improve the operational feasibility of sustainable transportation. The following are the elements of his idea, which are supplemented by statements from other important authors:

- Encouragement of a modal shift involves reducing car travel and promoting more ecologically friendly modes of transportation, such as bicycles and public transit. Shifting is supported by upgrading cycling and pedestrian facilities, promoting multimodality, limiting automobile parking spaces, and imposing higher road taxes. As a result, it is frequently the result of other mobility measures (Brög *et al.*, 2002).
- Minimizing the frequency of trips and shortening travel distances are key objectives, often achieved through traffic reduction strategies closely aligned with urban planning practices (Banister, 1999).
- Greater efficiency in transportation systems (Banister, 2008). The introduction of shared vehicle ownership and low-emission automobiles results in an improvement (Kraus *et al.*, 2021).
- The advancement of digital technologies provides users with a comprehensive range of mobility choices, promoting a shift in travel behavior away from private car usage (Hensher et al., 2020).

2.3 Measuring and evaluating sustainable development

Measuring any term, such as sustainability or sustainable development, necessitates first developing an operational definition. An operational definition should specify how the notion will be measured (Meier *et al.*, 2002). For example, an operational definition for meeting air quality standards for fine particulate matter (PM2.5) is: "Areas will comply with the annual PM2.5 standard when the 3-year average of the annual arithmetic mean PM2.5 concentrations is less than or equal to 15 g/m3." The operational definition establishes how air quality compliance (for fine particulates) will be measured. Mean PM2.5 concentrations serve as an indicator of compliance with air quality regulations.

The Brundtland Report's definition of sustainable development is probably the most frequently cited: "to ensure that [development] meets the needs of the present without jeopardizing future generations' ability to meet their own needs." Rather than an operational definition of sustainability, the Brundtland definition offers a general statement of principles. The economists' viewpoint provides one tractable technique to derive an "operational definition" of sustainability. The economist's perspective on sustaining the value of total capital, encompassing human, natural, social, and manufactured capital, can be applied if defined as the ability to "keep the capacity to deliver non-declining well-being across time" (Neumayer, 2003). By the mid-1990s, the World Bank had already stated that it would only fund projects that were "sustainable in economic, environmental, and social terms" (Serageldin, 1996, p. 2 [emphasis in original]) and, ostensibly, was defining sustainable development as a process by which current generations pass on as much, or more, capital per capita to future generations, with capital defined as human-made, natural, social, and human capital (Serageldin, 1996). That definitional approach suffers from measurement challenges, including, but not limited to, measuring the "stock" of social capital. Also, there are two competing - both non-falsifiable - positions regarding capital substitutability: "weak" sustainability (other forms of capital can substitute natural capital) and "strong" sustainability (other forms of capital cannot substitute natural capital). (rejecting such substitutability) (Neumayer, 2003).

2.4 Modelling the growth of transportation networks

Since Euler (1736) introduced the first transportation network in a scientific sense in the classical problem of the seven bridges of Konigsberg, professionals and academics have had a long-standing interest in gaining a deeper understanding of transportation network systems and their temporal changes. That topic has been the subject of voluminous written work (Euler, 1741). Fullerton (1975) introduced the evolution of British transportation networks (Fullerton, 1975), Taaffe et al. (1996) outlined the evolution of US transportation systems (Taaffe *et al.*, 1996), and Garrison and Levinson (2014) analyzed transportation experience throughout the centuries from the perspectives of transportation policy, planning, and deployment (Garrison *et al.*, 2014). Transportation network development is a multifaceted and evolving process that encompasses a wide array of dimensions. These include topological aspects (such as the creation or removal of connections between locations and facilities), morphological characteristics (like alterations in infrastructure form and layout), technological innovations (including new transport modes, improved pavement quality, and intelligent systems), economic factors (such as tolls, taxation, privatization, or nationalization), managerial interventions (e.g., regulations and traffic signal management), and political influences. Although the expansion of transport systems is inherently complex and typically unfolds over extended periods often measured in decades it can become more manageable and predictable when the driving mechanisms are thoroughly understood. In line with this understanding, disciplines such as transportation engineering, geography, regional science, urban planning, economics, and the natural sciences have committed substantial effort to the modeling and analysis of transportation networks.

Historically, five principal research trajectories have emerged. During the 1960s and 1970s, geographers approached network development as a topological transformation, seeking to either capture the processes behind structural evolution or replicate the spatial configurations of emerging transportation systems. From the 1970s onward, the widespread adoption of travel demand forecasting models equipped transportation economists and planners with tools to estimate traffic volumes and to simulate optimal network modifications, under the assumption that network growth stems from rational choices made by authorities, developers, and property owners in response to market dynamics and policy directives. With the rise of data availability and computational power, large-scale statistical studies have more recently examined how changes in transportation supply, such as infrastructure presence, service capacity, or frequency, correlate with socio-economic and demographic profiles of surrounding areas, as well as with infrastructure attributes and traffic performance. Economic analyses of network evolution further investigate the financial dimensions of development, drawing from transportation and public economics, network externalities, path dependency, and the formation of cooperative arrangements. Since the 1990s, the emergence of network science has introduced new perspectives on the dynamics of complex systems. Concepts like preferential attachment and self-organization have been employed to frame network development as a spontaneous and adaptive process.

2.4.1 Multi-Criteria Decision-Making (AHP, TOPSIS, etc.)

The Analytic Hierarchy Process (AHP) is a well-established multi-criteria decision-making (MCDM) approach introduced by Saaty in the 1970s. It has been widely applied for the analysis and structuring of complex decision scenarios. The methodology begins by breaking down the decision problem into a hierarchical structure of criteria and sub-criteria (Dagdeviren et al., 2009). AHP supports decision-makers by enabling them to assign weights to each criterion through systematic pairwise comparisons (Liberatore & Nydick, 1997; Yoo & Choi, 2006; Panda et al., 2014).

As outlined by Saaty and Vargas (2001) and further refined by Saaty (2008), the AHP process follows a series of well-defined steps:

Step 1: Construct the hierarchical structure of the decision problem, clearly identifying the overall objective, along with relevant criteria and sub-criteria.

Step 2: Develop a comparison matrix by performing pairwise comparisons among elements at each level, using Saaty's fundamental scale of relative importance as presented in Table 2.1.

Step 3: Compute the relative weights of the elements by deriving the eigenvector associated with the matrix’s largest eigenvalue.

Step 4: Assess the consistency of the pairwise judgments by calculating the Consistency Index (CI) and the Consistency Ratio (CR), ensuring the logical coherence of the comparisons (Sato et al., 2023).

$$CI = \frac{\lambda \max - n}{n-1} \qquad 2.1$$

where λ_{max} is the Eigenvalue corresponding to the matrix of pair-wise comparisons, and n is the number of elements being compared.

Consistency ratio (CR) is defined by (Sato *et al*.,2023:

$$CR = \frac{CI}{RCI} \qquad (2.2)$$

The Random Consistency Index (RCI), presented in Table 2.2, is used to evaluate the level of consistency in pairwise comparisons. A Consistency Ratio (CR) value below 0.1 is typically considered acceptable; if the CR exceeds this threshold, the judgments should be reviewed and adjusted to improve consistency.

Table 2-1: Scale of pair-wise comparison for AHP (Sato *et al*.,2023)

Relative importance	Definition
1	Equal importance
3	Weak importance
5	Strong importance
7	Demonstrated importance over the other
9	Absolute importance

Table 2-2: Average RCI values (Sato *et al*.,2023)

Number of criteria (n)	RCI
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

2.4.2 Fuzzy logic in setting standards and rating methods

In many scientific and engineering fields, researchers and designers often face challenges in dealing with imprecise data or standards that are difficult to express using exact or binary values. For instance, describing concepts such as 'good performance,' 'appropriate temperature,' or 'acceptable quality level' is not always feasible using strict numerical values (Celikyilmaz *et al.*, 2009).

Fuzzy Logic extends classical logic by allowing values to range continuously between 0 and 1 rather than being limited to only 0 or 1.

1. Defining Variables and Linguistic Terms: The first step in applying fuzzy logic is identifying the main variables under consideration and transforming them into linguistic variables. For example, a variable like 'temperature' can be classified into linguistic terms such as 'Low,' 'Medium,' and 'High.'

2. Assigning Membership Functions: Each linguistic term is associated with a membership function that defines the degree to which a numerical value belongs to a given category. These functions can be triangular, trapezoidal, or Gaussian in shape.

3. Building Fuzzy Rules: Based on the relationships between linguistic variables, fuzzy rules are constructed using 'IF...THEN...' statements. For example: 'IF performance is high AND consumption is low, THEN efficiency is high.' These rules form the basis for inference and decision-making.

4. Fuzzy Inference and Defuzzification: After applying the rules, fuzzy inference is used to compute the output. The final step is defuzzification, which converts fuzzy results into a precise value using

methods such as the centroid or weighted average method (Celikyilmaz *et al.*, 2009).

This methodology is more flexible and realistic than traditional binary approaches, making it widely applicable in intelligent control systems, performance evaluation, quality improvement, and predictive modeling.

Table 2-3: Example of Converting Numeric to Linguistic Variable (Temperature) (Stach *et al.*, 2008)

Numeric Value (°C)	Linguistic Variable
10 – 20	Low
18 – 30	Medium
28 – 40	High

Table 2.3 defines the fuzzy classification of temperature values in degrees Celsius into three linguistic variables: Low, *Medium*, and High. The *Low* temperature range is restricted between 10°C and 20°C, the Medium spans from 18°C to 30°C, and the High range spans from 28°C to 40°C. These intervals are intentionally overlapping to accommodate the nature of fuzzy logic, where a specific temperature can belong to more than one linguistic category with varying degrees of membership. This approach enhances the flexibility and realism of temperature-related reasoning in fuzzy inference systems.

Table 2-4: Example of Membership Degrees (Stach *et al.*,2008)

Temperature (°C)	Low	Medium	High
15	1.0	0.0	0.0
22	0.2	0.8	0.0
28	0.0	0.3	0.7
35	0.0	0.0	1.0

Table 2.4 illustrates the fuzzy membership values of selected temperature points (in °C) across three linguistic variables: Low, Medium,

and High. At 15°C, the temperature is fully classified as Low with a membership degree of 1.0, and has no affiliation with the other categories. At 22°C, the temperature exhibits partial membership in both Low (0.2) and Medium (0.8), indicating a transitional state between these two categories. Similarly, 28°C shows a partial degree of membership in both *Medium* (0.3) and *High* (0.7), reflecting its position within the overlapping region of those categories. Finally, at 35°C, the temperature is fully associated with the *High* category (1.0), and shows no membership in either *Low* or *Medium*. These membership values demonstrate the fundamental concept of fuzzy logic, where a single input may belong to multiple linguistic terms to varying degrees, enabling more nuanced and human-like reasoning.

Table 2-5: Example of Fuzzy Rules (Stach *et al*.,2008)

Rule	IF (Condition)	THEN (Result)
Rule 1	Temperature is Low	Ventilation Level is Low
Rule 2	Temperature is Medium	Ventilation Level is Medium
Rule 3	Temperature is High	Ventilation Level is High

Table 2.5 outlines a set of fuzzy inference rules used to determine the appropriate ventilation level based on temperature conditions. Each rule follows the standard "IF–THEN" structure commonly employed in fuzzy logic systems.

Rule 1 states that if the temperature is classified as *Low, then* the ventilation level should also be set to Low.

Rule 2 assigns a Medium ventilation level when the temperature is assessed as Medium.

Rule 3 suggests that High temperatures require a High level of ventilation.

These rules reflect a direct and intuitive mapping between the temperature range and the corresponding ventilation response. By applying these fuzzy rules in conjunction with the defined membership functions, the system is capable of making flexible and gradual control decisions rather than binary outputs, which is a key advantage of fuzzy logic-based control strategies.

Table 2-6: Example of defuzzification (Stach *et al*.,2008)

Fuzzy Output Value	Weight (Membership Degree)	Final Result (e.g., Ventilation Level)
Low (20%)	0.2	
Medium (50%)	0.5	→ Weighted Average = (0.2×1 + 0.5×2 + 0.3×3) ÷ 1.0 = 2.1
High (30%)	0.3	

Table 2.6 demonstrates the defuzzification process using the weighted average **(**centroid**)** method to derive a crisp output from fuzzy rules applied to a ventilation control system. Three fuzzy output categories, Low, Medium, and High, are assigned respective membership degrees (weights): 0.2, 0.5, and 0.3. These weights represent the degree to which each output category is activated based on the fuzzy inference process.

2.5 Evaluate studies

Table 2.7 provides a concise overview of each referenced study, highlighting the incorporation of sustainability criteria, the use of specific evaluation frameworks, and the methods employed for selecting relevant indicators. Nearly all studies applied targeted criteria to assess the sustainability of different transportation initiatives. These applications span a global context, including regions in Europe, Asia, and the Americas. A significant portion of the research focused on urban transportation projects, with Bojković et al. (2010) being the only study to examine sustainability at the national transportation system level. Notably, approximately 81% of the reviewed literature addressed all three pillars of sustainability: social, environmental, and economic. It is important to acknowledge that variations in terminology and presentation exist across the reviewed publications. Castillo *et al.* (2010), for example, refer to the social dimension as "equity and social inclusion". More than half of the respondents (52%) added one or more new dimensions, such as technology, efficiency, or system effectiveness. Only Gössling *et al.* (2019) included walking in their sustainability assessment. Only two publications, along with Castillo *et al.* (2010), were about cycling, which is notable because those are believed to be types of active and thus healthy transportation (Banister, 2008). A literature review was the most commonly utilized method of data collecting, appearing in 95% of all studies. For clarification, several authors included expert interviews. Most authors utilized criteria to assess the sustainability of transportation choices. Only one publication used criteria to provide a broad definition of what sustainable transportation entails.

Table 2-7: Studies containing sustainable transportation indicators.

	Author (s)	No. of criteria	Sustainability Dimension (Social, Environmental, Economic	What Criteria Are Used for
			other	
1	(Awasthi et al., 2018) (Awasthi *et al.*, 2018)	31	Technical	Evaluation of alternatives with multicriteria decision-making
2	(Bandeira et al., 2018) (Bandeira *et al.*, 2018)	14	-	Evaluation of alternatives with multicriteria decision-making
3	(Monzon et al., 2009) (Monzon *et al.*, 2009)	9	-	analyzing the sustainable transport
4	(Shiau and Liu, 2013) (Shiau *et al.*, 2013)	21	Renewable energy	integrating bus-exclusive lanes

	Author (s)	No. of criteria	Sustainability Dimension (Social, Environmental, Economic	What Criteria Are Used for
			other	
5	(Alonso et al., 2015) (Alonso *et al.*, 2015).	28	-	creation of composite indicators (CI) to measure the sustainability
6	(Toth-Szabo and Várhelyi, 2012) (Toth-Szabo *et al.*, 2012)	8	-	Monitor the sustainability of transport.
7	(Zito and Salvo, 2011) (Zito *et al.*, 2011)	29	-	Achieve a more sustainable mobility.
8	(Marletto and Mameli, 2012) (Marletto *et al.*, 2012)	13	-	Manage the high level of uncertainty and incommensurability feature.
9	(de Freitas Miranda and da Silva, 2012) (de Freitas Miranda *et al.*, 2012).	9	System effectiveness	Indicators as assessment tools for sustainable transport
10	(Nicolas et al., 2003) (Nicolas *et al.*, 2003)	13	Efficiency Safety Employing advanced technology	Indicators as assessment tools for sustainable transport
11	(Santos and Ribeiro, 2013) (Santos *et al.*, 2013)	16	Sustainable Transportation Intersections	Indicators as assessment tools for sustainable transport
12	(Bojković et al., 2010) (Bojković *et al.*, 2010)	16	-	Evaluation of alternatives with multicriteria decision-making
13	(Camargo Pérez et al., 2015) (Camargo Pérez *et al.*, 2015)	29	Technical and logistics (or economic) Safety (or social) Land use (or social/environmental)	Review of the criteria used in previous multicriteria decision analysis studies
14	(Castillo and Pitfield, 2010) (Castillo *et al.*, 2010)	46	Livable streets and neighborhood Health and safety	Indicators as assessment tools for sustainable transport
15	(de Almeida Guimarães and Junior, 2017) (de Almeida Guimarães *et al.*, 2017)	20	-	Performance evaluation of the eco-efficiency of alternatives
16	(Gössling et al., 2019) (Gössling *et al.*, 2019)	14	Travel time and vehicle operation Health, accidents, and perceived comfort Perceived safety and discomfort(Environmental only)	Parameters for executing a comparative cost-benefit analysis
17	(Kumar and Anbanandam, 2019) (Kumar *et al.*, 2019)	73	Environmental and Economic only	Input for a social sustainability index
18	(Liang et al., 2019) (Liang *et al.*, 2019)	13	Technological	Criteria for group decision support on alternatives

	Author (s)	No. of criteria	Sustainability Dimension (Social, Environmental, Economic	What Criteria Are Used for
			other	
19	(Malvestio et al., 2018) (Malvestio *et al.*, 2018)	16	Without Economic	Items to analyze documents of policy projects regarding social and environmental issues
20	(Miller et al., 2016) (Miller *et al.*, 2016)	16	System effectiveness	Indicators for sustainability analysis of alternatives
21	(Nag et al., 2018) (Nag *et al.*, 2018)	6	-	Sustainability assessment with Analytical Hierarchy Process
22	(Pathak et al., 2019) (Pathak *et al.*, 2019)	34	Efficiency Safety Employing advanced technology	Assessment of sustainability performance in an index
23	(Sdoukopoulos et al., 2019) (Sdoukopoulos *et al.*, 2019)	47	Sustainable Transportation Intersections	Overview of indicators previously used for sustainability performance measurement
24	(Shankar et al., 2018) (Shankar *et al.*, 2018)	9	-	Sustainability risk assessment regarding different goals
25	(Shiau, 2012) (Shiau, 2012)	10	Finance Energy	Priority ranking after a sustainability compound index assessment
26	(Stefaniec et al., 2020) (Stefaniec *et al.*, 2020)	6	-	Input for efficiency analysis
27	(De Campos et al., 2019) (De Campos *et al.*, 2019)	26	-	Impact evaluation of different fleets
28	(Yadav et al., 2017) (Yadav *et al.*, 2017)	21	Quality of Life Mobility System Performance (without Scial)	General explication of sustainable mobility
29	(Yang et al., 2016) (Yang *et al.*, 2016)	12	Financial feasibility of Sustainable transport (without Economic)	Evaluation criteria Evaluation Criteria for an Analytic Network Process
30	(Yazdani et al., 2020) (Yazdani *et al.*, 2020)	15	-	Input for multicriteria decision-making
31	(Liu et al., 2022) (Liu *et al.*, 2022)	14	-	Assessment of sustainability
32	(Jiang et al., 2022) (Jiang *et al.*, 2022)	20	System effectiveness	performance in an index
33	(McLeod and Curtis, 2022) (McLeod *et al.*, 2022)	63	-	Assessment of sustainability
34	(Hasan et al., 2022) (Hasan *et al.*, 2022)	13	Efficiency Safety Employing advanced technology	performance in an index

	Author (s)	No. of criteria	Sustainability Dimension (Social, Environmental, Economic	What Criteria Are Used for
			other	
35	(Li et al., 2022) (Li *et al.*, 2022)	16	Sustainable Transportation Intersections	Assessment of sustainability
36	(Boeing, 2022) (Boeing, 2022)	16	-	Indicators as assessment tools for sustainable transport
37	(Petrova et al., 2022) (Petrova *et al.*, 2022)	6	Finance Energy	Indicators as assessment tools for sustainable transport
38	(Shang et al., 2022) (Shang *et al.*, 2022)	34	-	Indicators as assessment tools for sustainable transport
39	(Zhang et al., 2022) (Zhang *et al.*, 2022)	47	-	Indicators as assessment tools for sustainable transport
40	(Boeing et al., 2022) (Boeing *et al.*, 2022)	9	System effectiveness	Indicators as assessment tools for sustainable transport

As detailed in the section on evaluating studies and summarized in Table 2.7, discrepancies were observed across the reviewed studies regarding the classification of dimensions or hierarchical levels, as well as the terminology used to describe them. These differences can be attributed to the diverse structuring methods and inconsistent nomenclature employed by various authors. In light of this, and to establish coherence throughout this thesis, a standardized framework is introduced below. This framework consolidates the hierarchical levels and sublevels identified in prior research and provides clear definitions to ensure consistency in their application throughout the subsequent analysis.

• The economy, society, and the environment are all components of sustainability, according to the 2030 Agenda for Sustainable Development (Nationerna, 2015). In addition to a few others, most of the authors in the reviewed literature used the terms dimension[(Bojković *et al.*, 2010), (Nag *et al.*, 2018), (Pathak *et al.*, 2019)] or category [(Awasthi *et al.*, 2018), (Bandeira *et al.*, 2018), (Malvestio *et al.*, 2018)] for social, economic, and environmental issues.

• Associated or similar subjects are grouped into several categories [(Miller *et al.*, 2016)], which are referred to in the evaluated publications as themes [(Bojković *et al.*, 2010) (Sdoukopoulos *et al.*, 2019) (Nag *et al.*, 2018)] or enablers [(Kumar *et al.*, 2019)] and occur along certain dimensions.

• A goal differs from an aim in that an objective implies a direction (to minimize or increase) [(Bryce *et al.*, 2014), (Keeney, 1996)]. In the literature, that phrase is not defined at all.

• According to Litman (2021), the sustainability goals should be higher in the hierarchy than the objectives. Both serve as guiding principles for the selection of indicators (Cohen, 2017), while the purpose is the overall goal to be measured, which is sustainable transportation.

• Attributes and criteria are utilized interchangeably and serve as performance indicators for the goal they characterize and operationalize. They must be measurable, intelligible, and operational to describe their aims. As a result, criteria must not be ambiguous; each level of success indicated by a criterion must have a meaning (Keeney, 1996), although criteria can also be qualitative expressions of objectives (Litman, 2021).

• The indicators serve as a scale against which a project's contributions to the various objectives are measured. Measurability is required for indicators. That is the most straightforward term in the literature.

2.6 Categorizing criteria

Related thematic criteria were grouped, and key elements were redefined using comprehensive phrases. Criteria with multiple distinct interpretations were first disaggregated and categorized under specific themes such as noise and vibration (Malvestio et al., 2018), safety and health (Shankar et al., 2018), safety, health, and security (De Campos et al., 2019), as well as speed and ease of service. This approach led to the formulation of five newly defined criteria. In the second stage, when authors applied multiple criteria with nearly synonymous meanings within the same dimension, those criteria were consolidated. For instance, the combination of "transit accidents" and "accident impact reduction" was unified under a broader category of incidents. As Stewart and Lord (Stewart et al., 2002) argued, the term "crash" encompasses both unintentional incidents and those resulting from deliberate or reckless behavior, thereby offering a more inclusive alternative to "accidents."

Furthermore, concentrations of air pollutant emissions and per capita air pollutant emissions were merged. Combinations reduced the number of criteria assessed by 11 in total. That process is shown in Figure 2.1.

A total of 202 individual criteria were initially identified and grouped into broader primary categories based on their relative importance. This process resulted in 38 consolidated key criteria, each serving as an umbrella term for conceptually similar elements. The paragraphs below provide a concise overview of selected key criteria and their associated components. In some cases, specific pollutants (e.g., PM_{10} or NO_x) were used as indicators of air pollution. In other instances, the scope extended too broadly to encompass land and water contamination. Consequently, air pollution was selected as a primary criterion, offering a balanced scope neither overly narrow nor excessively broad.

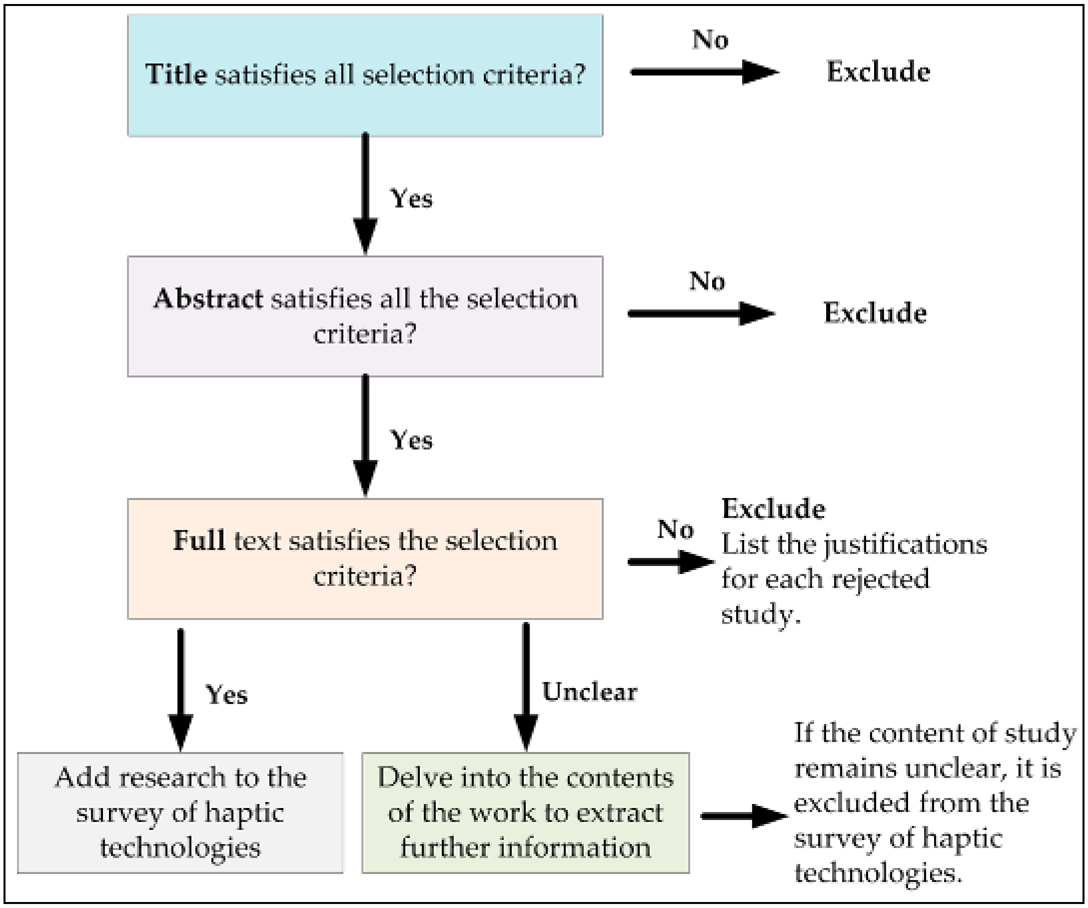


Figure 2.1:Explain the chosen paper in terms of the criteria (De Fazio et al., 2022).

The energy consumption criterion encompassed various subcomponents, including total energy use, energy intensity and efficiency, fossil fuel consumption, and natural resource utilization. Noise-related criteria such as noise pollution, perceived noise, measured decibel levels, and noise reduction strategies were integrated under the main noise criterion (De Campos et al., 2019).

Greenhouse gas emissions were considered relevant to both air pollution and climate change. Safety-related criteria focused on minimizing risk, defining safety standards, and enhancing perceived safety. The main health criterion included elements such as health benefits, exposure to health hazards, injury severity, traffic-related casualties, and health impacts from air pollution. Operating costs were defined to include implementation, maintenance, and fuel expenditures, excluding the initial capital investment. Travel time typically refers to commuting duration and the time needed to reach the nearest public transportation node (Miller et al., 2016).

Accessibility was also interpreted in terms of inclusivity for elderly and disabled individuals. Similar criteria were effectively grouped under the corresponding primary categories (Shiau, 2012). Once the primary criteria were finalized, they were assigned to the sustainability dimensions of social, economic, and environmental, most frequently cited in the literature. An exception was made for the criterion of travel time. Although it was often discussed in an economic context, it was reclassified under the social dimension, reflecting its greater relevance to passenger experience rather than service provider costs.

Certain criteria were excluded from the final framework, including frequency, customer satisfaction, alternative propulsion technologies, public transportation, and societal costs. After this refinement, 33 main criteria remained, accounting for 197 references across the literature. These were distributed among the three sustainability dimensions and ranked in Table 2.7 based on the frequency of citation. The application of the noise criterion varied, appearing in both environmental and social contexts. Additionally, journey time and affordability were recognized as overlapping dimensions, depending on whether the perspective was that of the user or the provider.

Ultimately, 13 key criteria were associated with the social dimension, 11 with the economic, and 9 with the environmental. In terms of citation frequency, social criteria were mentioned most often (42%), followed by environmental (37%) and economic (21%) dimensions. Notably, the three most frequently cited criteria were environmental, supporting the notion that environmental sustainability serves as a foundation for the social and economic aspects of sustainable transportation.

2.7 Classification of Sustainability Criteria

Indicators were proposed to exemplify the criteria to be measured, and the underlying objective of each criterion was extracted from the systematic literature review. To apply the criteria to a specific situation, they must be chosen from Figure 2.2 by assessing the availability of data relevant to the particular use case and the consistency of the set of criteria selected later, among other things.

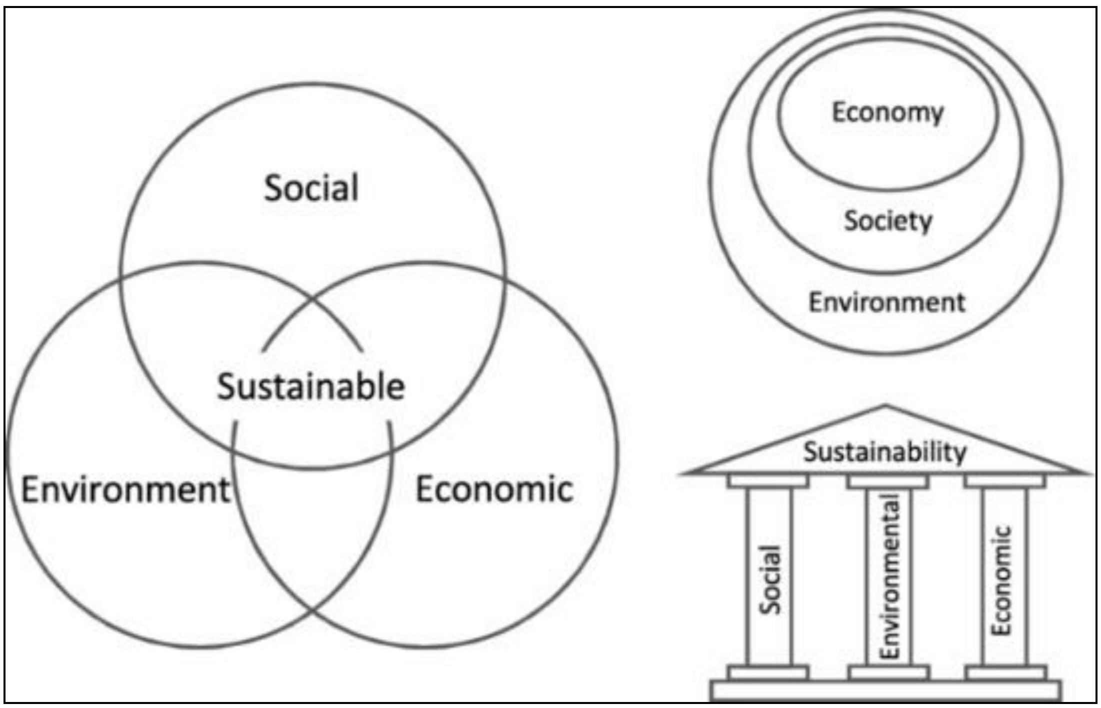


Figure 2.2: Depicts the main sustainability criteria (Bastante-Ceca et al., 2020).

The sustainable transportation measurement hierarchy is shown in Table 2.8.

Table 2-8:Sustainable transportation measurement

Dimension	objective	Criterion	Indicator
Environmental(Humphreys	Air pollution	Air pollution	Air pollution from transportation (

Dimension	objective	Criterion	Indicator
et al., 2003)	impact(min) (SIERRA-VARGAS *et al.*, 2012)		
	Passenger energy use (min) (Liu *et al.*, 2015)	Energy consumption	The ratio of passenger-km to respective energy consumption (max)
	Noise pollution impacts (min) (Lokhande *et al.*, 2018)	Noise	Noise pollution [dB levels)
	Climate change due to emitted (Hensher, 2008)	GHG emissions	Emission intensity of GHG [CO2 eq/pkm]
	Renewable energy usage (max) (Saray *et al.*, 2024)	Renewable energy	Share of renewables in overall energy consumption [%]
	Carbon footprint (min) (Postorino *et al.*, 2014)	CO2 emissions	CO2 emission from fossil fuel consumption [Gg CO2]
	Use of natural resources (min) (Potravny *et al.*, 2022)	Natural resource consumption	Degree of depletion of natural resources [%]
	Use of environmentally friendly modes (max) (Kreutzberger *et al.*, 2003)	Non-motorized modes	Share of non-motorized trips in overall trips [%]
	Vibration level (min) (Jarimopas *et al.*, 2005)	Vibration	Vibration level [Hz]
Social (Tiwari, 2003)	Protection against accidents (max) (Zapetri *et al.*, 2023)	Safety	The ratio of injured people to Km travelled per mode (per day) (min)
	Health impacts (min) (Mueller *et al.*, 2015)	Health	Injury severity level [-]
	Speed of transportation service (max) (Psaraftis *et al.*, 2013)	Travel time	Average speed in city[km/h]
	Equity & social	Accessibility	Mental accessibility [-]

Dimension	objective	Criterion	Indicator
	inclusion (max) (Manaugh, 2013)		
	Traffic clogging (min) (Marcaida *et al.*, 2018)	Congestion	Time spent travelling under congested conditions [minutes]
	Efficient pricing (max) (Roberts, 1970)	Affordability	The ratio of user cost for transportation to household income [%] (min)
	Road transportation accidents (min) (Wei *et al.*, 2021)	Accidents	Accident rate from traffic, including injuries and fatalities [-]
	Protection against thefts (max) (Cedillo-Campos *et al.*, 2024)	Security	Share of the population feeling safe against thefts & violation [%]
	Ease of reaching major location (max) (Mitra *et al.*, 2016)	Reachability	Time to get to next transportation mode [minutes] (min)
	Stakeholder participation (max) (Duleba *et al.*, 2018)	Participation	Share of steps with public involvement in transportation planning in all steps [%]
	Suitability to disabled customers (max) (Wu, 2009)	Equality	Share of citizens with physical access to overall citizens [%]
	Private car replacement (max) (Ogata *et al.*, 2022)	Fewer private cars	Number of private cars replaced [-]
	Protection against danger and risk (max) (Fisichella *et al.*, 2006)	Risk and danger	Perceived risks and danger [-] (min)
Economic (Zheng *et al.*, 2011)	Cost of operating a transportation made (min) (Mohring, 1972)	Operation cost	Operational, maintenance, and fuel costs [Dinar Iraqi]
	Transportation intensity (max) (Arvin *et al.*, 2015)	Occupancy	Overall system capacity utilization rate [%]
	Profit for the transportation operator	Revenues	The ratio of revenues to cost (investment or operational) [%]

Dimension	objective	Criterion	Indicator
	(max) (Li *et al.*, 2012)		
	Speed and ease of service (max) (Chica-Olmo *et al.*, 2018)	Quality	The time needed to handle customer complaints queries [day] (min)
	System economic efficiency (max) (Bian *et al.*, 2016)	Investment cost	Capital cost [Dinar Iraqi] (min)
	A positive attitude toward transportation means (max) (Green *et al.*, 2000)	Demand	Number of (potential) users [-]
	System independence (max) (Ganin *et al.*, 2019)	Subsidy	The sum of public expenditures, investment, and subsidies [Dinar Iraqi] (min)
	System reliability (max) (Shlayan *et al.*, 2011)	Reliability	Availability of transportation mode (on time) [%]
	Project viability (max) (Jeong *et al.*, 2016)	Technical feasibility	The ratio of benefit to risk [-]
	Operator productivity (max) (Tsai *et al.*, 2011)	Productivity	The ratio of output (users served) to input (paid labor hours) [-]
	The cost incurred by not serving on time (min) (Small, 1999)	Cost of delay	Opportunity cost for potential customers not served [Dinar Iraqi]

As previously noted, many criteria did not fit neatly within a single sustainability dimension, as several had overlapping and simultaneous effects. Much like assigning a criterion to a specific dimension, the interactions among criteria and their intended outcomes are complex and can be neutral, complementary (either unidirectional or mutual), or antagonistic. For instance, during the categorization process, it was observed that traffic congestion is closely associated with journey time. Air pollution not only contributes to negative health outcomes but is also strongly linked to greenhouse gas (GHG) and CO_2 emissions. Similarly, the major criterion of "non-motorized modes" influences these environmental indicators as well, with all such effects further exacerbated by congestion.

There are also direct interconnections between energy consumption and fuel costs. Another ambiguous factor is price, which presents a trade-off: while price increases may boost revenue for service providers, they simultaneously reduce affordability for users. Moreover, economic advancements often come at the expense of social or environmental performance. Therefore, it is crucial to examine the potential interdependencies and trade-offs among criteria before selecting them for decision-making processes. Selecting multiple criteria without accounting for their interactions can undermine the effectiveness of decision analysis rather than enhance it.

The measurement indicators identified in this study correspond to the initial stage of constructing a composite indicator, as outlined by the Organization for Economic Cooperation and Development (OECD). These indicators contribute to the theoretical framework required for a comprehensive understanding of sustainable transportation.

Nearly all reviewed studies employed a set of criteria to assess the sustainability of specific transportation projects, with a predominant focus on urban initiatives. Only Bojkovic et al. addressed the long-term sustainability of national transportation systems. The majority of publications (81%) considered the three core sustainability dimensions: social, environmental, and economic. For example, Castillo and Pitfield referred to the social dimension as "equity and social inclusion." More than half (52%) of the reviewed studies incorporated additional dimensions such as technology, efficiency, or system performance.

Notably, only Gössling explicitly included walking in his sustainability assessment. Similarly, only two publications alongside Castillo and Pitfield addressed cycling, which is surprising given that these are active modes of transport commonly associated with health benefits. The most frequently used data collection method across the reviewed studies was literature review, employed in 95% of cases. Some authors supplemented this with expert interviews for clarification. Most studies utilized criteria to evaluate sustainable transportation options, while only one publication used criteria to offer a general definition of what constitutes sustainable transportation.

2.8 Types of the street network

The road network has a fixed shape because of the nature of the area it serves. Brindle (1996) claimed that there are only two basic types of street network structures: grid networks and tree networks, which are distinguished by the degree of road connectedness (Brindle, 2005). According to Brindle, four types of urban street networks exist, as indicated in Figure 2.3.

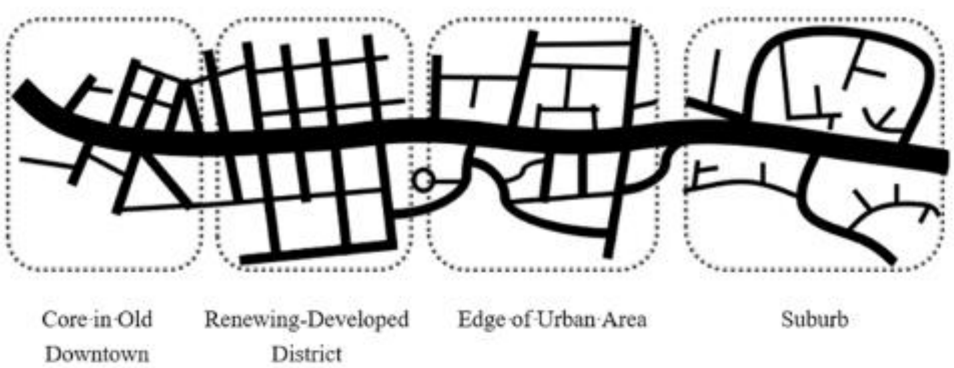
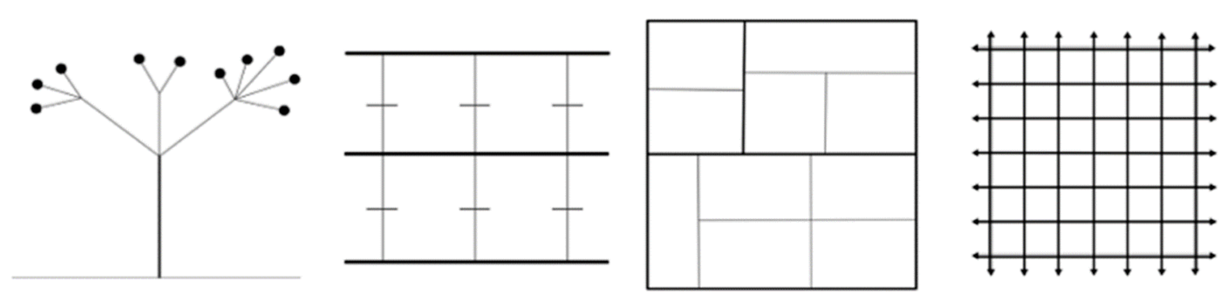


Figure 2.3: Four representative street network types in different regions of a city (Huang *et al.*, 2022)

The geometric structure of a street network is shaped by both the functional roles it fulfills and the physical geography of the area it serves. Typically, the road network adopts a relatively fixed form, influenced by the characteristics of the surrounding environment, including historical development and geographic context. The density and configuration of street blocks are often products of location-specific factors and urban evolution. Boeing conducted an extensive analysis of 27,000 street networks across the United States, encompassing metropolitan, municipal, and residential areas. This analysis examined the nature of street connections, including T-intersection ratios, X-intersection ratios, and cul-de-sac ratios, across various network types.

One notable distinction in urban form is evident between city centers and suburban areas: central districts tend to feature grid-like networks, while suburban areas are more likely to exhibit branching structures, akin to the patterns of trees or river systems. Although many networks can be broadly categorized as either grid-based or tree-like, they often display characteristics of both patterns. At finer scales, the boundary between these forms becomes blurred, and conventional planning metrics such as street density and spacing are often insufficient to differentiate them. As illustrated in Figure 2.4, representative street network types appear to correspond with specific urban zones, implying the presence of underlying principles that may govern the development of urban network structures.



(a). pure-tree-like type (b). cul-de-sacs type (c). T-type (d). pure grid-like type

Figure 2.4: Tree-like structure of four types of urban street networks (Huang *et al.*, 2022).

Brindle (2005) proposed that street networks generally fall into two primary categories: the grid network and the tree network, differentiated primarily by the level of road connectivity. This classification serves as the foundational premise of the present study. However, Brindle's framework does not account for the variations and complexities of intermediate network forms that fall between these two extremes. The tree-like network, characterized by its strict hierarchy and relative isolation, is often regarded as beneficial for pedestrian safety and for limiting through-traffic. Despite its adoption by early urban planning pioneers as far back as the 1930s, the model remains theoretically underdeveloped, and a comprehensive explanation for its continued application has yet to be established.

2.8.1 Geometry of the network

In the context of urban geometry, Strano et al. (2013) employed principal component analysis to categorize European urban road networks into distinct groups. However, as their study focused on the statistical properties of large-scale urban structures, the findings have limited applicability to smaller-scale or regional land-use planning. In a different geographical context, Von and Jaber conducted a systematic examination of the relationship between the form and texture of urban road networks and cultural characteristics in the Middle East. Their work explored strategies to modernize traditional Arab street networks by integrating Western planning concepts. One ongoing challenge in this field is the development of effective methods for describing structural differences between networks using standard planning indicators.

Traditionally, street network indicators have focused on geometric attributes such as distance, density, and area. However, these metrics often fail to capture significant differences in network patterns and functions, as their values may appear similar for networks with vastly different structural characteristics. Recent studies have increasingly concentrated on three dimensions of street network structure: hierarchical organization, connectivity, and spatial layout (Levin et al., 2015). The hierarchical structure, in particular, plays a critical role in influencing traffic flow and distribution patterns. Jiang (2009) and Bettencourt (2021) offered new insights into how urban street networks self-organize to support mobility, using geographic information as a foundation for their analyses.

Marshall emphasized the significance of network form in shaping travel behavior, residential and workplace distribution, land use, and overall urban morphology. Xie and Levinson (2007) introduced three novel metrics: heterogeneity (entropy), connection pattern, and continuity to capture the complexity of urban road networks better. Similarly, Barthelemy and Flammini (2008) demonstrated that, even in the absence of a centralized planning strategy, the evolution of many urban transportation networks tends to follow simple, underlying generative principles.

2.8.2 Structure and urban land use

The investigation of the relationship between street network structure and urban land use has emerged as a prominent research direction in urban studies. Southworth and Ben-Joseph (1997) explored the hierarchical and functional aspects of street networks by applying spatial syntax theory to assess network connectivity and accessibility (Mahdzar, 2008). Their findings partially succeeded in interpreting how individuals perceive and navigate the spatial configuration of street networks based on personal experience. Han *et al.* (2020) and Levinson et al. (2012) employed indicators such as network density, connectivity, and the presence of cul-de-sacs to analyze the impact of street network structure on connectivity and topological relations. Their results highlighted the influence of network characteristics on road safety outcomes. Terrible (2010) examined the complexity and robustness of 33 global metro systems, demonstrating that street network structures are shaped by a balance between minimizing travel costs and achieving efficient land use (Derrible *et al.*, 2010). Marshall, Gil, and colleagues undertook extensive data analysis and methodological experimentation to propose a comprehensive network modeling approach, outlining key features and the intricate interrelationships between various street network models (Marshall *et al.*, 2018). Boeing's global analysis of street network structures, which involved calculating structural indicators and clustering networks into distinct typologies, further enhanced understanding of the variation and scope of urban street forms (Boeing, 2017). Han *et al.* (2020) argued that street network structures should not be viewed in isolation as either hierarchical, connective, or layout-based; rather, they represent a dynamic integration of all three dimensions. In another notable contribution, Porta et al. utilized spatial syntax to analyze the structure and functionality of urban road networks, demonstrating the method's potential for uncovering the internal organization and deeper meaning of urban spatial systems (Yang, 2019).

Additionally, advances in the spatial analysis of complex networks have led to significant insights. For example, Mocnik's (2021) research on the polynomial volume law confirmed that while the spatial dimension of urban road networks tends to be stable, their concentration varies substantially. Collectively, these studies offer valuable foundations for future work on network type classification and functional attribute analysis.

2.8.3 Streets in that superblock structure

Observers have frequently conflated the various shifts that have occurred throughout the evolution of American street network design. One of the most significant milestones in this evolution came in 1928, when architects Clarence Stein and Henry Wright introduced their interpretation of the English Garden City model to the United States through the development of Radburn, New Jersey (Harding, 2023). The Radburn plan was among the first to challenge the traditional gridiron system by implementing a network of large neighborhood blocks referred to as "superblocks" ranging in size from 30 to 50 acres (South Worth and Ben-Joseph, 1997). Within this framework, streets were arranged hierarchically, a structure that has since become standard in contemporary suburban developments. A notable feature of this layout was the widespread use of cul-de-sacs. The intention behind this design was to eliminate through-traffic on residential streets, channeling vehicular movement instead onto collector roads and arterial streets.

The automobile was regarded as a disruptive element in urban life, and the growing volume of motor vehicles was seen as rendering the gridiron street pattern obsolete, comparable to dismantling the defensive walls of a fortified city. The grid's uniform accessibility was viewed as compromising safety and tranquility within neighborhoods (Southworth *et al.*, 1997). However, the claim that all streets within a grid are equally inviting to traffic represents a common misconception. Well-executed gridiron models, such as the street layout of Savannah, Georgia, reveal a distinct street hierarchy, achieved through subtle design variations that guide traffic flow and support differentiated use.

Significantly, the most influential initiative in promoting new network forms originated not from urban planners or engineers, but from an unexpected source, the Federal Housing Authority.

2.8.4 Hierarchical cul-de-sac designs

Established in 1934, the Federal Housing Administration (FHA) played a pivotal role in shaping American street network design. In the mid-1930s, the FHA issued Technical Bulletins No. 5 and No. 7 (Tunnard *et al.*, 1963). which strongly criticized traditional grid street patterns, labeling them monotonous, lacking character, uneconomical, and hazardous (South Worth and Ben-Joseph, 1997). These bulletins echoed the concerns of Clarence Stein and endorsed hierarchical street layouts, such as those employed in Radburn, which limited through-traffic and emphasized cul-de-sacs as both desirable and profitable. Over its first 15 years, the FHA oversaw the development of more than 22 million housing units (South Worth and Ben-Joseph, 1997), and its design recommendations became standard practice among developers, subsequently shaping zoning regulations nationwide. In this way, the federal government became the principal agent influencing local street network design.

The professional endorsement of hierarchical street patterns by transportation engineers began in earnest during the early 1950s. Despite the sweeping changes to network design, little empirical evidence initially supported this shift. One of the few studies from that period was a five-year investigation conducted by the Institute of Transportation Engineers (ITE) in Los Angeles. The study reported a significant reduction in crash frequency within areas designed with hierarchical cul-de-sac systems. However, the study lacked consideration for critical variables such as actual network geometry, density, crash migration potential, and severity of incidents.

Nonetheless, its findings likely contributed to ITE's endorsement of the hierarchical model.

In 1965, ITE published Recommended Practice for Subdivision Streets, which discouraged gridded layouts in favor of curvilinear streets with intentional discontinuities to discourage through-traffic. The report also advocated replacing four-way intersections with T-intersections and extensively incorporating cul-de-sacs. Although ITE's 1994 report Traffic Engineering for Neo-Traditional Neighborhood Design promoted a return to more traditional grid-based patterns, the most recent subdivision design standards continue to reflect principles introduced in the 1965 guidelines (Southworth *et al.*, 1997). Despite their decline in popularity, connected street networks remain valued for benefits such as route flexibility and directness of travel.

2.8.5 A pattern of building a hierarchical street

Despite the documented benefits of connected street networks, the prevailing viewpoint during much of the 20th century aligned with the concerns raised by Radburn architect Clarence Stein. Stein argued that such networks facilitated excessive through-traffic on local streets, thereby diminishing residential safety (Lerner-Lam *et al.*, 1992). Consequently, from the 1950s through the late 1980s, few new developments in the United States employed gridded street patterns. Instead, hierarchical layouts became the dominant model (Southworth *et al.*, 1997). By 1992, this trend began to shift, with over 50 neo-traditional neighborhood design projects either underway or in planning stages (Lerner-Lam et al., 1992). The resurgence of more traditional street layouts sparked renewed academic interest in examining the effects of street network design on urban outcomes such as vehicular usage and congestion.

Early studies conducted in the 1990s largely relied on theoretical models and simulation software. One such simulation, sponsored by the American Society of Civil Engineers (ASCE), found that cul-de-sac-heavy networks increased travel demand on arterial roads by 75% and on collector roads by 80%. In contrast, gridded street networks resulted in approximately 43% lower vehicle miles traveled (VMT) (Taylor, 2001). These findings suggest that increased connectivity can reduce overall VMT and congestion, which may imply improved safety due to reduced exposure. Moreover, the same study concluded that connected street networks decreased both travel times and speed factors, which could also influence road safety outcomes.

Nonetheless, most of the research from this period focused on travel efficiency and land-use implications rather than explicitly examining road safety. Where safety was addressed, the focus often centered on operational concerns, such as emergency response performance. For example, studies in Raleigh and Charlotte, North Carolina, demonstrated that increased network connectivity significantly expanded emergency service coverage areas and reduced response times (Handy et al., 2003).

Traditional road safety literature has largely concentrated on individual road segments or intersection characteristics. However, some evidence suggests that broader street network configurations may influence safety outcomes. Comparative studies have shown that while urban roads generally exhibit higher crash frequencies, rural roads, despite lower congestion, often display higher fatality rates (Janke, 1991; Litman, 2008). In the UK, Graham *et al.* (2003) observed that pedestrian casualties initially increase with rising intersection density but eventually decline as density reaches a high threshold.

2.9 Characteristics of the road network

Expanding a region's road network is often cited as a crucial factor in that region's economic growth. The primary goal of a well-developed road network is to facilitate the movement of people and goods between dispersed communities and major urban hubs. That aids in the progress of urban infrastructure. Maintaining and enhancing urban quality of life and guaranteeing sustainable development requires an effective transportation network (Sreelekha et al., 2016). There are topological and geometric differences in the road network structure. Several indices have been proposed that can be used to assess the features of a road system. These metrics have additional uses in transportation and urban development. Specific criteria are elaborated upon below:

2.9.1 Connectivity

The degree to which individual road segments are linked to one another is quantified by connectivity measurements. The term "connectivity" describes how easy it is to get from one place to another (Sreelekha et al., 2020). A network provides direct and continuous paths to its respective destinations with many short links, many crossroads, and few dead ends. Many connectivity indices have been created, as shown in Table 2.9. Alpha Index, Beta Index, Gamma Index, Eta Index, and Grid Tree Pattern Index are some of the indices used to evaluate the connectivity pattern of a road transportation network (Kansky, 1963; Noda, 1996).

The transportation system's arrangement, form, and design are referred to as the road network structure, a linked line system used to move resources. Topology is used in graph theory to examine the connections between lines, points, and sectors (Porta *et al.*, 2006). A network can be represented using graph theory as a group of nodes that stand in for intersections, cities, or terminals. A group of links, also known as edges, that represent the transportation infrastructure, such as highways, railroads, and airplanes, connect the nodes. Links function as linear characteristics that join two nodes together. Analyzing a network in graph theory entails examining its topology, concerned with the connections and spatial arrangement between links and nodes. A range of measures proposed in earlier studies has been applied to assess the features of transportation networks. The Alpha, Beta, and Gamma connection indices were created by. (Kansky *et al.*, 1989) And they are rooted in graph theory. Additionally, non-graph theory-based measurements like the Grid Tree Pattern (GTP) index, Network Density, Intersection Density, and Eta index characterize and assess the coverage and connectedness of the transportation network system in the research region.

The accessibility-based measure, as proposed by Anjomshoaa et al. (2017), Al-Bayati et al. (2023), and Tahmasbi et al., is highly valuable for evaluating the distance-related nature of the network architecture.

Table 2-9: Different Parameters of Network

Parameter	Formula *	Description	Range
Alpha	$\alpha = (e-v+1)/(2v-5)$	Number of essential circuits to maximum probable circuits (Baum *et al.*, 2021)	0 to 1
Beta	$\beta = e/v$	Number of links to several odes (Bakosi *et al.*, 2010)	0 when no edges 1 When one circuit exceeds one of the numerous circuits
Gamma	$\gamma = e/(3(v-2)$	The actual count of links to the maximum number of links (Zhou, 2015)	0 to 1
GTP	$GTP = (e-v+1)/((\sqrt{v}-1)^2)$	Designates network configuration (Zhang *et al.*, 2024)	0 for tree pattern 1 for the grid pattern

Parameter	Formula *	Description	Range
Eta	$\eta = \Sigma L/e$	Indicates average link length of network (Kansky, 1963)	
Network density (km per km2)	ΣL/A	Designates the network length per square kilometre of the area (Bento et al., 2003)	
Intersection density (per km2)	ΣI/A	Describes the intersections per unit area (Cervero and Kockelman, 1997)	
Cul-de-Sac Frequency Index (CF)	Cf=(P/e)	(Pérez-Martínez *et al.*, 2010)	**0** indicates a fully connected network with no cul-de-sacs. **Close to 1** means that most nodes are dead ends, reflecting a highly branched and non-permeable network

‘e’ is the number of edges (nodes), ‘v’ is the number of vertices (links), L is the road link length in km, I is the count of intersections, A is the geographical area in km2, and P is the number of Cul-de-Sacs.

2.9.2 Analysis of Buffer.

Buffer Analysis generates buffer polygons with a predetermined width around a point, line, or polygon feature. The current study is based on the hypothesis that urban systems exhibit growth patterns comparable to those of biological organisms. In that study, a ring buffer approach is proposed. The live organism begins as a solitary cell, often regarded as the core. Additionally, it fosters and disseminates throughout the core while adhering to its limitations. Similarly, a city or its subsystems expand from a central point (Guo *et al.*, 2020) and gradually extend outward, circumventing physical barriers like bodies of water, valleys, or other natural obstacles. In that context, the system refers to the road network in a certain area, which expands in proportion to its distance from the centre.

Figure 2.5a illustrates how an urban system might be divided into concentric rings to make it easier to analyze the data. The centre of the rings may be a singular site or a limited area around which the urban system has been created. The selected centre is the Central Business District of Al-Maslaha Street, the original catalyst for the development of the city. Within that centre, numerous circular zones with a consistent thickness of 2 kilometres each are generated using GIS, as shown in Figure 2.5b. Next, the quantity of the characteristics, specifically the transportation network system, was identified within all zones in each ring included in the study.

Overlay analysis in GIS is a spatial analysis technique that uncovers the attributes of objects located in many data layers. First, the spatial distribution of the road network is acquired using GIS. The buffer rings are utilized to superimpose and trim the areas with the road network to extract the zones within each buffer. Therefore, the road network topology and coverage information of the zones within each buffer ring are determined. In that study, buffering is employed to delineate the areas of influence inside the specific buffer zone. Buffers are created around the CBD with radii ranging from 0.5, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, and 7.5 kilometres.

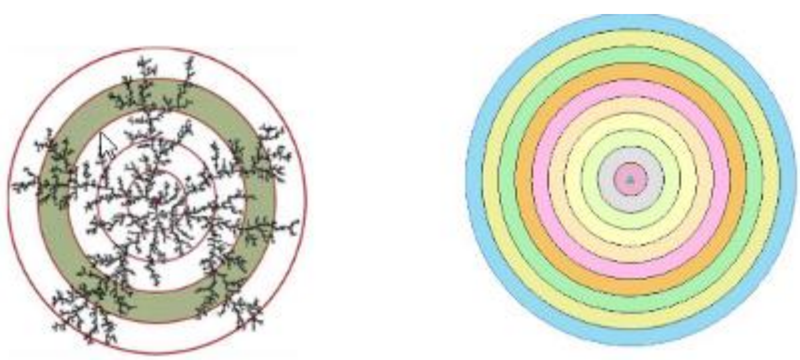


Figure 2.5 a) Feature overlapped on the buffer ring b) Buffer rings created using ArcGIS (Sreelekha et al., 2020)

2.9.3 An Explanation of a Graph

Road networks are explained in terms of relationships between locations and lines using graph theory. An edge that makes up a road is a line that connects the points that make up a start point and an endpoint (often road intersections) when a roadway with a total length of L, e points, υ the edges, and p components is in a region S.

A graph is made up of a set of edges (υ =) and a set of points (Guo *et al.*). It is described as G = (e, υ) and is connected to these places. |e| = m indicates the total number of points, and | υ | = n indicates the total number of lines. When two points ei, e j are connected by edges, the Euclidean distance between them is d (ei, e j), expressed as υi υj. A road network is represented by the graph GRN = (e, ERN), which is made up of road edges (ERN) and road points (P).

Generally speaking, a proximity graph is a graph that is determined by the proximity of points on a plane, as demonstrated by Delaunay triangulation (DT) and a minimal spanning tree (MST). Building a road segment can be simplified by generating a proximity graph based on road points collected from the existing road network, followed by comparing each graph edge to the actual road layout. One proximity graph is a relative neighbour graph (RNG), GRNG = (e, ERNG). If and only if the line has no additional points of e within its interior, RNG is generated by linking two points ei, e j of e with an edge. That line appears as the grey area in Figure 2.6.

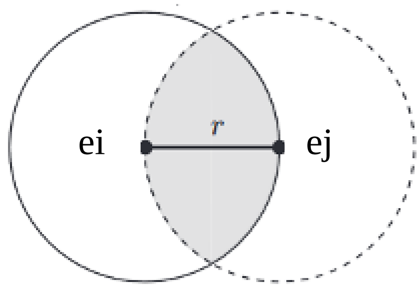


Figure 2.6: Search region for RNG

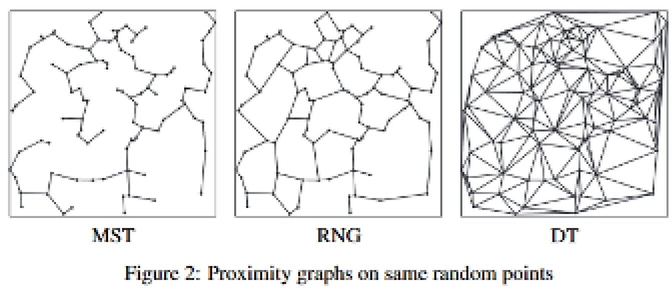


Figure 2.7:a) Graphs on random point(Shiau *et al.*,

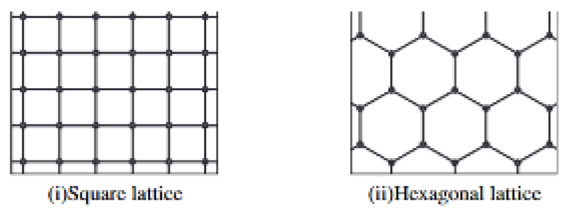


Figure 2.7: b) RNG with regular point (Shiau *et al.*, 2013).

It is possible to demonstrate that the edges of the minimum spanning tree are made up of RNG edges, and the edges of RNG are made up of Delaunay triangulation edges. The proximity graphs of the hexagonal and square lattices with regular points are displayed in Figure 2.7. On any lattice, RNG can build a standard grid road network.

2.10 The Capacity of the Road Network

Capacity, in simple terms, refers to the maximum volume of traffic a roadway can accommodate. In the context of Level of Service (LOS) analysis, it is essential to define capacity with consistency and reasonable precision, as it depends on various factors such as the roadway type (e.g., freeway, multilane highway without full access control, or rural road), free-flow speed, number of lanes, and lane and shoulder widths (Khisty and Lall, 1998).

At signalized intersections, capacity is defined as the highest flow rate that lane groups can achieve under existing traffic conditions. It is typically measured in vehicles per hour (veh/h), based on flows recorded during a 15-minute peak period (Garber and Hoel, 2009). According to Al-Azzawi (2003), several factors influence capacity, including lane width, traffic demand fluctuations during peak hours, and the location of the intersection within the urban area.

Control measures such as turning movements and vehicle composition (e.g., cars, buses, trucks) also impact capacity. Additionally, area type matters; for example, intersections in Central Business Districts (CBDs) typically have lower saturation flows due to constrained designs, pedestrian activity, and roadside friction.

During the initial seconds of the green phase and the amber phase, flow rates are typically reduced, as vehicles accelerate or hesitate. To simplify this, the green and amber intervals are replaced conceptually with an "effective green" time (where traffic flows at saturation rate) and a "lost" time (when no movement occurs). Since capacity is closely tied to effective green time, this approach proves useful.

According to the Highway Capacity Manual (HCM, 2016), the capacity of a lane group can be calculated as:

$c = s\ x\ \frac{g}{c}$(HCM,2016)……………………………………..(2.3)

Where: c: capacity of the lane group (veh/h); S: saturation flow of the lane group (veh/h); g: effective green time for the lane group (seconds); C: total signal cycle length (seconds).

2.11 Pedestrian Volume to Capacity Index (PVCI)

The Pedestrian Volume to Capacity Index (PVCI) is a widely used indicator in urban transportation studies to evaluate the level of interaction and potential conflict between pedestrians and vehicular traffic. It is calculated by dividing the pedestrian flow rate (pedestrians per hour) by the vehicular capacity of a roadway (vehicles per hour), and multiplying the result by 100 to express it as a percentage:

$$PVCI = \frac{Pedestrian(p/hr)}{vehicular\ flow\ (veh/hr)} X100 \quad \text{……………………….(.2.4)}$$

This index provides valuable insight into the degree of pedestrian impact on roadway performance and safety. According to classifications derived from research and traffic engineering guidelines (AASHTO, 2018; TRB, 2010), PVCI values can be interpreted as shown in Table 2.10. A PVCI less than 5% indicates very low conflict, while values exceeding 20% reflect very high pedestrian-vehicle conflict, warranting interventions such as pedestrian crossings, signal optimization, or traffic calming

Table 2-10: Classification of Pedestrian-Vehicle Conflict Level Based on PVCI (Litman, 2022)

PVCI (%)	Conflict Level
0–5	Very Low Conflict
5–10	Low Conflict
10–15	Moderate Conflict
15–20	High Conflict
> 20	Very High Conflict

2.12 Level of Service (LOS)

Level of Service (LOS) is a qualitative measure used in transportation engineering to evaluate the operational conditions of roadways and the perception of those conditions by users. It is most commonly determined using the Volume to Capacity (V/C) ratio, which compares the actual traffic volume on a roadway segment to its maximum capacity. A lower V/C ratio indicates smoother traffic flow and higher service levels, while a higher ratio reflects congestion and reduced efficiency.

Table 2.11 illustrates the Level of Service (LOS) classification according to the Highway Capacity Manual (HCM, 2010), LOS can be categorized based on V/C values as follows: a ratio of ≤ 0.60 corresponds to LOS A–B (free to stable flow), 0.61–0.70 corresponds to LOS C (stable flow with acceptable delays), 0.71–0.80 to LOS D (approaching unstable flow), 0.81–0.90 to LOS E (unstable flow with significant delays), and > 0.90 to LOS F (oversaturated flow or breakdown conditions). This classification framework helps engineers and planners assess current performance and identify the need for roadway improvements or traffic management strategies (TRB, 2010).

Table 2-11: Level of Service (LOS) Based on V/C Ratio (HCM,2010)

V/C Ratio	Level of Service (LOS)	Description
≤ 0.60	A–B	Free to stable flow; minimal delay
0.61 – 0.70	C	Stable flow; acceptable delay
0.71 – 0.80	D	Approaching unstable flow
0.81 – 0.90	E	Unstable flow; significant delays
> 0.90	F	Breakdown flow; oversaturated

Table 2.12 presents service volumes (vehicles per hour) for different lane configurations and traffic classes (Class I to IV) under varying levels of service (A to E). It quantifies the maximum traffic flow that can be accommodated on one to four lanes, reflecting roadway capacity and operational conditions. Higher classes and more lanes correspond to increased vehicle volumes, while levels of service indicate traffic quality, with A representing free flow and E nearing capacity. This data is typically sourced from the Highway Capacity Manual (HCM, 2010), which provides standardized methodologies and empirical values for evaluating highway and roadway performance. The HCM is widely used in transportation engineering to analyze traffic flow, capacity, and congestion levels (Transportation Research Board, 2010).

2.13 Travel time

Travel time serves as a critical indicator of the performance of transportation systems and carries significant societal implications (Carrion and Levinson, 2012; Zheng et al., 2018). While minor variations exist across different transportation modes, the fundamental definition of travel time remains universally applicable, regardless of mode or modal combinations (Carrion and Levinson, 2012).

Table 2-12: Service volumes for urban streets (Adopted by HCM, 2000).

Lanes	Service volumes(veh/h)				
	A	B	C	D	E
Class I					
1	N/A	860	930	1020	1140
2	N/A	1720	1860	2030	2280
3	N/A	2580	2780	3050	3430
4	N/A	3450			
Class II					
1	N/A	N/A	670	850	890

2	N/A	N/A	1470	1700	1780
3	N/A	N/A	2280	2550	2670
4	N/A	N/A	3090	3400	3560
Class III					
1	N/A	N/A	480	780	850
2	N/A	N/A	1030	1600	1690
3	N/A	N/A	1560	2410	2540
4	N/A	N/A	2140	3220	3390
Class IV					
1	N/A	N/A	540	780	800
2	N/A	N/A	1200	1570	1620
3	N/A	N/A	1900	2370	2430
4	N/A	N/A	2610	3160	3250

Travel speed is often employed as a proxy to assess travel time reliability, as kinetic traffic flow theory suggests a negative correlation between average travel speed and travel time variability, indicating that lower mean speeds are typically associated with greater variability in travel time (Fredriksson et al., 2023). Travel time comprises two primary components: running time, which refers to periods when the transport mode is in motion, and stopped delay time, which relates to intervals when movement ceases or slows to near-standstill speeds (typically below 8 km/h or 5 mph) (Turner et al., 1998). Data on travel time and delay are essential for assessing and improving roadway capacity, optimizing traffic signal performance, and managing incidents on arterials and freeway networks (Li, 2013).

2.13.1 Travel time influencing factors.

The factors influencing travel time are subdivided into two groups:

1. Factors influencing traffic demand.
2. Factors influencing traffic supply characteristics.

In Figure 2.8, a general overview is presented of both categories of factors:

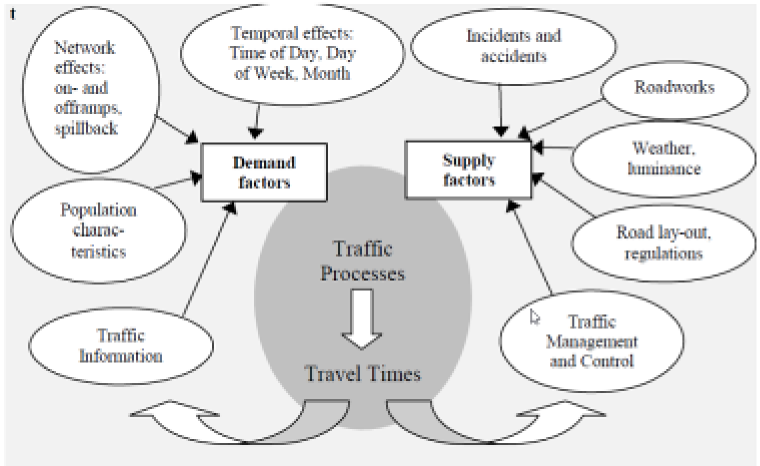


Figure 2.8: General (not exhaustive) overview of factors influencing travel time (Malone et al., 2014).

2.14 Traffic flow

The number of cars that pass a particular spot along a lane or roadway in a given period can be measured in two ways: volume and flow rate. These terms shall have the following meanings (HCM, 2010).

Volume is the number of vehicles that go over a specified point or part of a lane or roadway within a specified time interval. While volumes can be stated in terms of any time interval, they are most commonly defined in annual, daily, hourly, or sub-hourly periods.

Flow rate is the number of vehicles per hour that travel across a certain distance in less than an hour, often 15 minutes.

2.15 Speed on an urban street

When deciding between multiple routes or means of transportation, speed is a major consideration for passengers. An individual's perception of a transportation facility's worth in moving people and products is based on the facility's ease of use and cost-effectiveness (AASHTO, 2001). The speed of the vehicle on the road or highway depends on the physical characteristics of the street, the amount of roadside interference, the weather, the presence of other cars, and the speed limitations (established either by law or by traffic control devices). Speed on urban roads is significantly affected by the surrounding geometric and traffic parameters.

2.15.1 Free flow speed

FFS is an important characteristic for capacity and level of service analysis of urban arterials. The FFS has several definitions depending on the application or context. It is defined as the desirable average speed adopted by the driver when not restricted by other vehicles in the stream under a particular set of road conditions (HCM, 2010). Two key definitions are provided. First, the FFS on an urban roadway is the speed at which a vehicle travels in low-traffic conditions when all of the street's signals are green for the entire trip. The average driver's chosen speed is the FFS when vehicle interaction and traffic control are not involved. Second, it is the average speed of the traffic stream when traffic numbers are low enough that drivers are unaffected by the presence of other cars and feel comfortable motoring, and when intersection traffic control is absent or distant enough away not to affect speed choice (HCM, 2010). In theory, FFS should be the speed at which the flow and density are zero. Three principal factors influencing its value (Baruzzi et al., 2008; Bassani et al., 2012):

(a) roadway geometry and condition. (b) driver’s attributes and (c) environment have been reported to influence the values in the American urban traffic streams and highways (Lamm et al., 1990).

The factors considered for free speed per the IHCM are listed below (IHCM, 1993). 1. Carriageway width (m) 2. Pedestrian movement 3. Vehicles stopping on the roadway, 4. Vehicles turning into or out of the segment.

2.16 Summary

The thesis explores sustainability from three main dimensions environmental, economic, and social   and connects them to transportation planning.

- Environmental aspects include air quality, greenhouse gas emissions, noise pollution, and land use efficiency.
- Economic aspects focus on operational costs, travel time savings, infrastructure investment, and economic productivity.
- Social aspects encompass safety, accessibility, equity, and public satisfaction.

Traffic theory and urban road network characteristics are reviewed, emphasizing the importance of free-flow speed, traffic volume, level of service (LOS), and accident rates. The literature review also examines previous methodologies for sustainability assessment, the selection of indicators, and the application of decision-making models such as AHP and fuzzy logic in transportation research.

Chapter Three: Sustainable Transportation

3.1 Introduction

Transportation has a prominent and indispensable role in contemporary society, serving as a fundamental facilitator that permeates nearly all aspects of human endeavours. Advocating for advancing transportation sustainability is a rational progression toward achieving comprehensive sustainable development. Transportation sustainability policies are designed to identify and implement strategies that effectively mitigate the adverse externalities associated with transportation. These externalities include environmental factors such as pollution, CO2 emissions, noise, and economic considerations such as congestion. These policies also consider societal concerns such as equity and accessibility, and the crucial aspects of health, safety, and security (Dobranskyte-Niskota *et al.*, 2009).

The present chapter provides a comprehensive overview of the concept of sustainable transportation and its urban design, along with an examination of methodologies for evaluating sustainability within the realm of transportation. Additionally, that chapter cites previous research conducted in that domain.

3.2 Sustainability and Transportation

The attainment of sustainability within the transportation system poses a significant and pressing challenge for transportation professionals, researchers, and decision-makers, as well as for urban planners and environmentalists (Hassan *et al.*, 2015). The operational and performance aspects of transportation systems directly or indirectly impact all three pillars of sustainability, namely the environment, society, and economy. The functioning of transportation infrastructure significantly impacts virtually all areas within our communities (Åkerman *et al.*, 2006). Regrettably, the current trajectory of transportation networks worldwide is deemed unsustainable, a consensus widely acknowledged by scholars such as. The correlation between population growth and transportation is further substantiated by the concurrent increase in car ownership (Bodor *et al.*, 2013). Throughout a relatively short period, there has been a significant increase in the global number of cars, rising from 71.1 million in 2010 to 77 million in 2024 (Global-car-sales, 2023), as explained in Figure 3.1.

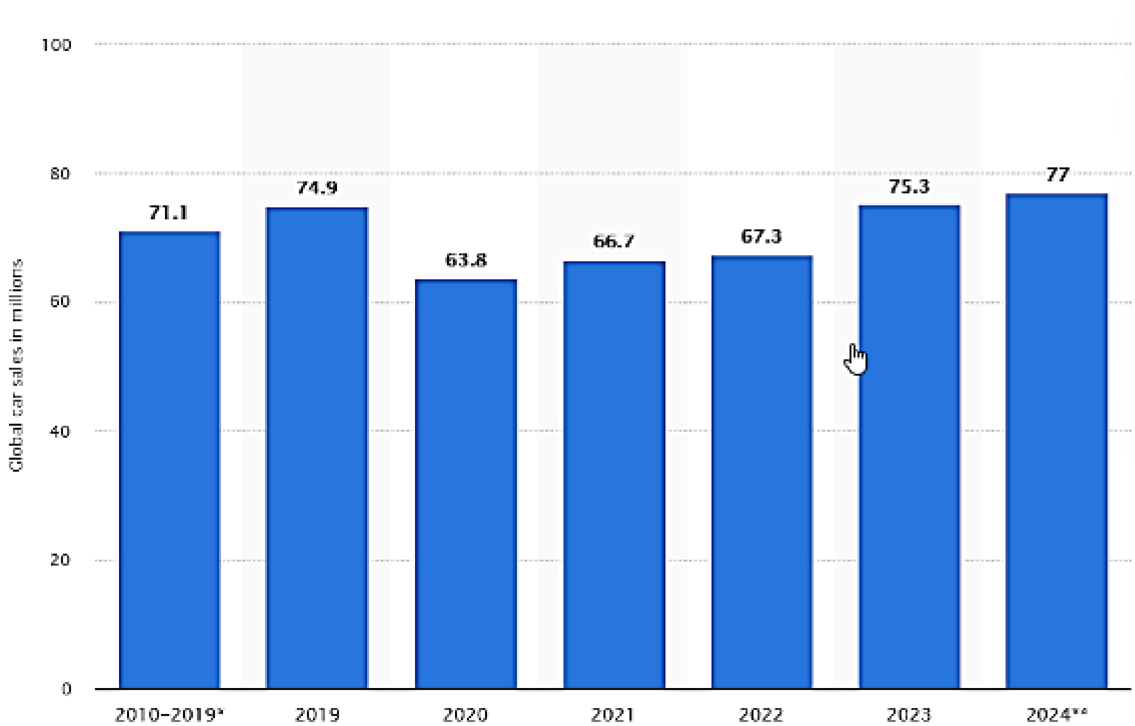


Figure 3.1: Number of cars in the world (Global-car-sales, 2023)

That growth has been accompanied by a corresponding rise in the consumption of non-renewable resources (Dobranskyte-Niskota *et al.*, 2007; Dobranskyte-Niskota *et al.*, 2009), a heightened demand for transportation infrastructure (Goulder *et al.*, 2008), and growing concerns regarding safety. Consequently, transportation systems worldwide have become increasingly dominated by cars, leading to a decline in sustainability (Pojani *et al.*, 2015). In contrast to industrialized nations, the challenges mentioned above are exacerbated in deprived countries (Al-Twaijry *et al.*, 2003). Achieving sustainable transportation (ST) remains ambiguous and constrained unless transportation system problems are quantified (Günay *et al.*, 2021). The importance of quantifying sustainability in transportation systems is evident through an increasing body of research aimed at defining and assessing that concept (Mihyeon Jeon *et al.*, 2005). Various sustainability rating systems employ different methodologies for evaluating and prioritizing sustainability variables (De Luca *et al.*, 2017; Cinelli *et al.*, 2014).

3.3 Sustainable urban street

According to Greenberg (2009), sustainable streets refer to multimodal rights of way intentionally designed and managed to generate advantages in terms of transportation, environmental impact, and community well-being (He *et al.*, 2009). These benefits align with a broader sustainability agenda, encompassing environmental, social, and economic considerations. In addition, implementing sustainable urban streets has the potential to enhance the quality of residential areas, rendering them more conducive to human habitation. The primary objective of constructing a sustainable street is to mitigate energy consumption, primarily through promoting non-motorized transportation, thereby minimizing the strain on environmental resources, mitigating adverse effects on the natural environment, and fostering biodiversity. One approach to mitigating the consumption of material resources in construction is to use recycled materials. That practice reduces the demand for new resources and contributes to the design's longevity and resilience.

Additionally, fostering healthy urban communities can be achieved by promoting public services near residential areas. That integration enhances public health, safety, and security, creating a more sustainable and harmonious urban environment. According to El-Shimy and Ragheb (2017), assisting with sustainability during implementation is important.

In recent years, strategies aimed at reducing automobile usage have gained significant attention due to the associated environmental and social challenges. Key interventions have included road pricing, traffic calming measures, parking regulations, and the provision of park-and-ride services. While such policies play a critical role, other determinants, most notably land-use planning, exert substantial influence over travel behavior. The configuration and distribution of urban land uses directly shape mobility patterns and modal choices. To address automobile dependency, enhanced transit infrastructure offers a viable solution. Expansion of urban areas toward peripheral zones can alter the spatial structure of cities, with shifts in land use and socioeconomic variables exerting a considerable impact on transit ridership (Loo *et al.*, 2010).

For example, in Copenhagen, investments in public transportation have improved central area accessibility, leading to increased commuter flows from broader regions, including an average of 19,380 daily cross-border passengers from Sweden (Knowles, 2012). Transit-oriented development represents an effective approach that delivers mobility levels comparable to car usage, while advancing sustainable urban growth. Figure 3.2 illustrates a comparison between car-dependent and transit-oriented cities, demonstrating similar levels of urban mobility under both frameworks.

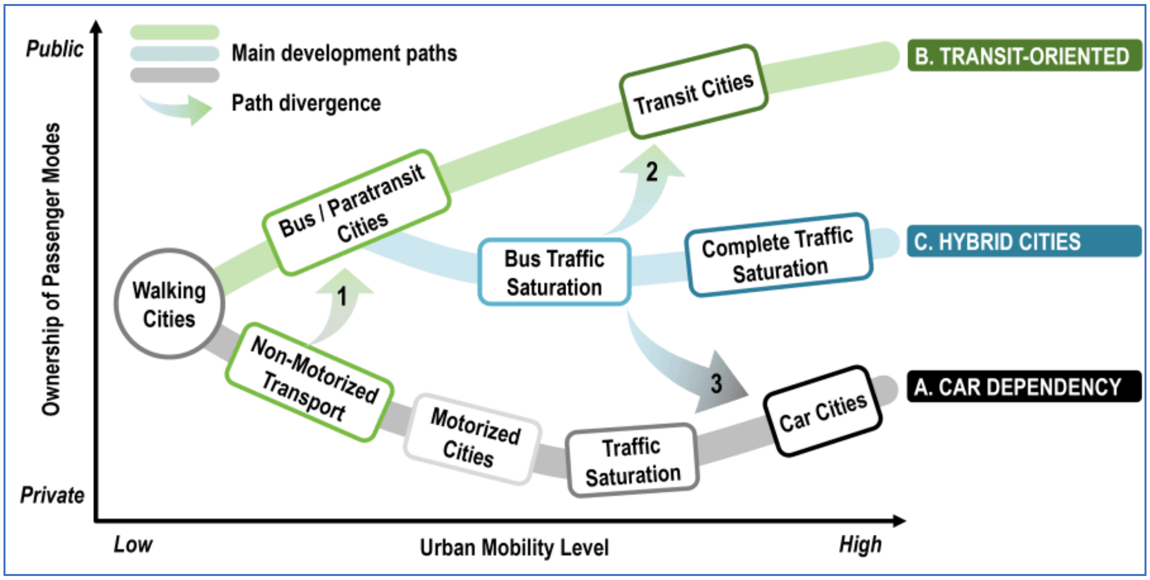


Figure 3.2: Urban Mobility Levels. Source (Rodrigue, 2020)

3.4 The concept of sustainable transportation

The term "sustainable transportation" encompasses various methods, practices, and endeavours related to transportation that yield beneficial environmental effects. These include non-motorized modes of transportation such as walking and cycling, the implementation of Transit Oriented Development (TOD), the utilization of green vehicles, the practice of car sharing, the establishment or preservation of fuel-efficient transportation systems in urban regions, the conservation of space, the promotion of healthy lifestyles, and the cultivation of vibrant communities (Jeon et al., 2005). According to Deakin (2001), sustainable transportation refers to the provision of mobility services that effectively address the transportation needs of individuals while concurrently safeguarding and enhancing environmental quality, promoting economic advancement, and ensuring social fairness for both current and future generations. Additionally, the objective is to achieve that through recognizing and executing various transportation modes that mitigate the adverse impacts of transportation on the environment, economy, and society. These approaches encompass a range of alternatives, as Meyer (2004) outlined:

- Incorporating energy-efficient modes of mobility, such as walking, cycling, and utilizing public transportation.
- To enhance the efficacy of automobile usage, one can employ several strategies, such as utilizing more efficient gasoline, opting for vehicles with higher fuel efficiency, and improving the process of car assembly.
- The utilization of technology to substitute or diminish the necessity for physical transportation, such as through remote work or online shopping.
- Urban areas are experiencing a notable increase in vibrancy and pedestrian-friendliness through integrating urban design strategies that prioritize a comprehensive understanding of individuals and their requirements.
- Policies that facilitate the cultivation of these choices and grant permission for their implementation.

When assessing sustainability, it is imperative to consider both social and environmental issues. Transportation significantly impacts the environment, mostly by producing carbon dioxide and energy utilization, resulting in air pollution (Miralles-Guasch and Domene, 2010). Transportation infrastructure and operations exert notable sustainability ramifications, as shown in Table 2.8 of Chapter 2.

3.4.1 Environmental dimensions.

Transportation systems, encompassing both infrastructure and vehicle operations, exert profound environmental impacts, ranging from local noise and air pollution to global climate change. The environmental impacts of transportation are multifaceted and interrelated, falling into three categories:

direct effects (e.g., carbon monoxide emissions), indirect effects (e.g., health damage from particulate matter), and cumulative effects such as climate change, which stem from complex feedback loops across ecosystems (Er Kara et al., 2021; Roth et al., 2020; Eilers, 2021).

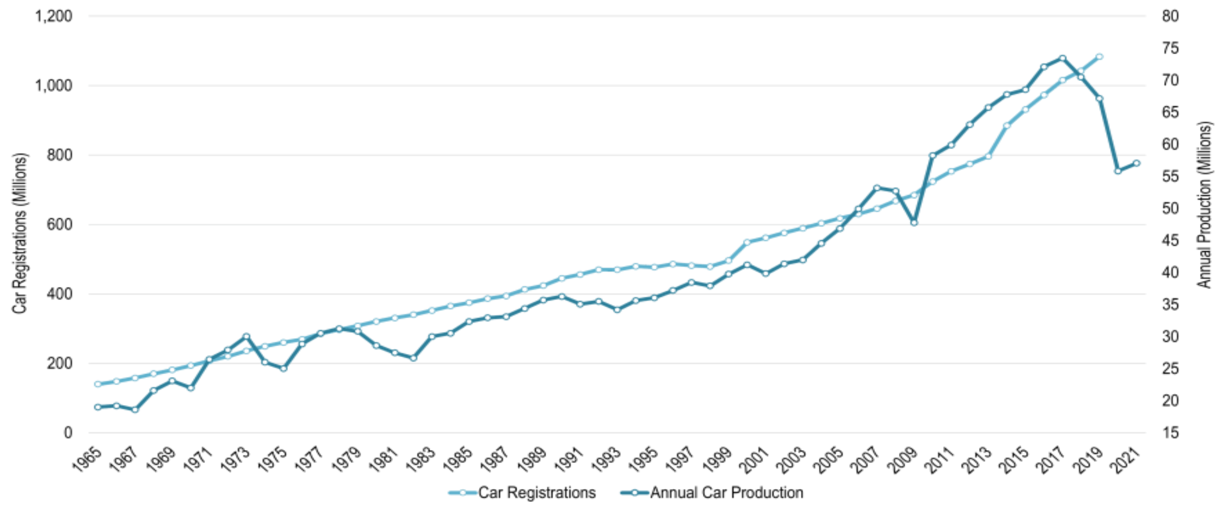


Figure 3.3: Annual car production (Reimers, 2021)

As Figure 3.3 illustrates, rising motorization over recent decades, fueled by economic growth and consumer demand, has contributed to escalating emissions, despite occasional downturns caused by crises like the 2008 financial collapse and the COVID-19 pandemic (Reimers, 2021; Le et al., 2021). The transportation sector now accounts for approximately 25% of global CO_2 emissions, a share even higher in industrialized countries (Aminzadegan et al., 2022). Notably, these emissions are more influenced by the intensity of each transport mode than by volume alone. Furthermore, transportation often incurs substantial external costs, including social and environmental damages not reflected in market prices, leading to indirect subsidies that favor private vehicle use and exacerbate ecological degradation (Rodrigue, 2024).

3.4.2 Economic dimensions

Transportation plays a pivotal economic role by enhancing societal welfare through the development of both physical and human capital. While traditional policies have prioritized infrastructure, recent sustainable development approaches emphasize the interplay between tangible assets such as roads, utilities, and telecommunications and intangible assets like education, skills, and governance (Taghvaee et al., 2022). Efficient transportation systems not only facilitate economic activities but also generate positive multiplier effects, including improved market access, employment expansion, and increased investment potential. Regions with dense, well-integrated transport networks often experience higher levels of development (Mačiulis et al., 2009). Conversely, deficiencies in transportation infrastructure can lead to elevated operational costs and reduced quality of life. At a macroeconomic scale, robust transport systems minimize cross-sectoral costs, while inefficiencies, such as congestion, may arise from underpriced or overutilized infrastructure. Although often viewed as a negative externality, congestion can also reflect vibrant economic conditions surpassing infrastructural capacity (Mo et al., 2022). Moreover, infrastructure represents a form of "lumpy capital" requiring substantial upfront investment and long-term maintenance, making it susceptible to market inefficiencies when demand falls short (Rodríguez-Sanz et al., 2022). These complex interactions between infrastructure, governance, and economic performance are shaped by multiple spatial and institutional factors, as illustrated in Figure 3.4, which highlights the key drivers influencing transportation system development (Rodrigue, 2020).

Scale	Environmental	Historical	Technological	Political	Economic
Local	Hydrography and geomorphology	Culture and settlement patterns	Roads	Zoning	Employment and distribution
Regional	Climate	Urban system	Railways and canals	Taxation and regulations	Modal competition and complementarity
National / Transnational	Distance	Nation state / Colonialism / Imperialism	Corridors and sea routes	Trade agreements	Markets
Global	Oceanic masses	Globalization	Air transport and tele-communications	Multilateral agreements (WTO)	Interdependency and comparative advantages

© GTS

Figure 3.4: Factors behind the Development of Transportation Systems (Rodrigue, 2020)

Since the Industrial Revolution, transportation development has been central to economic growth, with each wave of advancement such as maritime ports, inland waterways, railways, roads, air transport, and telecommunications reshaping global production and distribution systems (Groumpos, 2021; Bonaldo, 2022; Rodrigue et al., 2024; Pyrgidis, 2021; Mohapatra et al., 2023; Schneider, 2021). These modes have enhanced economic opportunity by expanding market reach, lowering costs, and facilitating mobility. As illustrated in Figure 3.5, each mode offers distinct advantages based on spatial coverage, cargo type, and scale economies (Mouratidis et al., 2021). Before industrialization, economic activities were limited by poor transport capacity, but modern systems now enable global commercial integration (Taj et al., 2022).

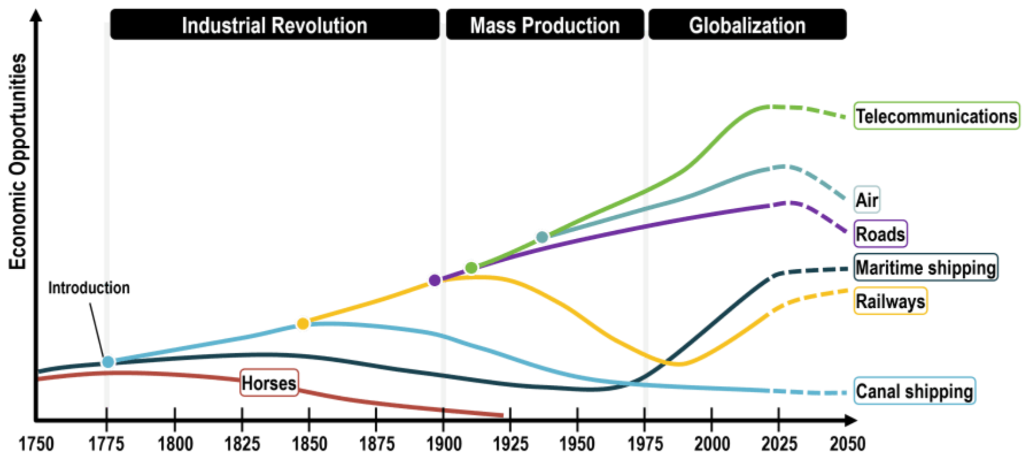


Figure 3.5: Economic opportunities for transportation mode (Mouratidis *et al.*, 2021)

3.4.3 Social dimension

Transportation systems significantly influence social development by enhancing accessibility, equity, and quality of life. Improved mobility enables better access to education, healthcare, employment, and social services, factors that are crucial for social inclusion and human well-being (Kenyon et al., 2002). However, unequal transport distribution often reinforces spatial and social disparities, particularly affecting low-income or marginalized populations (Lucas, 2012). Urban sprawl and automobile dependency can also lead to social fragmentation, reduced community cohesion, and health issues related to sedentary lifestyles and pollution exposure (Gössling, 2016).

As shown in Figure 3.6, transportation shapes spatial equity through its influence on mobility patterns, land use, and access to opportunities. Well-integrated systems promote social cohesion, while poorly planned networks may exacerbate exclusion and segregation (Mattioli et al., 2020). The social dimension of sustainable transport thus involves balancing efficiency with inclusiveness, ensuring that mobility benefits are equitably shared across different groups and geographies (Benevolo et al., 2016).

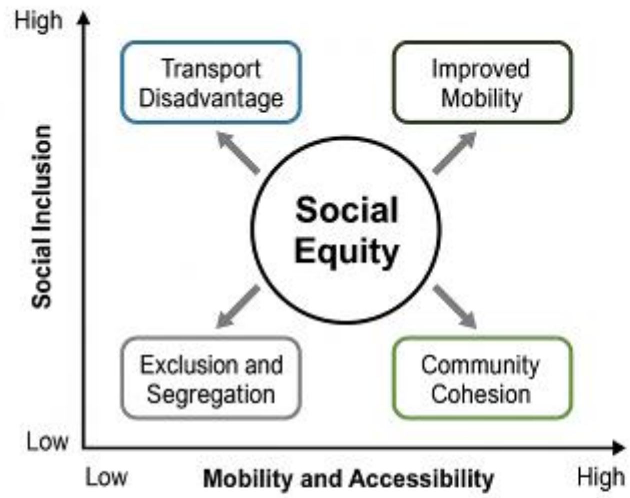


Figure 3.6: Social dimension of transportation system (Mattioli et al., 2020)

3.5 Aspects of urban road network sustainability

3.5.1 Traffic noise

Noise annoyance, including feelings of displeasure, disruption, and aggravation, is closely associated with environmental noise, particularly from road traffic. Traffic noise is one of the most significant environmental health risks, contributing heavily to noise pollution in urban areas, where the majority of people are exposed to harmful noise levels. The World Health Organization (WHO) has recognized traffic noise as a health hazard, linking it to an increased risk of cardiovascular diseases, such as ischemic heart disease and stroke (Münzel et al., 2019). Noise levels above 55 dB are considered harmful to public health (Khomenko et al., 2022). Various factors, such as road type, traffic volume, vehicle speed, and the presence of heavy vehicles like trucks, all contribute to increased noise levels. For example, expressways generate higher noise than local roads, and the noise from large vehicles can exceed that of smaller cars (Wen et al., 2019; Shukla et al., 2009). Traffic noise is also influenced by factors such as road composition, intersection design, and urban building height (Litman, 2021).

In urban areas, more than 94% of people are exposed to traffic noise levels exceeding 55 dB, with heavy vehicles and speed being major contributors (Nieuwenhuijsen and Khreis, 2018). Additionally, factors like vehicle load, speed, and traffic volume further influence noise levels, as well as environmental factors such as distance from the source and obstacles like noise barriers (Shukla et al., 2009).

3.5.1.1 Traffic noise limits

According to the Central Pollution Control Board (CPCB), Table 3.2 shows the standard noise levels for different areas (CPCB, 2015):

Table 3-1: Ambient Noise Standards (CPCB, 2015).

Category of Area/zone	Noise Level dBA /Day Time	Noise Level dBA /NightTime
Industrial Area (I)	75	70
Commercial(C)	65	55
Residential Area (R)	55	45
Silence Zone (S)	40	50

WHO Community Noise Guidelines. In 1999, the World Health Organization (WHO) published guidelines on community noise because it recognized noise pollution, particularly traffic noise, as a severe public health issue (Berglund et al., 1999). These recommendations outline the noise levels above which a negative impact on human health and well-being should be anticipated. The WHO expanded the recommendations in 2020, concentrating on the negative effects of nighttime noise on health. Table 3.3 lists the pertinent threshold values for various contexts. The guideline values are established at the lowest negative health effect (also known as the "critical health effect") when numerous negative health effects are found for a particular setting.

Table 3-2: Community noise guidelines ((World-Health-Organization, 2020)

No	Environment	Critical Health Effect	Sound Level (dB)	Time Limits (hrs)
1	Outdoor Living Areas	Annoyance	50-55	16
2	Indoor Dwellings	Speech Intelligibility	35	16
3	School Classrooms	Sleep Disturbance	35	During Class
4	Industrial, Commercial, And Traffic Areas	Disturbance Of Communication	70	24
5	Music Through Earphones	Hearing Impairment	85	1
6	Ceremonies And Entertainment	Hearing Impairment	100	-
7	Bedrooms	Hearing Impairment	30	8

Most urban areas are experiencing an alarming increase in traffic noise, causing concern for those near major thoroughfares. The adverse effects of noise on society can be mitigated by limiting its level. There are a few possible outcomes that could lead to lower noise levels: motor vehicle regulation, noise barriers, dead-end streets for residential complexes, lowering freeways and arterial roads to ground level, and increasing the distance between roads and buildings were all proposed as possible solutions to the problem of noise pollution (Peterson, 1980).

3.5.2 Traffic gas emissions

Transportation activities significantly contribute to environmental pollution, with a third of atmospheric chlorofluorocarbons (CFCs), a fifth of carbon dioxide (CO_2), and half of nitrogen oxides (NO_x) originating from this sector. Emission levels are influenced by factors like vehicle performance, acceleration, and speed, with idle rates accounting for 50% of total emissions, acceleration for 35-40%, and deceleration for 10% (Cheba and Saniuk, 2016). Additionally, oversized vehicles like trucks and buses emit significantly lower amounts of CO_2 compared to smaller cars (Washburn et al., 2016). While emission control systems have reduced some pollutants, they are less effective on older vehicles and defective systems, resulting in higher emissions. Acceleration, cold engines, stop-and-go traffic, and varying speeds also increase emission rates (Garber and Hoel, 2014).

3.5.2.1 Emissions standards

The WHO Global Air Quality Guidelines (AQG) provide comprehensive global guidance on the thresholds and limits for key air pollutants that pose health risks. Developed through a transparent and evidence-based process, these guidelines are of high methodological quality. In addition to setting guideline values, the WHO AQG includes interim targets to facilitate a gradual reduction of pollution concentrations. The guidelines also offer qualitative recommendations on best practices for managing certain types of particulate matter (PM), such as black carbon/elemental carbon, ultrafine particles, and particles from sand and dust storms, where there is insufficient data to establish specific AQG levels.

National Ambient Air Quality Standards (NAAQS) are divided into primary and secondary standards. Primary standards aim to safeguard human health, including vulnerable groups such as children and individuals with respiratory conditions, by providing an adequate margin of safety.

Table 3-3: Recommended 2021 AQG level (World-Health-Organization, 2020)

Pollutants	Time	Concentrations (µg/m3/or ppm)
PM_{10}	Annual mean	15 µg/m^3
	24-hour mean	45 µg/m^3
$PM_{2.5}$	Annual mean	5 µg/m^3
	24-hour mean	15 µg/m^3
O_3	8-hour mean	100 µg/m^3
NO_2	Annual mean	10 µg/m^3
	1-hour mean	25 µg/m^3
SO_2	24-hour mean	40 µg/m^3
	10 minutes means	500 µg/m^3
CO	15	90 µg/m^3
	30	50 µg/m^3
	1 hour	25 µg/m^3
	8 hour	10 µg/m^3
Pb	Annual mean	0.5 µg/m^3

Secondary standards focus on protecting public welfare, including preventing damage to property, transportation hazards, economic impacts, and ensuring personal comfort and well-being against the adverse effects of pollutants (CPCB, 2015).

These standards are regularly updated to reflect the latest scientific findings, with a review conducted every five years by the Clean Air Scientific Advisory Committee (CASAC), which is composed of seven members appointed by the EPA administrator. The EPA has established NAAQS for six major pollutants, which also serve as criteria for air quality assessment, as detailed in Table 3.5.

Table 3-4: NAAQS (EPA, 2009)

Pollutant	Type	Standard	Averaging Time	Form[a]
Sulfur dioxide (SO2)	Primary	75 ppb	1-hour	99th Percentile of 1-hour daily maximum concentrations averaged over three years
	Secondary	0.5 ppm (1,300 µg/m^3)	3-hour	Not to be exceeded more than once per year
Particulate matter (PM_{10})	Primary and Secondary	150 µg/m^3	24-hour	Not to be exceeded more than once per year on average over three years
Fine particulate matter ($PM_{2.5}$)	Primary	12 µg/m^3	annual	Annual mean averaged over three years
	Secondary	15 µg/m^3	annual	Annual mean averaged over three years.
	Primary and Secondary	35 µg/m^3	24-hour	98th percentile averaged over three years
Carbon monoxide (CO)	Primary	35 ppm (40 mg/m^3)	1-hour	Not to be exceeded more than once per year.
	Primary	9 ppm (10 mg/m^3)	8-hour	Not to be exceeded more than once per year
Ozone (O3)	Primary and Secondary	0.12 ppm (235 µg/m^3)	1-hour[s]	expected number of days per calendar year, with a maximum hourly average concentration greater than
	Primary and Secondary	0.070 ppm (140 µg/m3)	8-hour	Annual fourth-highest daily maximum 8-hour concentration averaged over 3 years.
Nitrogen dioxide (NO2)	Primary and Secondary	0.053 ppm (100 µg/m3)	annual	Annual mean
	Primary	0.100 ppm (188 µg/m3)	1-hour	98th percentile of 1-hour daily maximum averaged over 3 years
Lead (Pb)	Primary and Secondary	0.15 µg/m3	Rolling 3 months	Not to be exceeded

3.9.4.2 Air quality index (AQI)

The Air Quality Index (AQI) was developed by the United States Environmental Protection Agency (USEPA) to inform the public about air quality levels and their potential impact on human health. It serves as a tool to educate people about the state of the air, how it can affect health, and measures they can take to protect themselves.

The AQI is based on the concentrations of five primary air pollutants: Carbon Monoxide (CO), Sulfur Dioxide (SO2), Particulate Matter (PM10), Ozone (O3), and Nitrogen Dioxide (NO2). These pollutants are divided into six categories, each representing different levels of air quality, and each category is associated with a specific description of the air quality.

Table 3-5: AQI and pollution concentration limits.

CO (ppm)	SO2 (ppm)	NO2 (ppm)	Values of AQI	Health Concern's Level
0-4.4	0.0-0.034	0	0-50	Good
4.5-9.4	0.035-0.144	0	51-100	Moderate
9.5-12.4	0.145-0.224	0	101-150	Unhealthy for Sensitive Group
12.5-15.4	0.225-0.304	0	151-200	Unhealthy
15.5-30.4	0.305-0.604	0.65-1.24	201-300	Very Unhealthy
30.5-40.4	0.605-0.804	1.25-1.64	301-400	Hazardous
40.5-50.4	0.805-1.004	1.65-2.04	401-500	Hazardous

The AQI scale runs from 0 to 500, with higher AQI values indicating greater levels of air pollution and associated health concerns (Table 3-6), and Table 3-7 lists cautionary statements for each pollutant. For example, an AQI value of 50 or below represents "Good" air quality, while an AQI value over 300 represents "Hazardous" air quality.

Table 3.6: The Air Quality Index (AQI) Levels of Health Concern, Numerical Values, and Meanings

For that AQI	Use that descriptor	And that color	Description of Air Quality
0 to 50	Good	Green	The air remains clean and does not present any meaningful threat to human health.
51 to 100	Moderate	Yellow	Although air quality is within acceptable standards, individuals with heightened sensitivity to pollutants may still face potential health risks.
101 to 150	Unhealthy for sensitive groups	Orange	Individuals belonging to sensitive groups may encounter health-related symptoms, whereas the wider population is unlikely to be significantly impacted."
151 to 200	Unhealthy	Red	Certain individuals within the general population may begin to experience health symptoms, while those in sensitive groups are at greater risk of more severe effects."
201 to 300	Very unhealthy	Purple	Health alert: Everyone's health risks are increased.
301 to 500	Hazardous	Maroon	Health warnings of emergency conditions indicate that everyone is more likely to be affected.

Table 3-7: Pollutant-Specific Sub-indices and Cautionary Statements for Guidance on the Air Quality Index (AQI)

AQI Categories (Index Values)	Ozone (ppm)		Particulate Matter (µg/m³)		Carbon Monoxide (ppm) [8-hour]	Sulfur Dioxide (ppb) [1-hour]	Nitrogen Dioxide (ppb) [1-hour]
	[8-hour]	[1-hour]	$PM_{2.5}$ [24-hour]	PM_{10} [24-hour]			
Good (Up to 50)	0 - 0.054 None		0 – 12.0 None	0 - 54 None	0 – 4.4 None	0 - 35 None	0 - 53 None
Moderate (51 - 100)	0.055 - 0.070 Unusually sensitive people should consider reducing prolonged or heavy outdoor exertion.		12.1 – 35.4 Unusually sensitive people should consider reducing prolonged or heavy exertion.	55 – 154	4.5 – 9.4 None	36 - 75 None	54 - 100 Unusually sensitive individuals should consider limiting prolonged exertion especially near busy roads.

Unhealthy for Sensitive Groups (101 - 150)	0.071 - 0.085	0.125 - 0.164	35.5 – 55.4	155 – 254	9.5 – 12.4 People with heart disease, such as angina, should limit heavy exertion and avoid sources of CO, such as heavy traffic.	76 - 185 People with asthma should consider limiting outdoor exertion.	101 - 360 People with asthma, children, and older adults should limit prolonged exertion, especially near busy roads.
	People with lung disease (such as asthma), children, older adults, active outdoors (including outdoor workers), people with certain genetic variants, and people with diets limited in certain nutrients should reduce prolonged or heavy outdoor exertion.		People with heart or lung disease, older adults, children, and individuals from lower socioeconomic backgrounds should limit prolonged or heavy exertion.				
Very Unhealthy (201 - 300)	0.106 - 0.200	0.205 - 0.404	150.5 – 250.4	355 – 424	15.5-30.4 People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic.	305 – 604 [24-hour] Children, people with asthma, or other lung diseases should avoid outdoor exertion; everyone else should reduce outdoor exertion	650 - 1249 People with asthma, children, and older adults should avoid all outdoor exertion; everyone else should avoid prolonged exertion, especially near busy roads.
	People with lung disease (such as asthma), children, older adults, active outdoors (including outdoor workers), people with certain genetic variants, and people with diets limited in certain nutrients should avoid all outdoor exertion; everyone else should reduce outdoor exertion.		People with heart or lung disease, older adults, children, and individuals from lower socioeconomic backgrounds should avoid all outdoor physical activity. Everyone else should avoid prolonged or heavy exertion.				
Hazardous (301 - 500)	-	0.405 - 0.604	250.5 – 500.4	425 – 604	30.5 – 50.4 People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic; everyone else should limit heavy exertion.	605 – 1004 [24-hour] Children with asthma or other lung diseases should remain indoors; everyone else should avoid outdoor exertion.	1250 - 2049 People with asthma, children, and older adults should remain indoors; everyone else should avoid all outdoor exertion.
	Everyone should avoid all outdoor exertion.		Everyone should avoid all physical activity outdoors; people with heart or lung disease, older adults, children, and people of lower socioeconomic status should remain indoors and keep activity levels low.				

Table 3-7 lists these and other common air pollutants, sources, and the range expected in the outdoor

Table 3-8: Common Air Pollutants, Their Sources, and Concentration Ranges to Expect in Outdoor Air.

Pollutant(Abbreviation)	Examples of Outdoor Sources	Typical Hourly Outdoor Concentration Range to Expect within the U.S.
Ammonia	Agriculture, animal husbandry, fertilizers, and mobile sources	0 to 3 μg/m^3
Benzene	Gasoline, evaporative losses from above-ground storage tanks, and mobile sources	0 to 7 μg/m3 (0.03 to 2.3 ppb)
Black Carbon (BC)	Biomass burning and mobile sources	0 to 15 μg/m^3
Carbon Dioxide (CO2)	Fuel combustion from electric utilities and mobile sources	350 to 600 ppm
Hydrogen Sulfide (H2S)	Natural sources (e.g., volcanoes, hot springs, bacterial breakdown of organic matter) and industrial sources (e.g., refineries, natural gas plants, petrochemical plants, food processing, tanneries)	0 to 20 ppm
Lead (Pb)*	Smelting, aviation gasoline, waste incinerators, electric utilities, and lead-acid batteries	0 to 0.1 μg/m3
Mercury (Hg)	Combustion of coal, oil, and wood	0.001 to 0.17 μg/m3
Methane (CH4)	Industry (e.g., natural gas operations), agriculture, and waste management	1,500 to 2,000 ppb
Nitrogen Dioxide (NO2)*	Fuel combustion from mobile sources and electric utilities	0 to 50 ppb
Ozone (O3)*	Formed via ultraviolet (UV) radiation in sunlight and the presence of other key pollutants (e.g., nitrogen oxides, volatile	0 to 125 ppb

	organic compounds)	
Particulate Matter (PM2.5)*	Fuel combustion (mobile sources, electric utilities, industrial processes), dust, agriculture, fires, and formation in the atmosphere due to chemical reactions	0 to 40 µg/m3 (100 to 1,000 µg/m3 near wildfires)
Particulate Matter (PM10)*	Dust (e.g., agriculture, roads, construction), brake/tire and engine wear from mobile sources, and fires	0 to 100 µg/m3 (500 to 1,000+ µg/m3 in dust storms)
Sulfur Dioxide (SO2)*	Fuel combustion from electric utilities, refineries, and industrial processes	0 to 100 ppb (100 to 5,000 ppb near active volcanoes)
Ultrafine Particles (UFP)	Fuel combustion (mobile sources, industries), gasoline evaporation, and solvent usage	3,000 to 200,000 particles/cubic centimeter (cm3)
Volatile Organic Compounds (VOCs)	Fuel combustion (mobile sources, industries), gasoline evaporation, solvents, and consumer products	5 to 100 µg/m3

Table 3-10: WHO Air Quality Guidelines – Urban Pollutant Limits

Gas / Pollutant	Reference	Recommended Limit	Averaging Time
Carbon Monoxide (CO)	WHO (Indoor Air, 2010)	3.5 ppm (≈4 mg/m³)	24-hour average
		8.7 ppm (≈10 mg/m³)	8-hour average
		30 ppm (≈35 mg/m³)	1-hour average
Nitrogen Dioxide (NO_2)	WHO AQG (2021)	0.010 ppm (≈10 µg/m³)	Annual mean
		0.025 ppm (≈25 µg/m³)	24-hour average
Sulfur Dioxide (SO_2)	WHO AQG (2021)	0.040 ppm (≈40 µg/m³)	24-hour average
	Interim target	0.500 ppm	10-minute average
Ozone (O_3)	WHO AQG (2021)	0.100 ppm (≈100 µg/m³)	8-hour average
Formaldehyde	WHO Indoor Air Guidelines (2010)	0.08 ppm (≈100 µg/m³)	30-minute average
Particulate Matter ($PM_{2.5}$)	WHO AQG (2021)	0.005 ppm (≈5 µg/m³)	Annual mean
PM_{10}	WHO AQG (2021)	0.015 ppm (≈15 µg/m³)	Annual mean

Ammonia (NH_3)	WHO (occupational, not ambient)	~25 ppm (occupational exposure)	8-hour workday
Hydrogen Fluoride (HF)	WHO (occupational)	~3 ppm (TLV in workplaces)	8-hour average
Hydrogen Cyanide (HCN)	WHO / OSHA / NIOSH	10 ppm (IDLH); 4.7 ppm (TWA)	Short-term
Phosgene	WHO (occupational)	0.1 ppm (IDLH)	Short exposure
Chlorobenzene	Not specified by WHO	~75 ppm (OSHA PEL)	Workplace reference
Acetic Acid	Not specified by WHO	~10 ppm (TLV)	Occupational limit
Acetaldehyde	WHO (Indoor)	0.05–0.1 ppm	Indicative (Indoor only)

Table 3.10 presents the World Health Organization (WHO) permissible limits for various gaseous pollutants typically found in urban street environments. The table includes key air contaminants such as carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and benzene, with concentration limits provided in parts per million (ppm) based on exposure duration (e.g., 1-hour, 24-hour, or annual averages). These limits are established to protect public health, particularly in densely populated and traffic-congested areas. For other compounds like formaldehyde, acetaldehyde, and ammonia, WHO guidelines are supplemented with occupational or indoor air standards due to limited direct outdoor benchmarks. Some pollutants, such as methane (CH_4), nitrous oxide (N_2O), and propane, are not directly addressed in WHO ambient air guidelines due to their low acute toxicity or global background presence.

3.6 Public transportation

Urban transportation crises are a common issue in many cities due to rapid economic growth and urbanization. The unprecedented rise in the number of private vehicles has led to significant traffic congestion, high accident rates, air pollution, and increased greenhouse gas emissions (Leather et al., 2011). In Karbala city, the existing public transportation system suffers from limited accessibility. The growing traffic congestion is a direct consequence of the heavy reliance on private cars as the primary mode of transportation. This dependency is reflected in the widespread occurrence of traffic jams (Hussein and Ismael, 2022). A noticeable result of road congestion is the increase in travel times along heavily trafficked routes (Christodoulou and Christidis, 2021). The inadequate public transportation infrastructure also leads to higher vehicle operating costs, making it more challenging to move around the city (Hussein and Ismael, 2022).

Furthermore, public transportation benefits everyone, as it is accessible not only to those who own and can drive cars but to the broader population as well. As such, cities require public transportation systems that provide greater mobility than rural areas can offer (Teodorović and Janić, 2022). The efficiency of a public transport system is largely determined by its affordability, its ability to meet demand, and the time it takes for passengers to transfer between routes (Kiliç and Gök, 2014). Iraq's population has grown overall, with Karbala city experiencing a direct and proportional increase in the number of vehicles in service in recent years. The dramatic rise in the number of cars correlates directly with the growing traffic congestion in Karbala. According to data published by the Ministry of Planning and the Central Bureau of Statistics, the number of private vehicles and all types of plates (Permanent, Manifest, New Plate) registered with the Directorate of Traffic from 2016 to 2020 has increased significantly, with notable surges occurring in recent years.

Figure 3.7 illustrates the global projections, indicating substantial growth in the transportation sector between 2015 and 2040. The number of passenger cars is expected to rise from 1.1 billion in 2015 to 1.5 billion by 2025, reaching 2.0 billion by 2040.

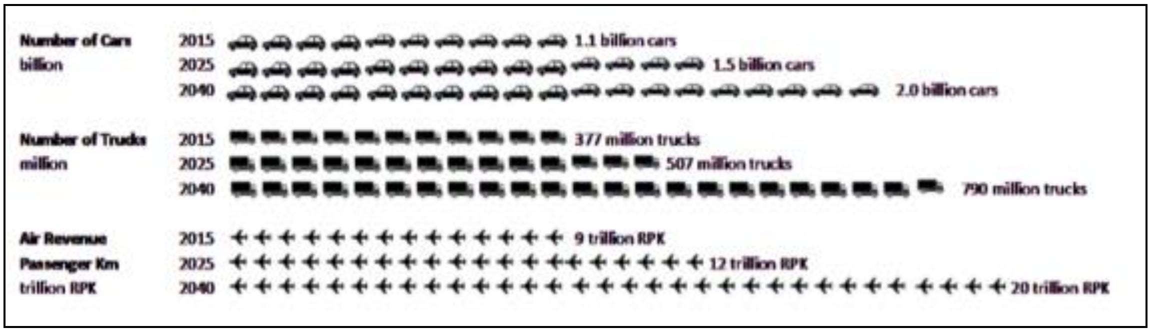


Figure 3.7: Increase in Numbers of vehicles from 2016-2040 (world-economic-forum, 2016)

Similarly, the global truck fleet is projected to expand significantly, from 377 million units in 2015 to 507 million in 2025, and further to 790 million by 2040. In parallel, air transportation is forecasted to experience remarkable growth, with revenue passenger kilometers (RPK) increasing from 9 trillion RPK in 2015 to 12 trillion RPK by 2025, ultimately doubling to 20 trillion RPK by 2040. These trends underscore an accelerating demand for mobility and logistics services worldwide, raising critical implications for infrastructure development, energy consumption, and environmental sustainability.

3.7 Summary

A comprehensive list of sustainability indicators relevant to the Karbala case study is identified. Examples include: Environmental: CO_2 emissions, particulate matter (PM10, PM2.5), noise levels, fuel consumption. Economic factors include travel time cost, vehicle operating cost, and public transport availability. Social: accident rate, pedestrian facilities, accessibility to services. The study emphasizes the interdependency of these indicators and the necessity for integrated analysis to avoid trade-offs that harm long-term sustainability goals.

Chapter Four: Methodology and Collect Data

4.1 Introduction

Traffic data gathering is fundamental to transportation engineering (Al-Bahr et al., 2019). That chapter provides an overview of the essential attributes of the research field. That text provides a comprehensive examination of the techniques employed to assess the influence of traffic movement on air pollution, noise levels, and all criteria collected. Additionally, it explores the correlation between speed and traffic flow, particularly emphasizing elements such as public transportation and pedestrian infrastructure. Additionally, the travel duration will be ascertained to assess the quality of service in the chosen urban network. That chapter comprises multiple sections, encompassing the delineation of the study region, the execution of a field survey, and the subsequent analysis. Furthermore, it entails precisely determining the data-gathering process for the chosen urban road network, which includes divided and undivided streets in Karbala City.

4.2 Study Area

Karbala is an Iraqi city and the administrative center of Karbala Governorate, located in the Middle Euphrates region. It has a population exceeding three million according to 2024 estimates, making it the seventh-largest city in Iraq. Karbala is situated about 105 km southwest of Baghdad, near the western edge of the Euphrates River and on the left bank of Al-Husseiniyah creek. The city lies approximately 36 meters above sea level, within the coordinates of 41°10′ to 44°20′ E longitude and 31° to 32° N latitude. It shares borders with Al-Anbar to the north and west, Al-Najaf to the south, and Babylon to the east and northeast (ICTR, 2007; Theyab, 2021).

The city holds major religious and cultural importance, attracting millions of pilgrims annually due to the presence of significant religious shrines. The origin of the name "Karbala" is debated; some scholars attribute it to the ancient term "Karbalato" or remnants of Babylonian settlements such as Kar Babel, Karbella, and others, indicating a deep historical and linguistic heritage.

This study focuses on the urban highway network linking the central business district (CBD) with key high-density residential, commercial, and educational zones in the heart of Karbala. The study area is illustrated in Figure 4.1, showing the interconnected street segments and nodes.

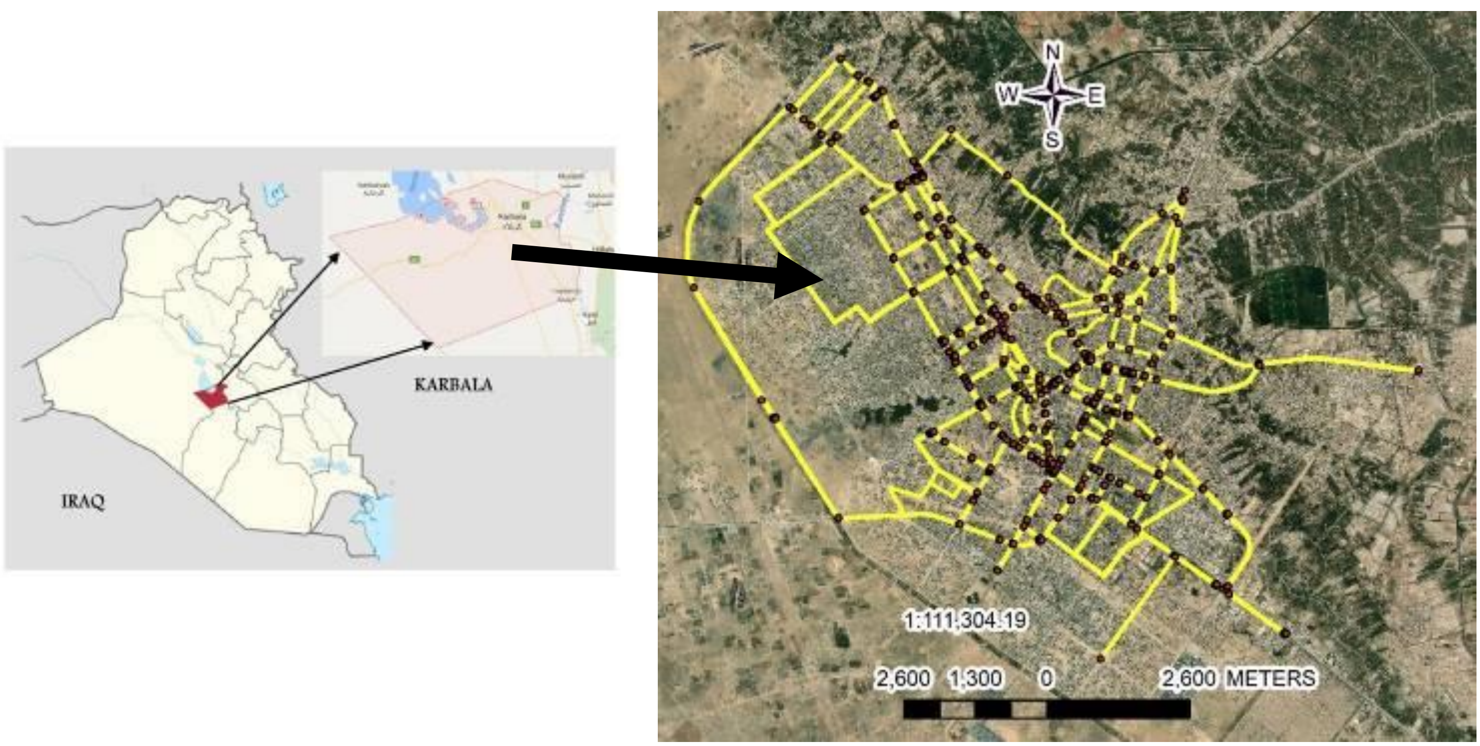


Figure 4.1: Location of Karbala city in Iraq and street segments with nodes

4.3 Data and measurement tools used

That phase aims to gather all data required to evaluate the traffic flow condition in the study area and its impact on the environment and performance. The needed data, including traffic flow, speed, noise, and pollution, will be collected on October/2023to in the morning at peak hours (6:00 AM – 9:00 AM) during good weather and normal days; Mondy in 10/9/2023, Tuesday in 10/10/2023 and Wednesday in 11/10/2023, for three day and 18th position in Network of Karbala city as explain in the Figure 4.2.

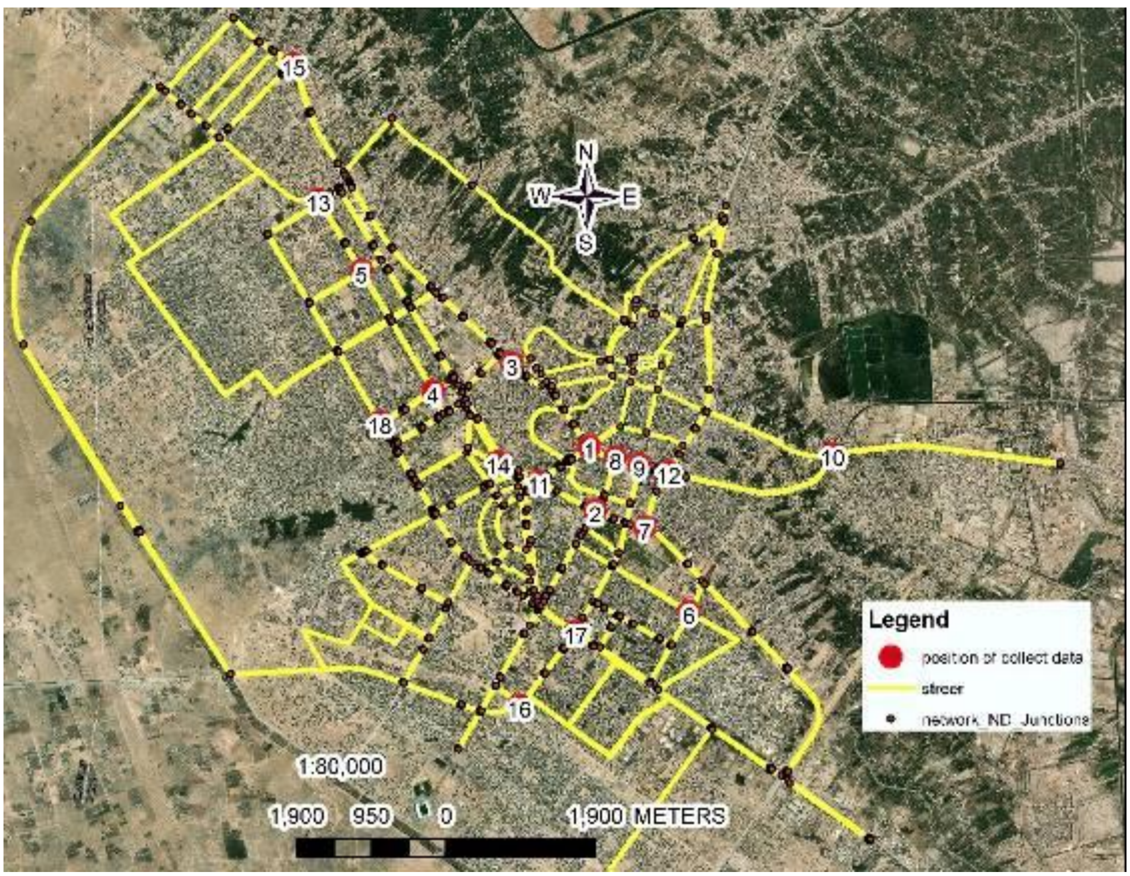


Figure 4.2: Number of positions of data collection

The names of the collected data positions are explained in Table 4.1; each position has a number on the map, as shown in Figure 4.2.

Table 4-1: Position of collected data

No	Position Name	No	Position Name
1	Roundabout of AL-Tarbiyah	10	Roundabout of Qantarat Alsalam
2	Roundabout of Alsafina	11	Intersection of Fatimat Al-Zahraa
3	Roundabout of Al-Jameia	12	Intersection of Al-Abaas
4	Roundabout of Al-Muealimin	13	Roundabout of Al-Thawra
5	Roundabout of Mustawsaf	14	Roundabout of Hay Ramadan
6	Roundabout of Al-Mulhak	15	Roundabout of Tariq Alhure
7	Roundabout of Eamil Alnazafa	16	Roundabout of Al-Kawthar
8	Roundabout of Al-Baladia	17	Intersection of Al-Emam Ali
9	Roundabout of Almuhafaza	18	Roundabout of Al-Gader

4.4 Research Methodology

Figure 4.3 provides a comprehensive representation of the methodological framework adopted in this thesis. It presents, in a systematic flow, all the critical phases of the research, beginning with the stage of data collection from relevant sources, and moving forward through the processes of data preparation, cleaning, and organization. The diagram also highlights the subsequent steps of analysis, modeling, and evaluation, while clearly pointing out the main tools, techniques, and software programs applied at each stage to ensure accuracy and reliability. Overall, this Figure plays a vital role in demonstrating the logical sequence of the research workflow, offering readers a clear, detailed, and well-structured understanding of how the study was conducted from start to finish.

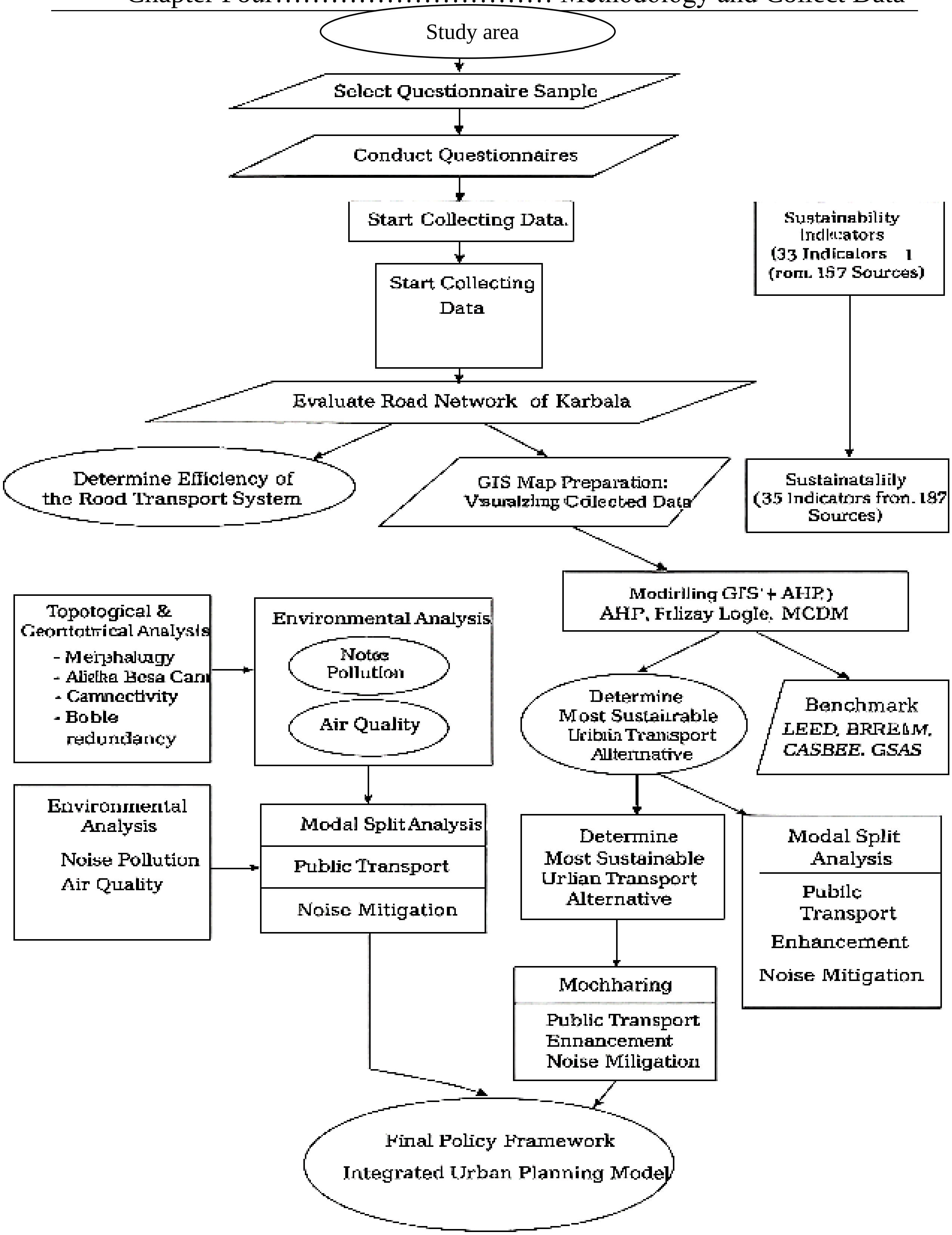


Figure 4.3: Research Methodology

4.5 Traffic flow data

The traffic volume of the chosen network was captured via camera observation to understand the network's unique traffic patterns better. Record traffic patterns, high-definition cameras were put at critical roadways and exits. The number of vehicles passing a certain point in the research area is an example of volume data. Video recordings were analyzed for data, which was then numbered by hand. Videotaping is favoured because of several factors, including:

- The easy way to obtain data.
- The ability to record a wide range of situations.
- Adjustments and additional analyses can be made to the collected data at any time.
- Information such as traffic volume, speeds, and maneuvers can be gleaned visually from the tapes.

There was sufficient coverage for parts of the research area, with cameras placed on the ground and in buildings. The various camera configurations employed are depicted in Figure 4.4.

Figure 4.4:The methodology framework for the current study

specifically from the Holy Karbala Governorate/Camera and Video Surveillance Department. These cameras were strategically placed at various locations throughout the roadway network in Karbala. Figure 4.5 explains some of the cameras.

Figure 4.5: Camera related to Karbala Governorate

4.6 Free Flow Speed data

Road conditions influence the driver's speed decision. The free flow speed (FFS) is the average driver's preferred speed when there is no vehicle interaction or traffic management. The FFS of a traffic stream is its average speed when traffic volumes are low enough that the presence of other vehicles has no effect on drivers and when intersection traffic control (i.e., signal or sign) is absent or far enough away not to affect speed choice. Therefore, FFS is generally seen in the middle of metropolitan areas (HCM, 2016). FFS was calculated using a speed gun. A radar speed gun (also a radar gun and speed trap gun) is a device used to measure the speed of moving objects; it is a Doppler radar unit that may be hand-held, vehicle-mounted, or static. It measures the speed of the objects at which it is pointed by detecting a change in frequency of the returned radar signal caused by the Doppler effect, whereby the frequency of the returned signal is increased in proportion to the object's speed of approach if the object is approaching, and lowered if the object is receding.

Figure 4.6: Speed gun details

Figure 4.6 illustrates a Bushnell radar speed gun, a handheld device used for measuring the speed of moving objects. The device consists of two main components: the radar gun itself and the digital display screen.

The radar gun features an ergonomically designed grip and includes a trigger, which activates the speed measurement function when pressed. At the rear end of the device, the battery cap is located, providing access to the power source. The screen includes a radar icon, which indicates that the device is actively detecting speed, and a power button located below the screen for turning the device on and off.

4.7 Noise data

Noise pollution is exposure to high amounts of sound that can harm people or other living organisms. According to the World Health Organization, proper levels of less than 70 dB are not detrimental to living beings, no matter how long or constant the exposure is. One source of noise pollution is street traffic noise from cars, buses, pedestrians, ambulances, and other vehicles. Decibel readings were taken with the help of a hand-held noise meter.

UNI-T decibel meter sound level reader UT353. Measures from 30 dBA to 130 dBA. +/- 1.5 dBA with 0.1 dBA resolution. User-friendly interface. White backlight and clear LCD screen for easy visibility in dark situations, as shown in Figure 4.7. Aside from the median, it was also placed on the side of the road in the study area. Multiple applications exist for that tool:

- Lightweight and portable. Battery-powered, used to measure sound pressure levels directly.
- Keeping records.
- The “maximum/minimum” measuring system.
- Free conversion between a “rapid” sample rate and a “slow” sampling rate.
- A sensor technology based on micro-condenser microphones and a bandpass weighting network design.
- It has been tested and found to meet the “European Union standard.”
- Fast and accurate measurement.
- Windshield sponge ball.
- Professional capacitive sensor. Noise measurement data from case studies are beneficial in assessing the potential noise problem.

Figure 4.7: Portable noise meter device

4.8 Pollution data

Air pollution is the most significant environmental threat to public health globally; most air pollution caused by transportation comes from internal combustion engines and traditional fuels (Krasenbrink et al., 2005). CO2 is one of the gases available in the atmosphere. It is necessary for the life of plants. However, if it exceeds the permissible concentrations, it is considered harmful to the ozone layer (WHO, 2000).

The advanced, easy-to-use Gasmet DX4040 FTIR Gas Analyzer is designed for on-site measurements of organic and inorganic compounds at low concentrations in ambient air.

The Gasmet DX4040 combines Fourier Transform Infrared Spectroscopy (FTIR) analysis technology, a rhodium-gold coated sample cell, a built-in sample gas pump, and signal processing electronics in a compact unit that provides reliable measurements with low detection limits and true multi-compound analysis capability.

Air pollution measurements were conducted using the GASMET DX4040 portable FTIR gas analyzer. This advanced instrument is capable of detecting up to 25 different gaseous compounds simultaneously, delivering validated results within approximately 25 seconds. Utilizing Fourier Transform Infrared Spectroscopy (FTIR), the DX4040 ensures high-precision measurements with low detection limits and enables comprehensive multi-gas analysis. One of its key advantages lies in its customizable gas library, which users can easily modify through an intuitive interface, making the device highly adaptable to a wide range of field monitoring requirements. The analyzer draws ambient air samples through a handheld particle filter and Tygon tubing using an integrated pump system. Operating in continuous measurement mode, the DX4040 records time-weighted average concentrations over intervals defined by the user, ranging from 1 second to 5 minutes. The instrument setup and usage during the fieldwork are illustrated in Figures 4.8 and 4.9.

Figure 4.8 : **The instrument GASMET DX4040**

Figure 4.9: The instrument used in the data collection position

4.9 Data collection

After highlighting the importance of the data required for the study, a wide set of key variables was collected and used in the analyses presented in the following chapters. These variables include, but are not limited to, traffic volume, travel time, noise levels, operating and free-flow speeds, as well as a broad range of environmental, geometrical, and operational indicators such as air pollution, side friction, road density, accidents, and renewable energy use. The data were gathered along the designated road network during average weekdays under favorable weather conditions to ensure consistency and reliability. The data are collected as follows:

Traffic data; Noise data; Air pollution data; Travel time data; Side friction data; Road density data; Geometrical data; Passenger energy data;

Renewable energy used; Carbon footprint data; Natural resources and environmentally friendly modes used; Accidents; Speed of transportation.

4.9.1 Traffic data

The following traffic-related data were gathered along the mid-block urban road segments used in the study region: A. Flow data. These statistics were extracted from video recordings for specific sites in the study region and manually calculated. Vehicles travelling through an imaginary line were tallied. Traffic volume studies are carried out to determine the movements, numbers, and types of highway vehicles at a specific location. That information can be used to locate crucial flow periods. The traffic stream is identified as follows:

Private passenger car; Taxi passenger car; Motorcycle; Mass Transit Rail (MTR); Four-tire single-unit vehicle; Minibus; Heavy truck (H-truck); Standard truck; Bus; Three-wheel double-unit vehicle.

4.9.1.1 Roundabout Al-Tarbiyah

To accurately assess traffic volumes along the primary corridors of Al-Tarbiyah Street, a comprehensive data collection effort was conducted using strategically positioned surveillance cameras. These cameras were installed at key points along the street to monitor vehicular movement continuously over an extended period. The recorded footage provided reliable, real-time data on traffic flow patterns, peak hour volumes, and vehicle classifications. This method ensured high precision in capturing the dynamic nature of traffic conditions. The collected data were then systematically analyzed to quantify traffic volumes and to identify congestion hotspots, as illustrated in Figure 4.10, Al Tarbiya roundabout. This approach not only enhanced the robustness of the traffic assessment but also provided a solid empirical foundation for subsequent planning and analysis.

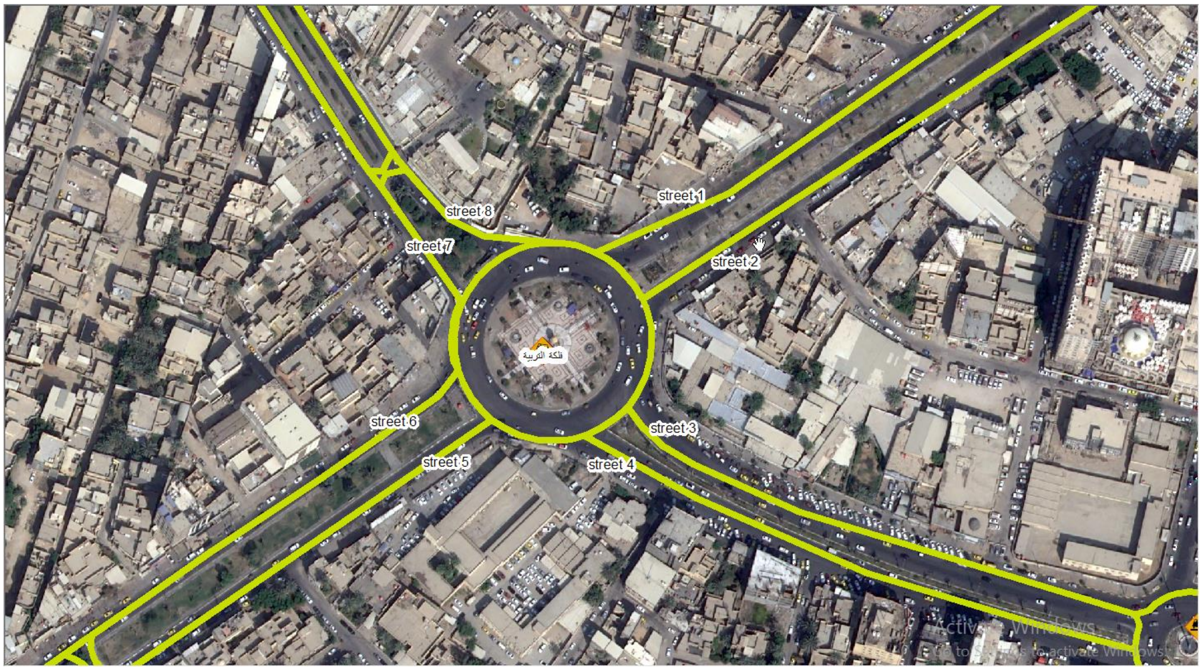


Figure 4.10: Roundabout Al-Tarbiyah

4.9.1.1.1 Roundabout of AL- Tarbiyah street segment 1

Figure 4.11 illustrates the section of AL-Tarbiyah Street where traffic volume measurements were taken at five-minute intervals over three days during peak hours. The data collected during this period allowed for the identification of the maximum traffic flow observed on the street. As shown in Figures 4.12, 4.13, and 4.14, the maximum traffic flow values for the respective sections of the street were determined and visually represented. This data serves as a critical foundation for analyzing the capacity of the street and performance during high-demand periods.

Figure 4.11: Road AL- Tarbiyah street segment 1

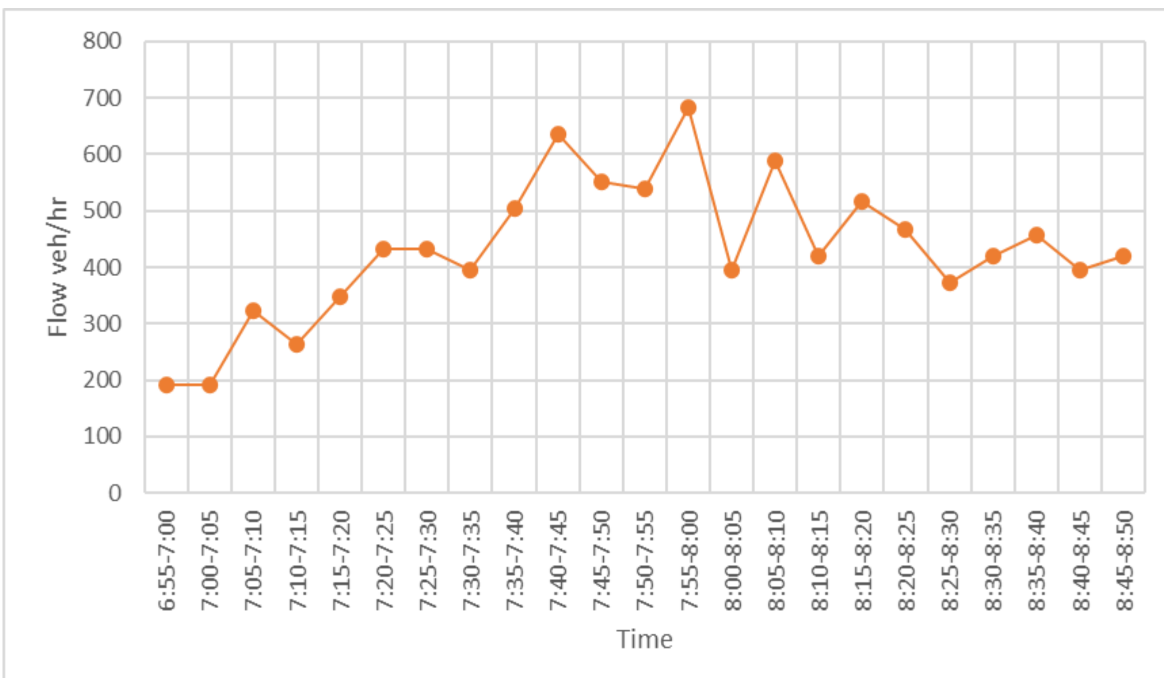


Figure 4.12: Fluctuation of flow with time for Street 1 on 9/10/2023

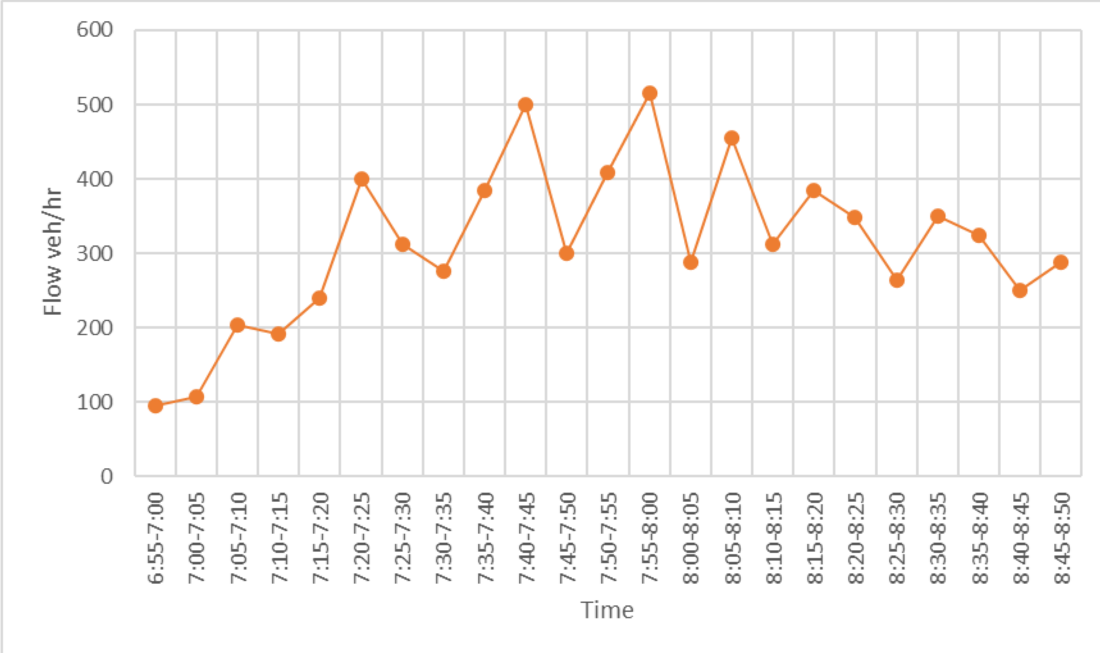


Figure 4.13: Fluctuation of flow with time for Street 1 on 10/10/2023

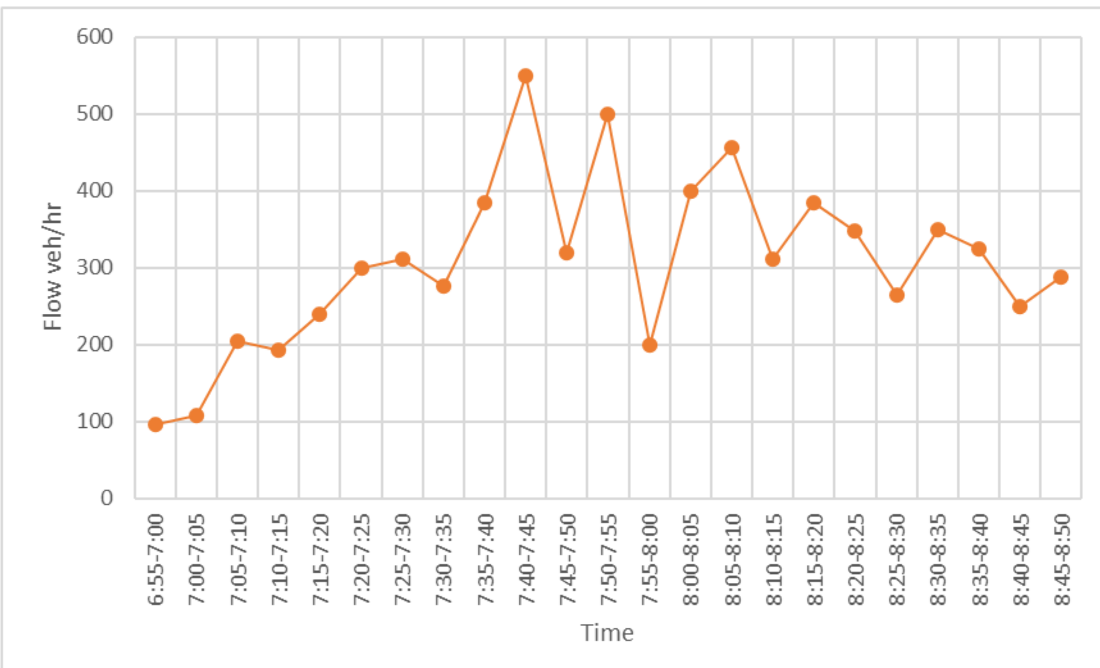


Figure 4.14: Fluctuation of flow with time for Street 1 on 11/10/2023

The peak traffic flow on AL-Tarbiyah Street 1 was recorded over three days, specifically on Monday, Tuesday, and Wednesday. To visually represent these findings, the collected data were compiled and are displayed in Figure 4.15. Among the recorded peak values, the maximum traffic flow was identified as the most significant value. This value was then mapped onto the street network using GIS tools, allowing for a precise spatial projection that enhances the analysis of traffic distribution across the urban network.

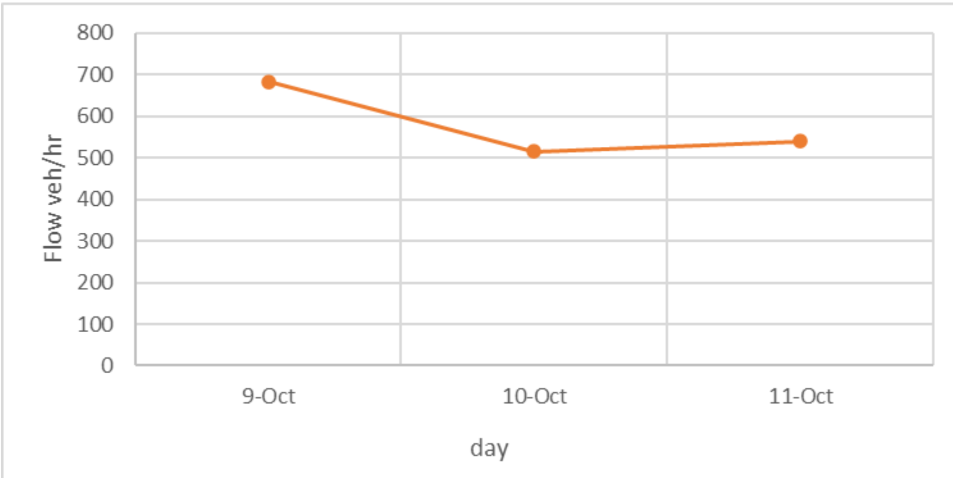


Figure 4.15: Maximum flow in three-day Street 1

4.9.1.1.2 Roundabout of AL- Tarbiyah Street segment 2

After completing the traffic volume analysis for Street 1, a similar detailed assessment was carried out for Street 2 at the same intersection, which is the Al-Tarbiyah Intersection. The analysis followed the same methodology and procedural steps applied previously, ensuring consistency in data collection, classification, and interpretation. This included observing peak-hour traffic flows, categorizing vehicle types, and recording pedestrian movements. By maintaining the same analytical framework, the results for Street 2 can be directly compared with those of Street 1, enabling a more comprehensive understanding of the operational performance of the entire intersection and identifying potential areas for traffic flow improvement. as illustrated in Figures 4.16 to 4.18.

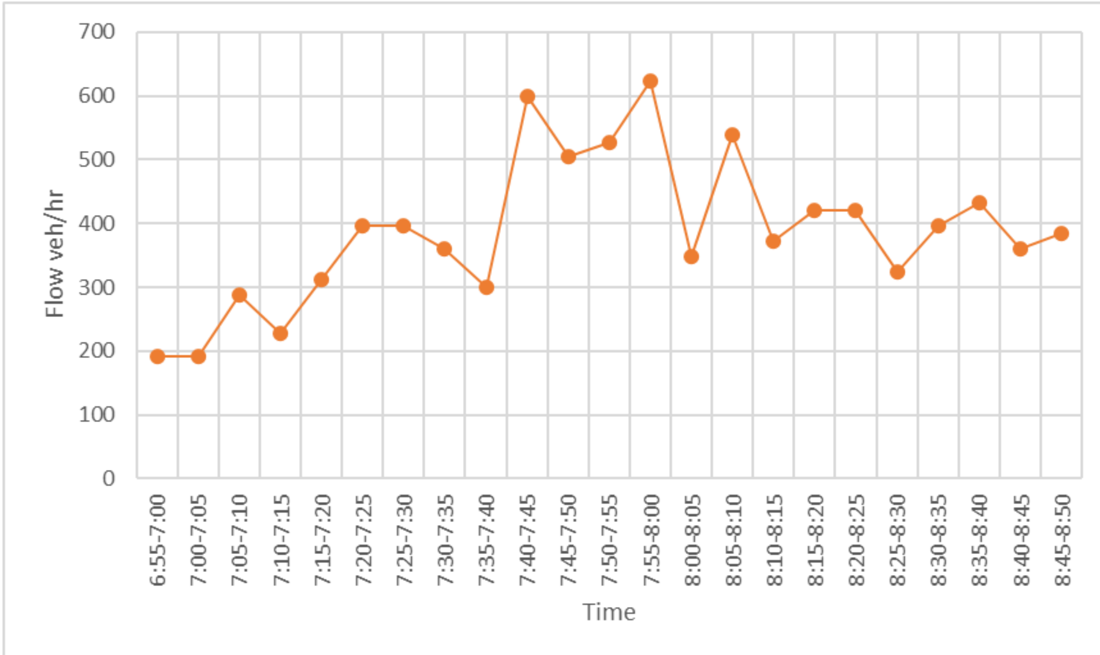


Figure 4.16: Fluctuation of flow with time for Street 2 on 9/10/2023

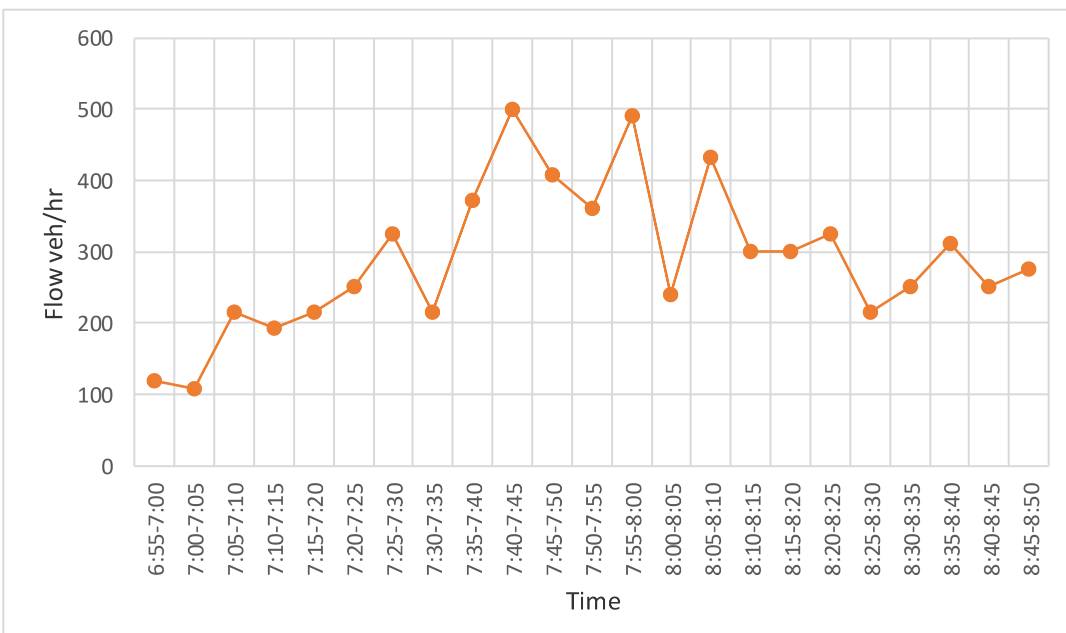


Figure 4.17: Fluctuation of flow with time for Street 2 on 10/10/2023

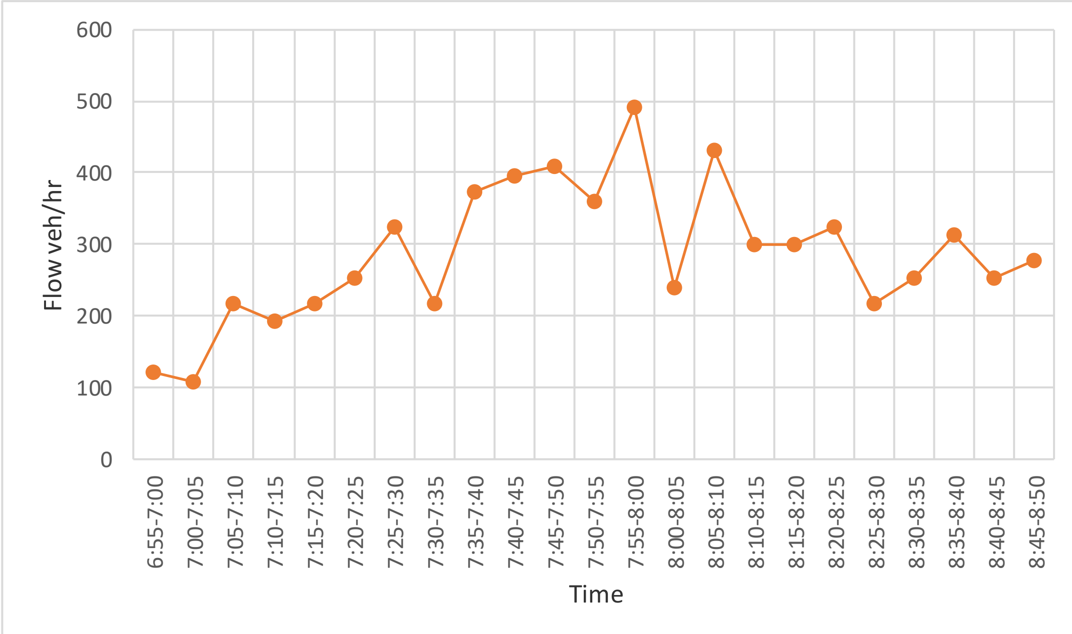


Figure 4.18: Fluctuation of flow with time for Street 2 on 11/10/2023

As shown in Figure 4.19, the three highest traffic volume values are presented. These values were identified based on the analysis conducted in the previous section.

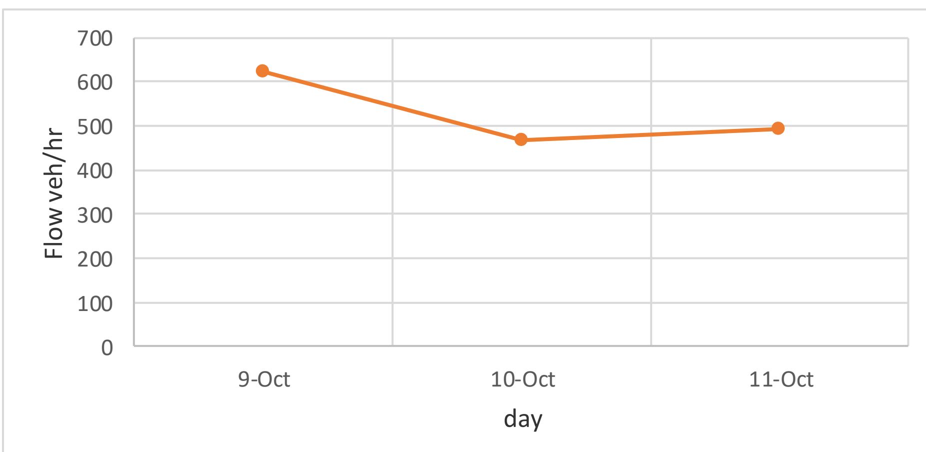


Figure 4.19: Maximum flow in three-day Street 2

4.9.1.1.3 Roundabout of AL- Tarbiyah Street segment 3

After analyzing the traffic volume for Street 1 and Street 2, an evaluation was also conducted for Street 3 at the Al-Tarbiyah Intersection.

The assessment used a slightly adjusted approach, focusing on peak-hour vehicle counts, pedestrian activity, and flow patterns. This allowed for a targeted comparison with previous streets to highlight specific operational challenges and potential improvements, as illustrated in Figures 4.21 to 4.23.

Figure 4.20: Illustrate the Street3&Street4

Figure 4.20 presents an image of Al-Tarbiyah Street, specifically segments 3 and 4, showing the number of vehicle lanes in each direction. The image clearly illustrates the roadway layout and lane configuration, providing a visual reference for traffic flow analysis. This photograph was captured using official government surveillance cameras installed at the intersection. Such visual documentation supports the accuracy of field data and enhances the reliability of the traffic assessment.

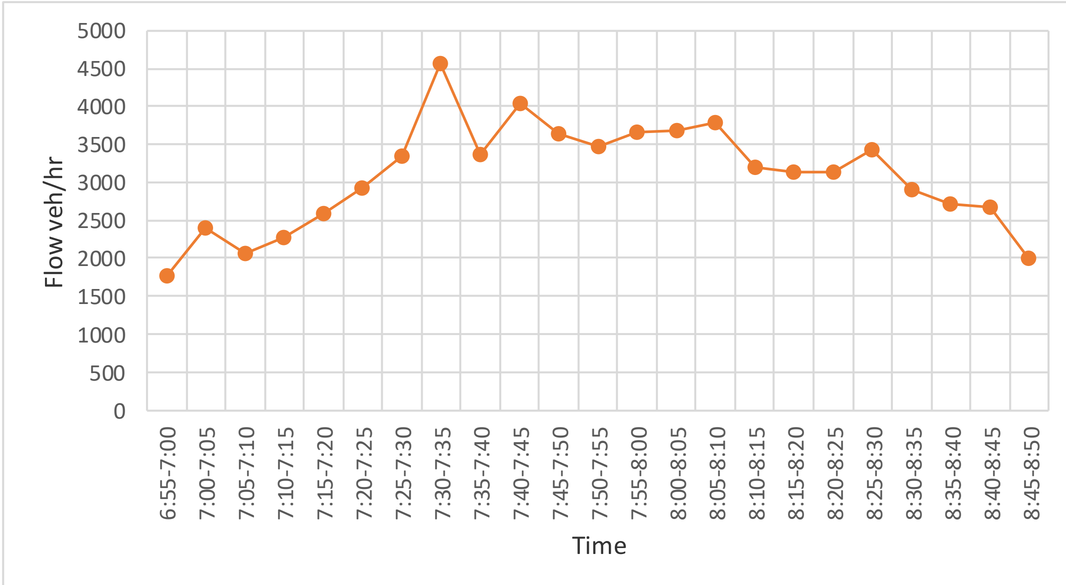


Figure 4.21: Fluctuation of flow with time for Street 3 on 9/10/2023

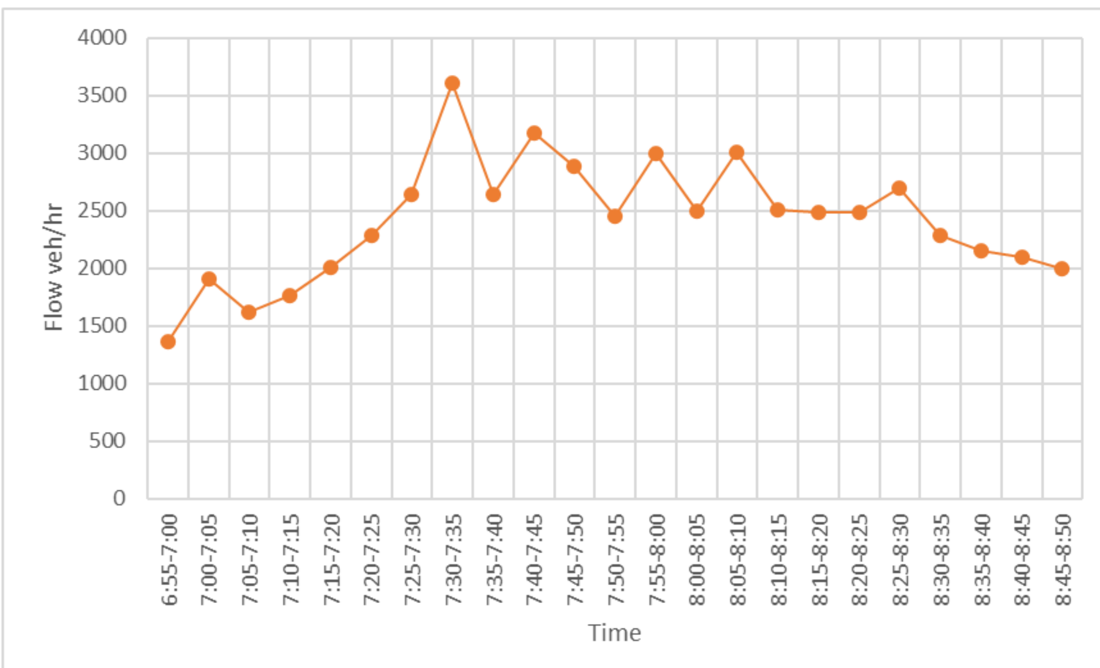


Figure 4.22: Fluctuation of flow with time for Street 3 on 10/10/2023

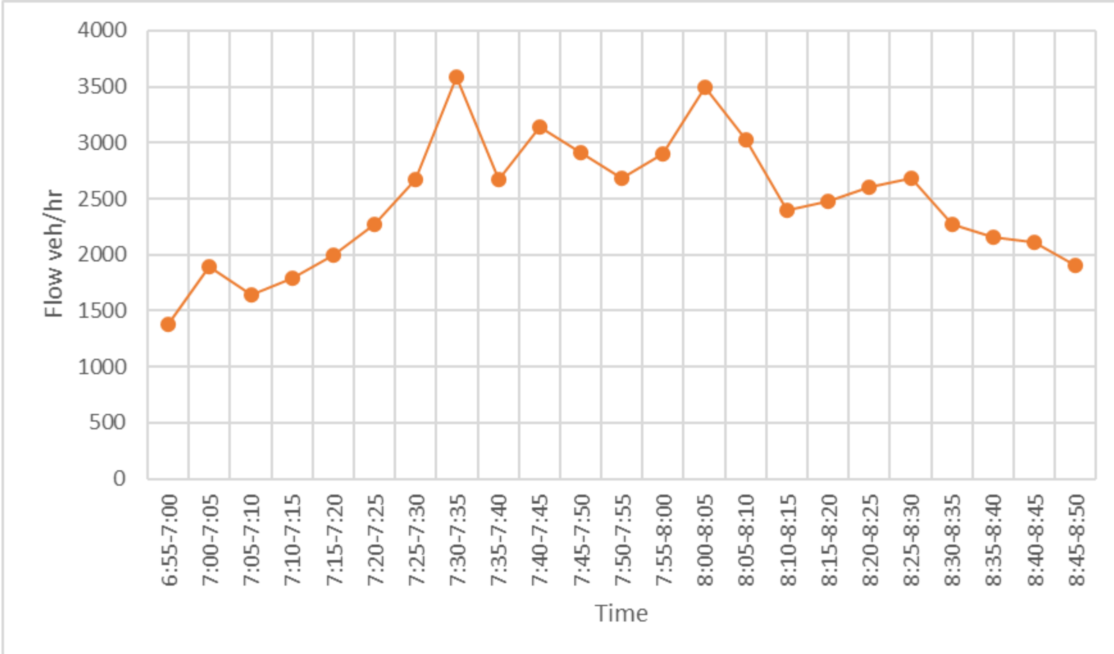


Figure 4.23: Fluctuation of flow with time for Street 3 on 11/10/2023

As shown in Figure 4.24, the three highest traffic volume values are presented. These values were identified based on the analysis conducted in the previous section.

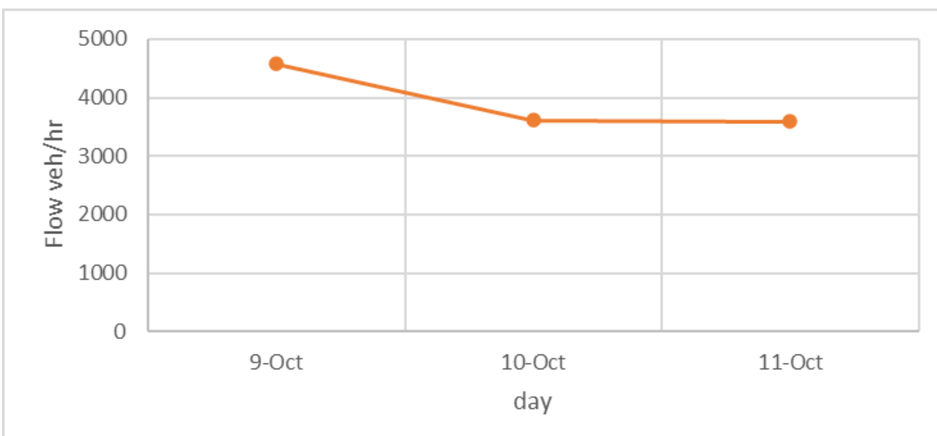


Figure 4.24: Maximum flow in three-day Street 3

4.9.1.1.4 Rounabout of AL- Tarbiyah Street segment 4

Following the completion of traffic volume assessments for Streets 1 through 3, a separate analysis was performed for Street 4 at the Al-Tarbiyah Intersection. This analysis emphasized identifying traffic density trends, lane utilization, and pedestrian crossings during critical periods of the day. The results were then compared with the earlier street evaluations to detect unique patterns and site-specific issues, as illustrated in Figures 4.25 to 4.27. These findings contribute to a deeper understanding of how intersection dynamics differ from standard roadway segments. Furthermore, they provide valuable insights for proposing targeted improvements aimed at enhancing both traffic efficiency and pedestrian safety

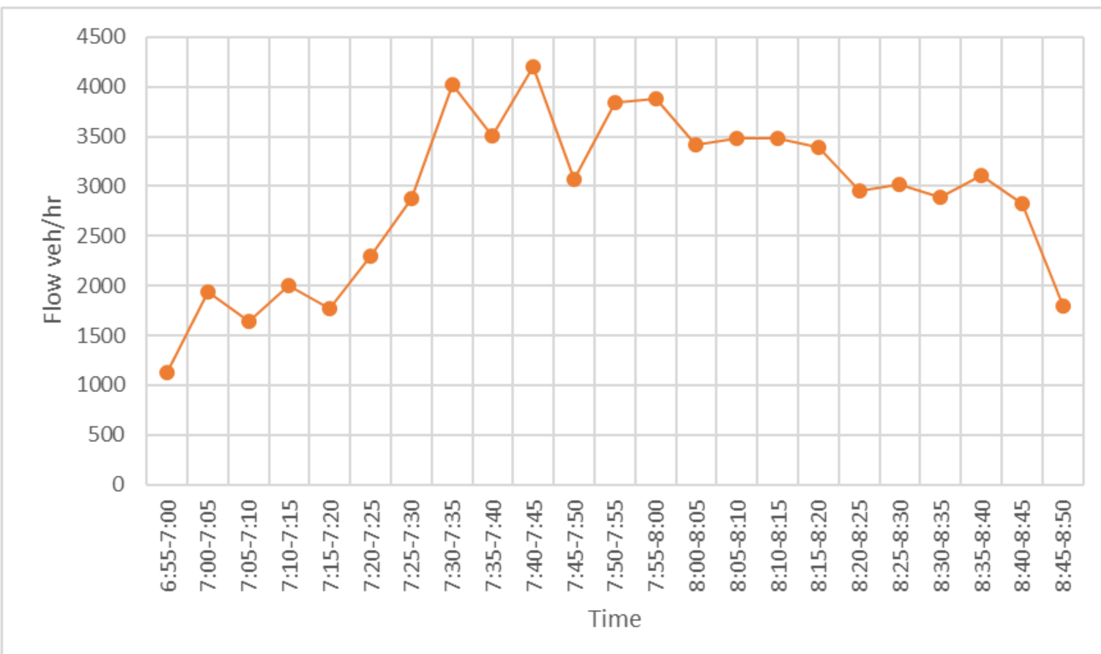


Figure 4.25: Fluctuation of flow with time for Street 4 on 9/10/2023

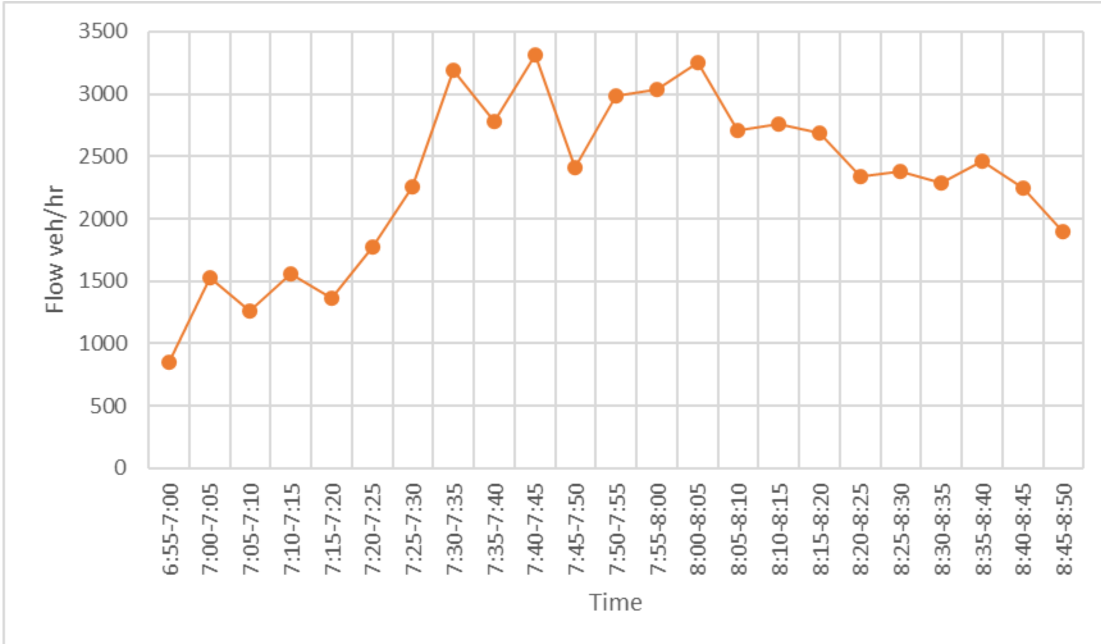


Figure 4.26: Fluctuation of flow with time for Street 4 on 10/10/2023

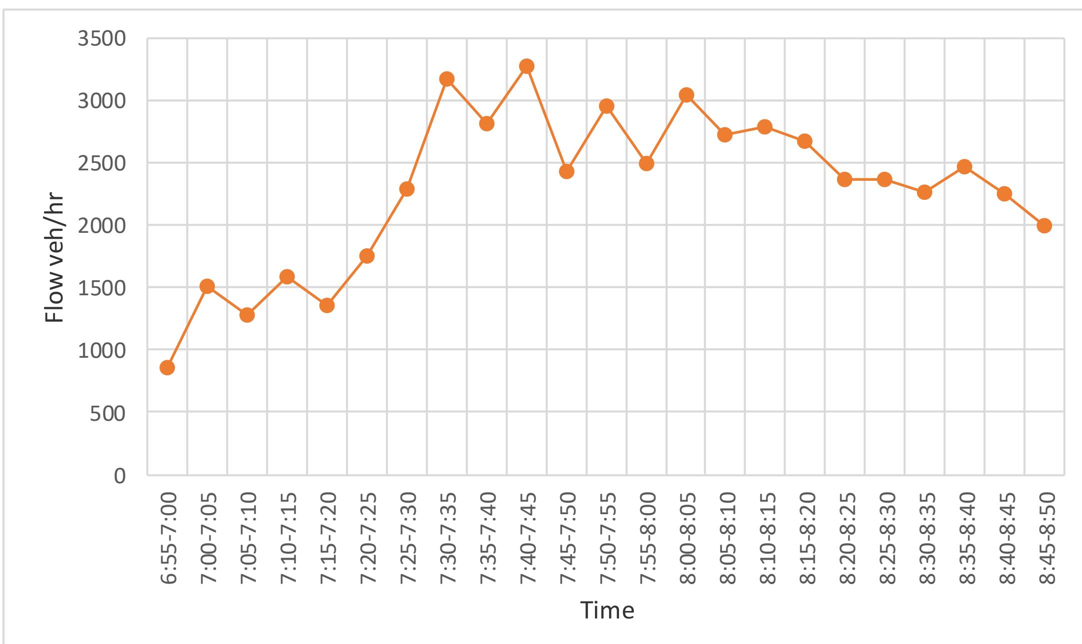


Figure 4.27: Fluctuation of flow with time for Street 4 on 11/10/2023

As shown in Figure 4.28, the three highest traffic volume values are presented. These values were identified based on the analysis conducted in the previous section.

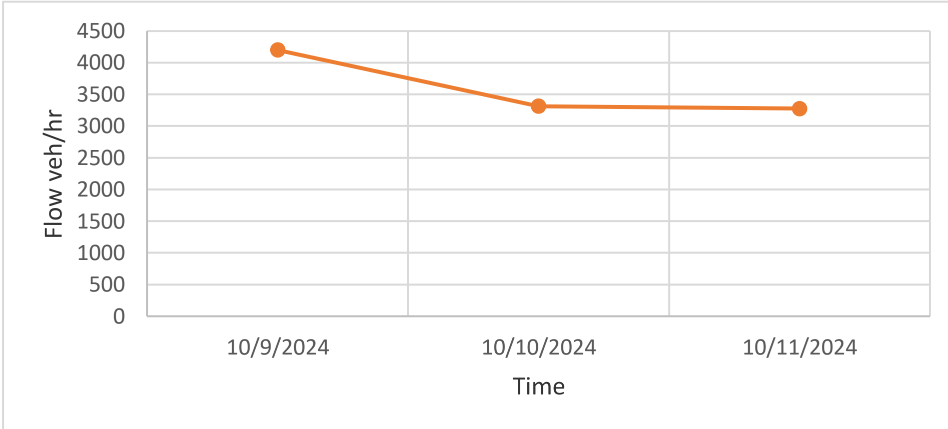


Figure 4.28: Maximum flow in three-day Street 3

4.9.1.1.5 Roundabout of AL- Tarbiyah Street segment 5

After completing the studies for Streets 1 to 4, traffic conditions on Street 5 at the Al-Tarbiyah Intersection were examined in detail. The review focused on overall flow efficiency, vehicle mix distribution, and pedestrian interaction with vehicular movement during busy hours. Findings from Street 5 were contrasted with previous analyses to pinpoint distinct operational characteristics and opportunities for improvement, as illustrated in Figures 4.29 to 4.31.

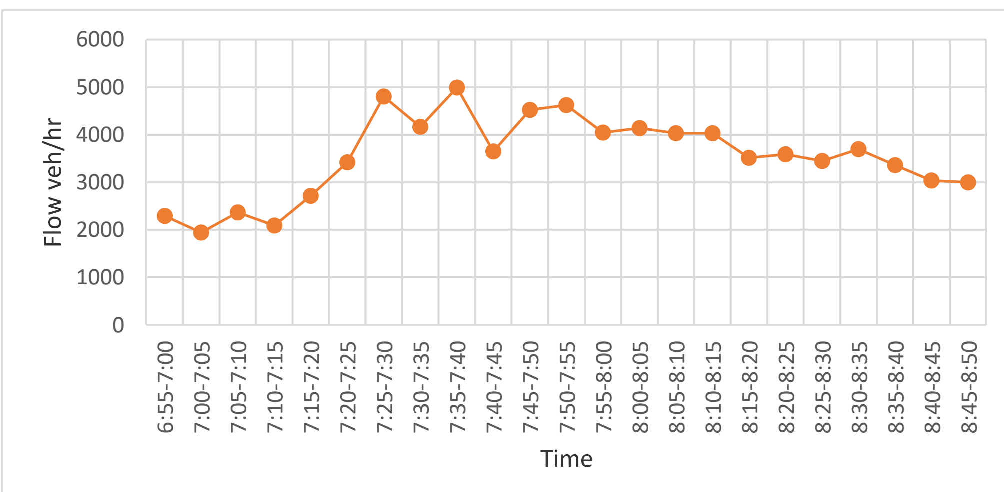


Figure 4.29: Fluctuation of flow with time for Street 5 on 9/10/2023

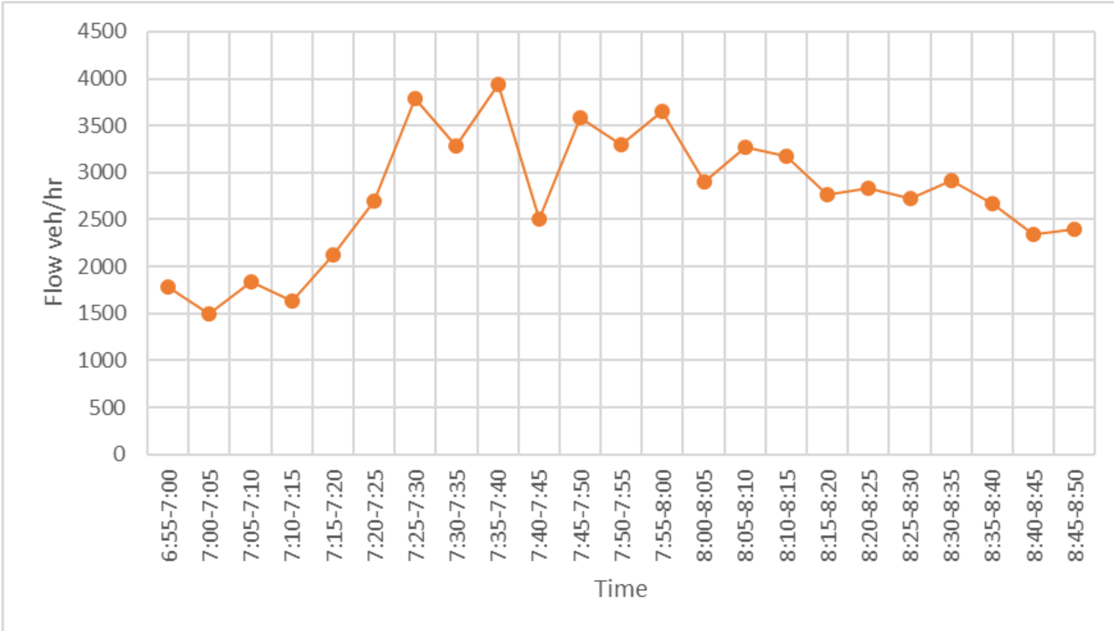


Figure 4.30: Fluctuation of flow with time for Street 5 on 10/10/2023

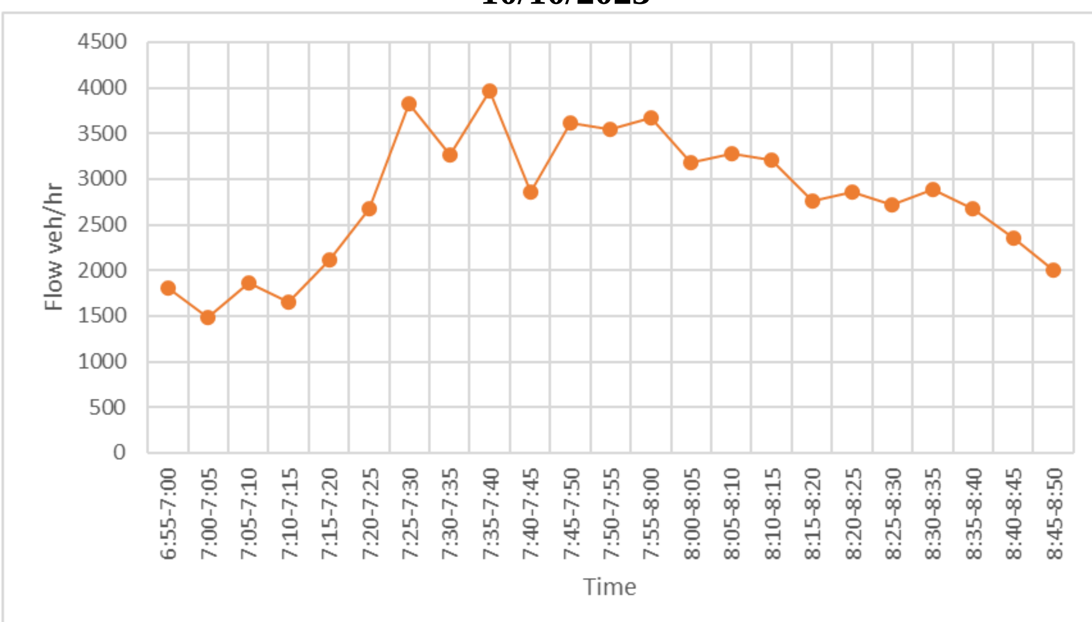


Figure 4.31: Fluctuation of flow with time for Street 5 on 11/10/2023

As shown in Figure 4.32, the three highest traffic volume values are presented. These values were identified based on the analysis conducted in the previous section.

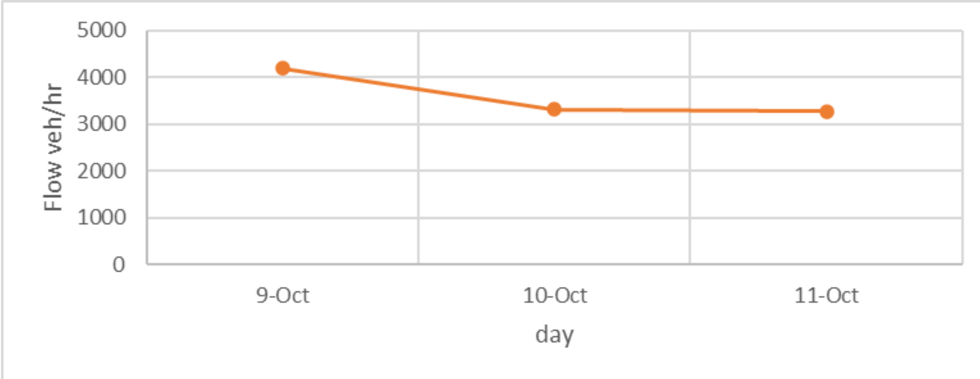


Figure 4.32: Maximum flow in three-day Street 3

4.9.1.1.6 Roundabout of AL- Tarbiyah Street segment 6

Building on the analyses conducted for Streets 1 through 5, a focused traffic study was carried out for Street 6 at the Al-Tarbiyah Intersection. The evaluation addressed peak-period congestion levels, lane capacity usage, and pedestrian movement patterns in relation to vehicle flow. Insights from Street 6 were compared with earlier results to highlight specific challenges and recommend targeted enhancements, as illustrated in Figures 4.33 to 4.35.

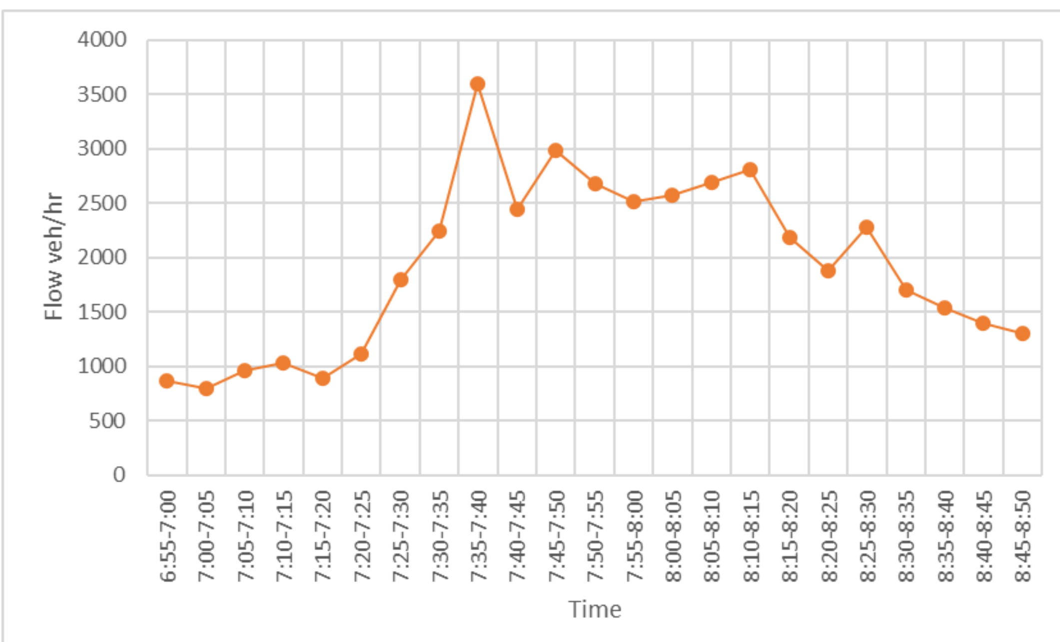


Figure 4.33: Fluctuation of flow with time for Street 6 on 9/10/2023

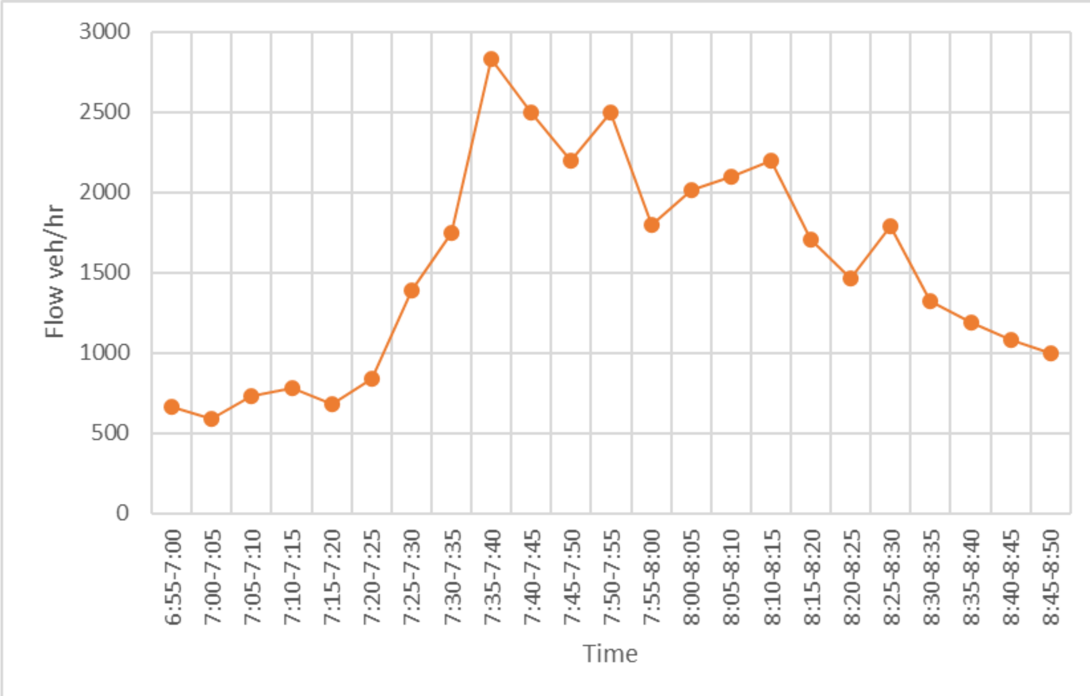


Figure 4.34: Fluctuation of flow with time for Street 6 on 10/10/2023

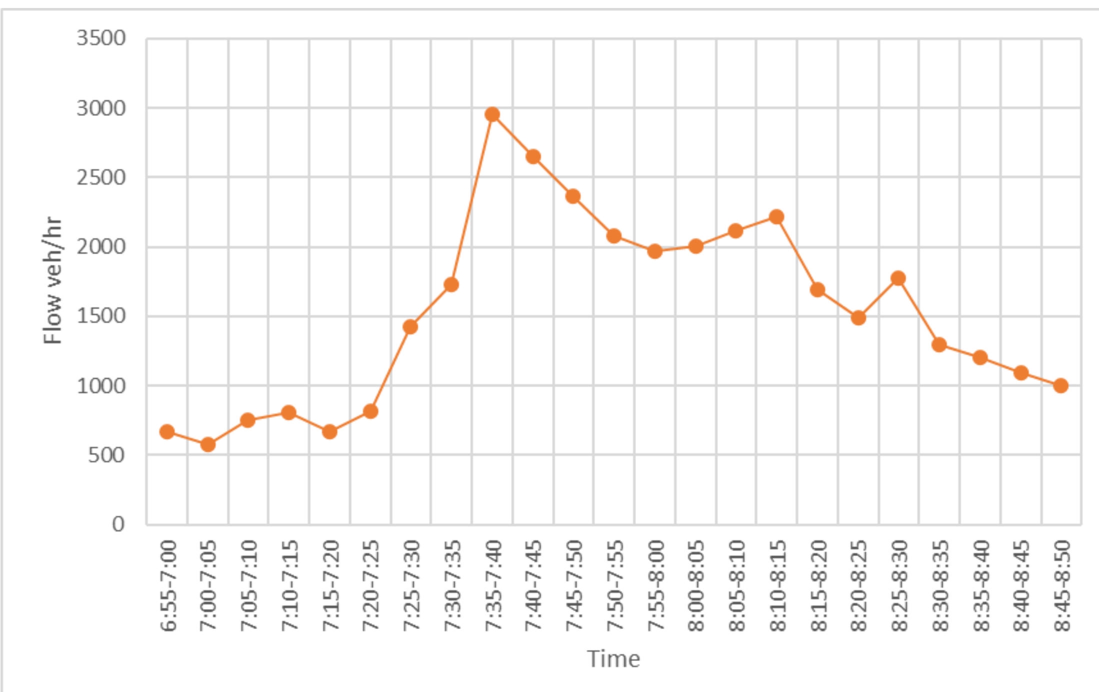


Figure 4.35: Fluctuation of flow with time for Street 6 on 11/10/2023

As shown in Figure 4.36, the three highest traffic volume values are presented. These values were identified based on the analysis conducted in the previous section.

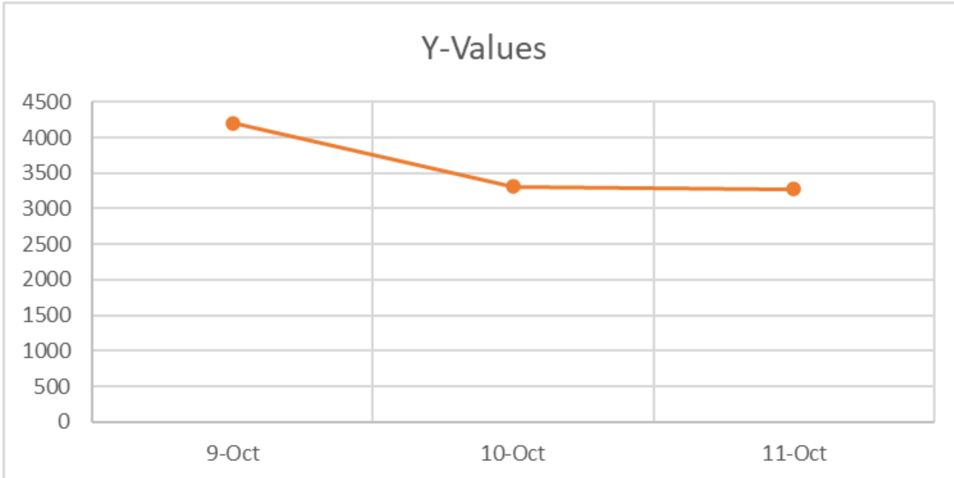


Figure 4.36: Maximum flow in three-day Street 3

4.9.1.1.7 Roundabout of AL- Tarbiyah Street segment 7

For Street 6 at the Al-Tarbiyah Intersection, a dedicated traffic analysis was undertaken following the earlier studies of Streets 1 to 5. The assessment examined vehicle flow rates, lane performance, and pedestrian crossings during the most congested periods. These observations were then evaluated alongside previous street analyses to identify unique traffic behaviors and propose suitable improvements, as illustrated in Figures 4.37 to 4.39.

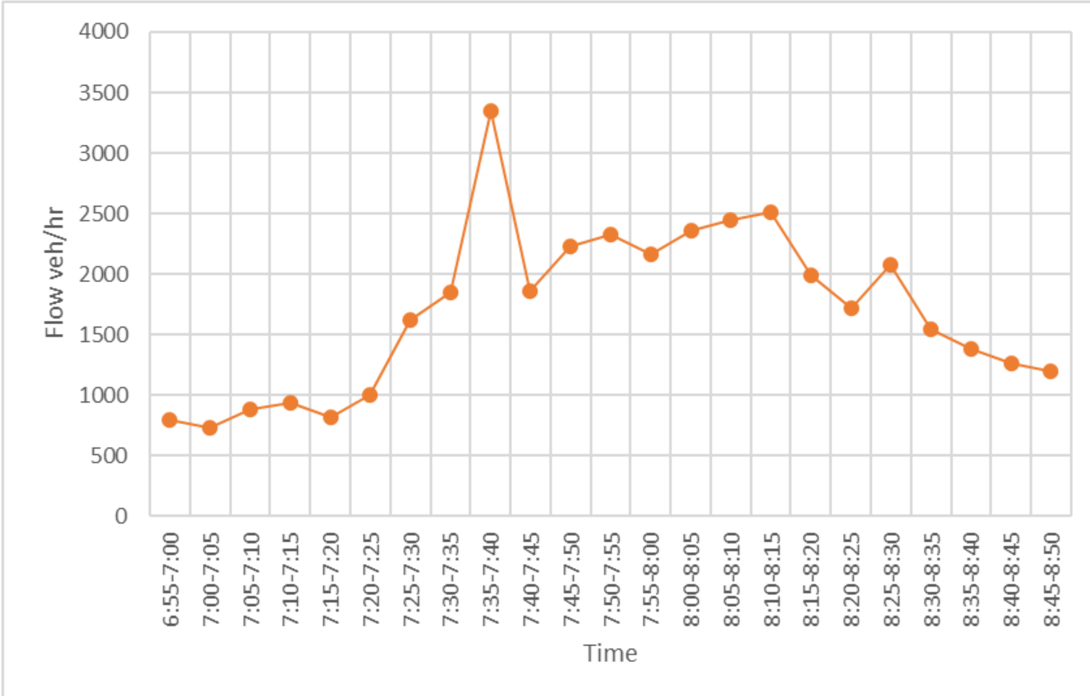


Figure 4.37:Fluctuation of flow with time for Street 7 on 9/10/2023

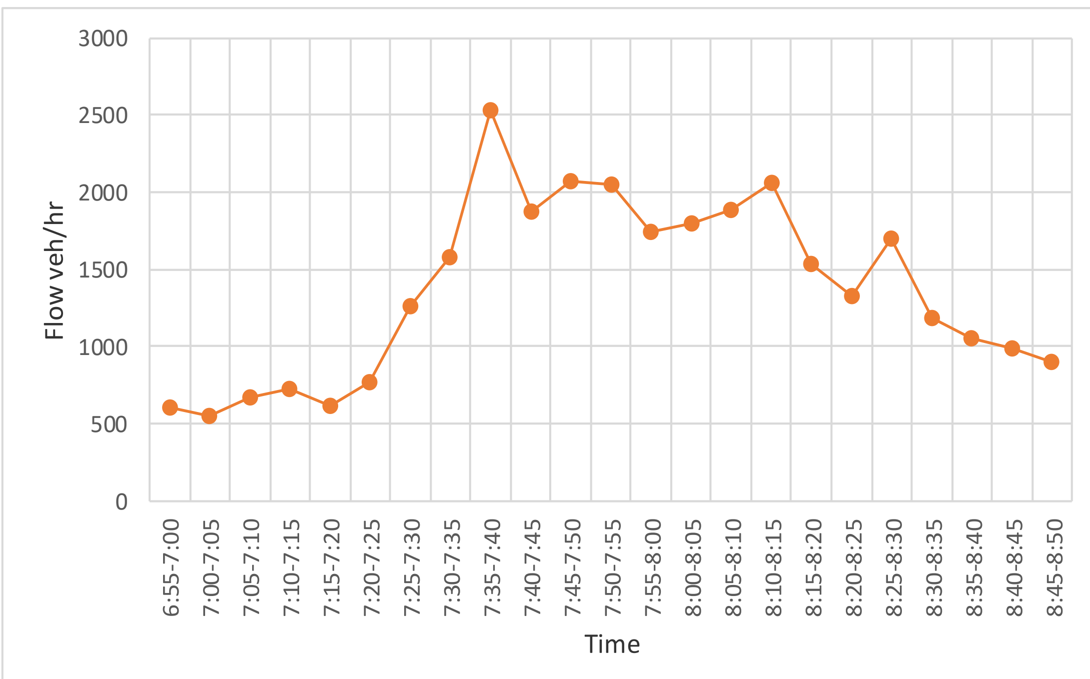


Figure 4.38: Fluctuation of flow with time for Street 7 on 10/10/2023

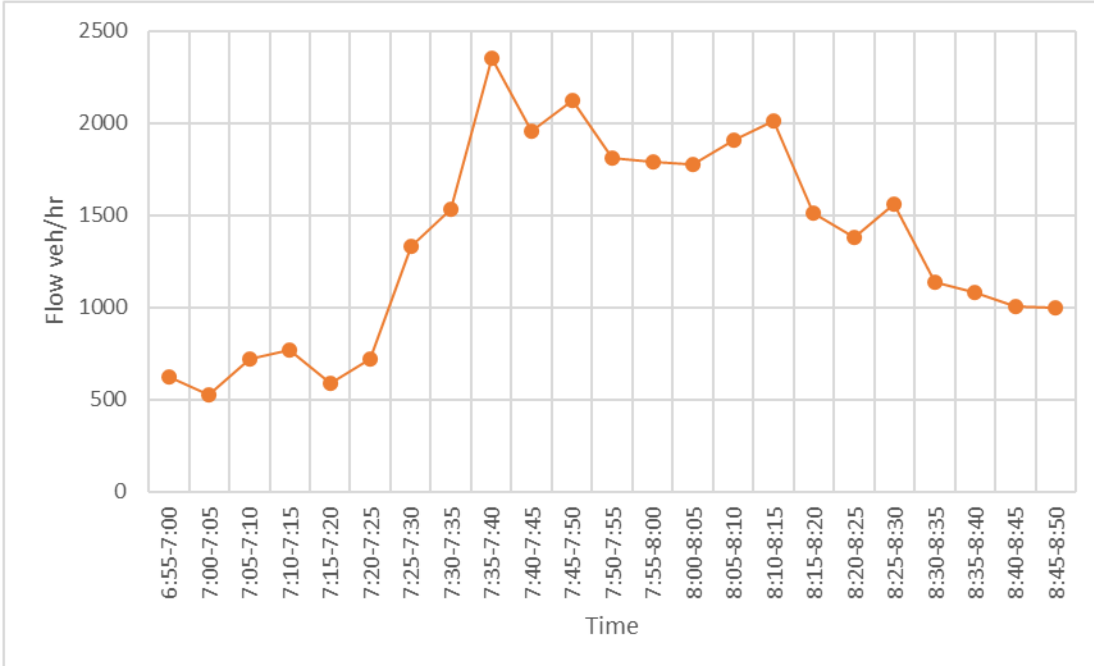


Figure 4.39: Fluctuation of flow with time for Street 7 on 11/10/2023

As shown in Figure 4.40, the three highest traffic volume values are presented. These values were identified based on the analysis conducted in the previous section.

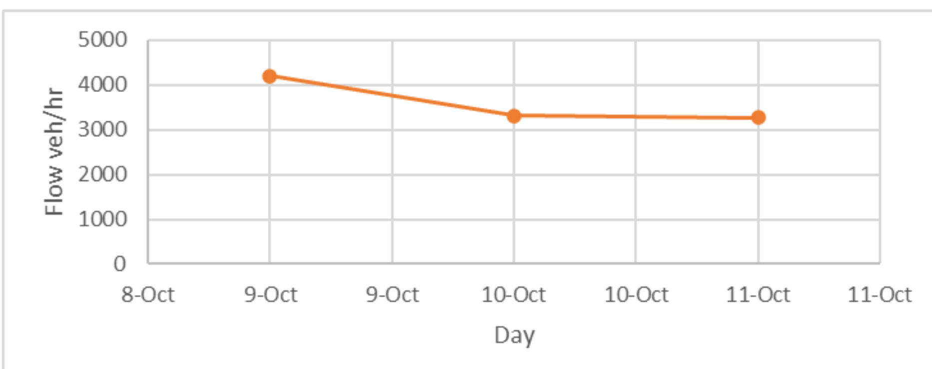


Figure 4.40: Maximum flow in three-day Streets 3

4.9.1.1.8 Roundabout of AL- Tarbiyah Street segment 8

For Street 8 at the Al-Tarbiyah Intersection, a comprehensive traffic assessment was performed after completing the evaluations for the preceding streets. The study focused on measuring traffic volumes, assessing lane functionality, and observing pedestrian activity during peak demand hours.

Results from Street 8 were compared with prior findings to uncover distinctive flow patterns and determine potential strategies for improving intersection performance, as illustrated in Figures 4.41 to 4.43.

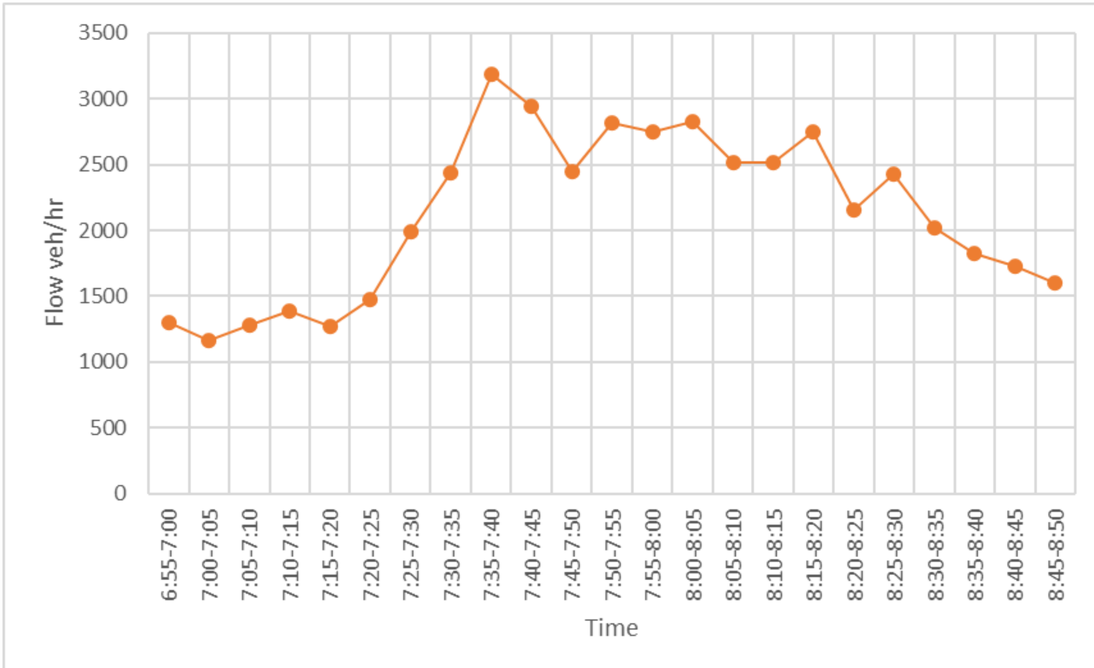


Figure 4.41: Fluctuation of flow with time for Street 8 on 9/10/2023

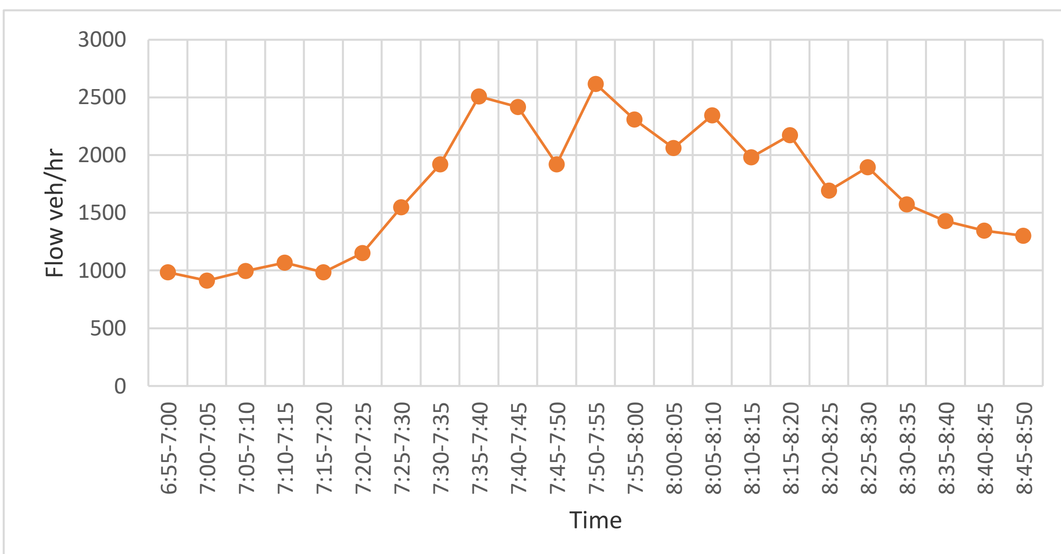


Figure 4.42: Fluctuation of flow with time for Street 8 on 10/10/2023

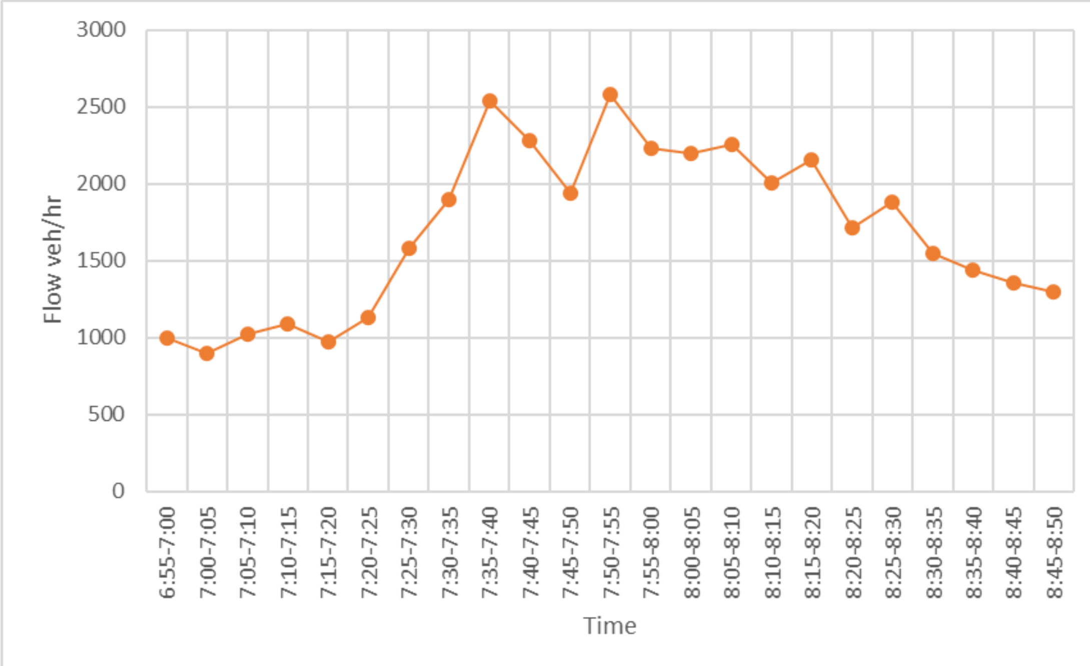


Figure 4.43: Fluctuation of flow with time for Street 8 on 11/10/2023

As shown in Figure 4.44, the three highest traffic volume values are presented. These values were identified based on the analysis conducted in the previous section.

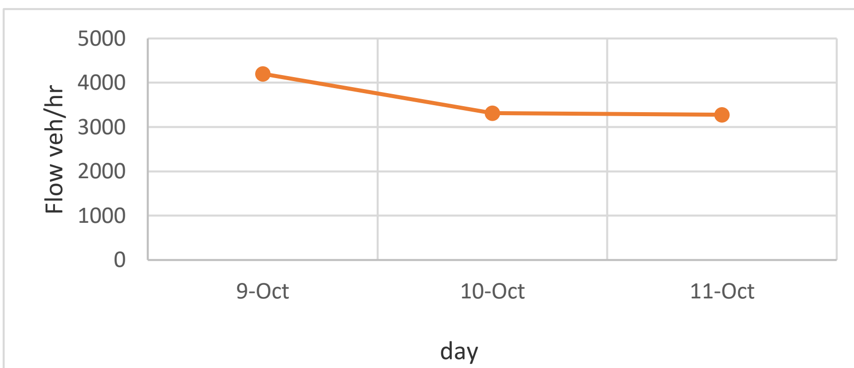


Figure 4.44: Maximum flow in three-day Street 3

4.9.1.2 Points collected data on intersections

After clarifying the locations for data collection in the Karbala city street network, the remaining intersections have been reviewed the where data was collected, except for the two intersections mentioned previously (the Tarbiya and Thawra intersections), which were reviewed in detail at the Tarbiya intersection, while the Thawra intersection was reviewed in the forms related to the data.

From Figure 4.45 to Figure 4.60, the most important intersections in the Karbala Governorate network are shown, which are the main axis of this network. The streets were numbered from 1 to 8. This numbering is an explanation of the intersection, highlighting the information collected. This numbering was placed on the GIS program maps, and the data tables were named according to this numbering to indicate that the table is specific to this numbered street. The numbered forms below were placed with the aerial image. The tables from which data were collected are presented in Appendix A, detailing the times, types, and numbers of cars that contributed to the final discharge of traffic volumes at the Tarbiya intersection. Go to Appendix A to view all the tables related to what was mentioned previously.

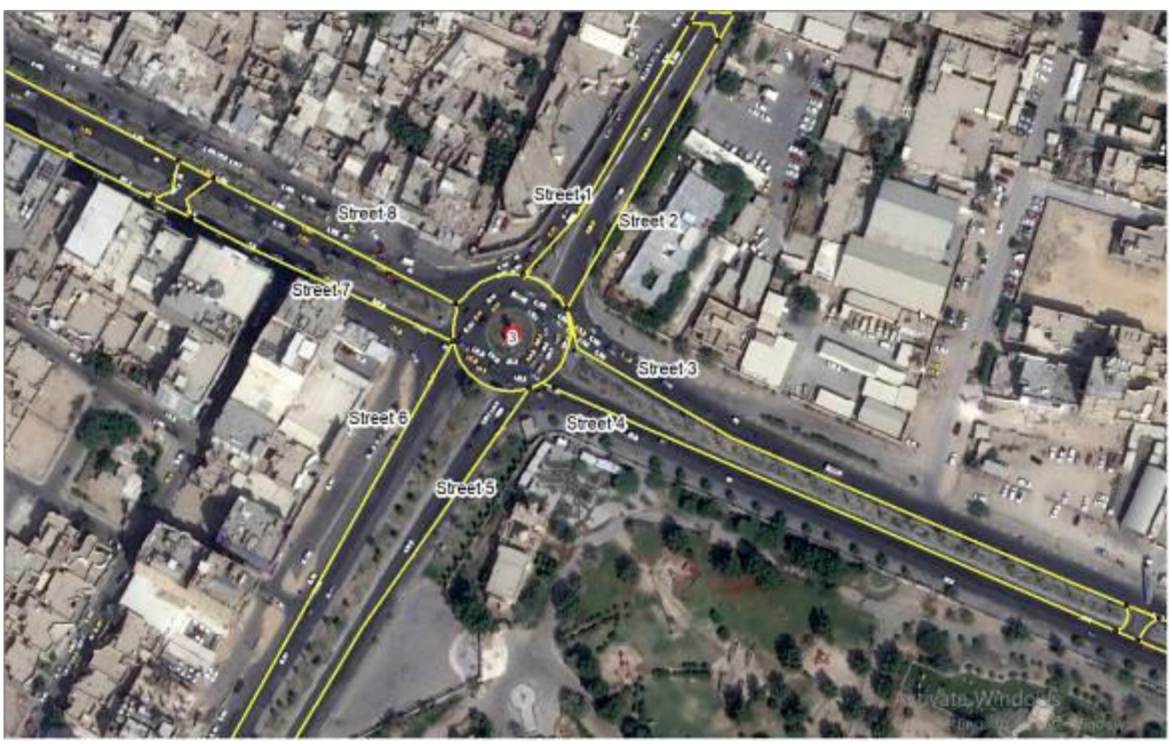


Figure 4.45: Roundabout of Al-Safina

Figure 4.46: Roundabout of Al-Jameia

Figure 4.47: Roundabout of Al-Mualimin

Figure 4.48: Roundabout Mustawsef Hay Al-Hur

Figure 4.49: Roundabout of Al-Mulhak

Figure 4.50: Roundabout of Amel Al-Nazafa

Figure 4.51: Roundabout of Al-Baladia

Figure 4.52: Roundabout Al-Muhafadha

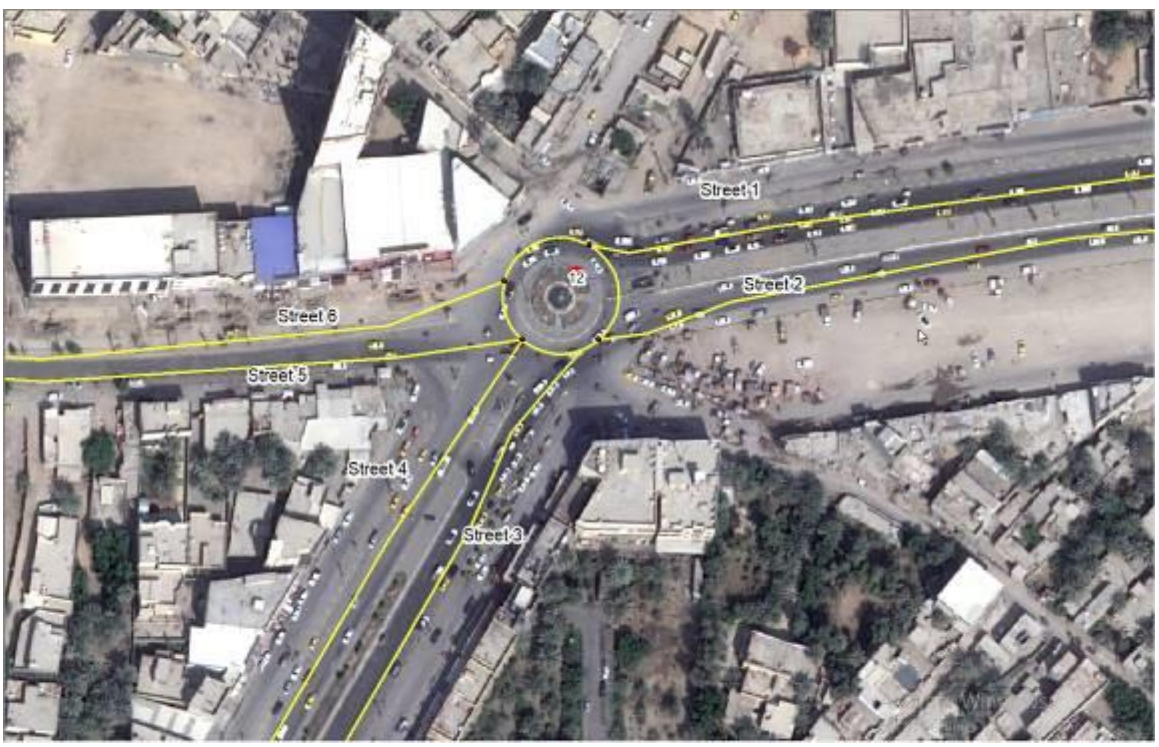


Figure 4.53: Roundabout of Qantarat Alsalam

Figure 4.54: Intersection of Fatimat Al-Zahraa

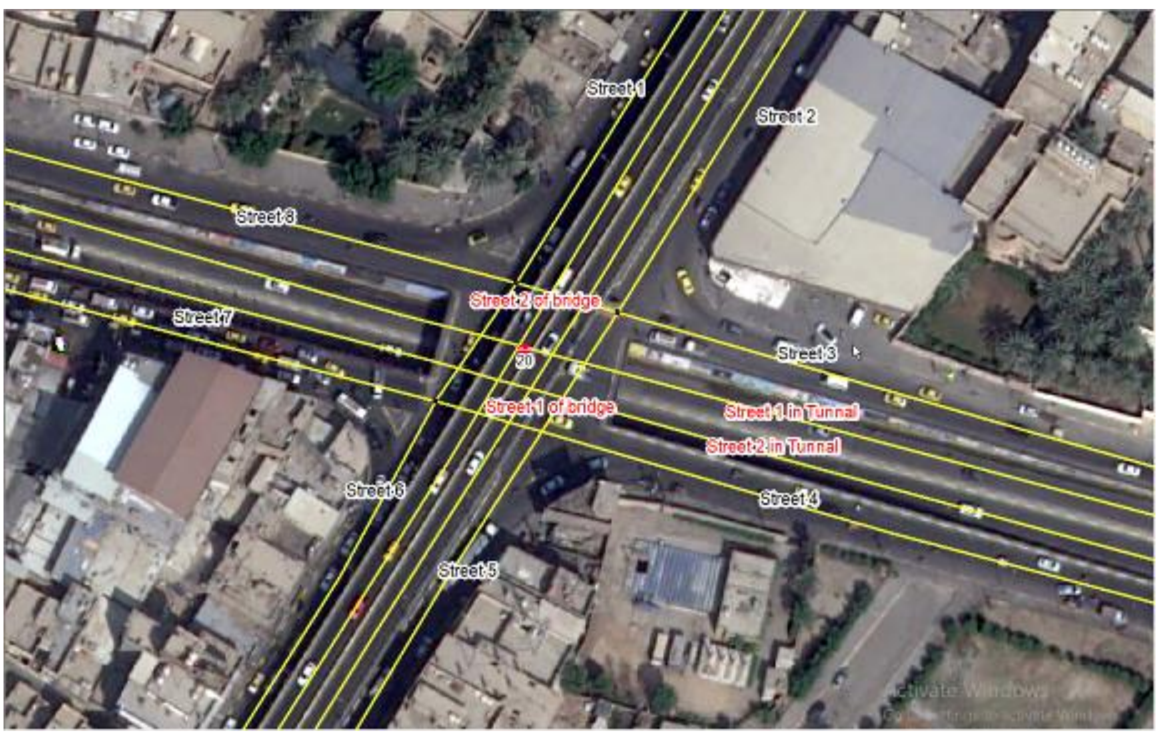


Figure 4.55: Intersection of Al-Abbas

Figure 4.56: Roundabout of Hay Ramadan

Figure 4.57: Roundabout of Tariq Al-Hure

Figure 4.58: Roundabout of Al-Kawthar

Figure 4.59: Intersection of Al-Emam Ali

Figure 4.60: Roundabout of Al-Gader

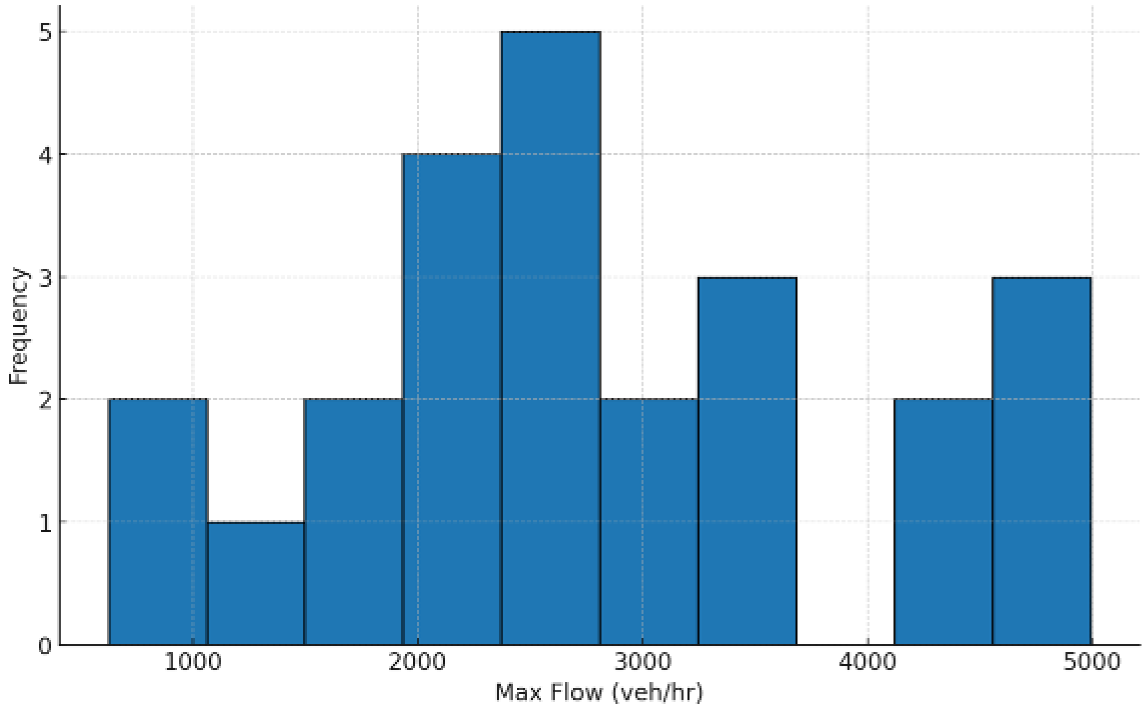


Figure 4.61: Histogram of max flow of street

Figure 4.61 the histogram presents the distribution of the maximum traffic flow (vehicles per hour) across the surveyed streets in Karbala's road network.

The x-axis represents the maximum vehicle flow (veh/hr), while the y-axis indicates the frequency of streets that fall within each flow range.

From the graph, we can observe that:

The most frequent traffic flow range is between 2500–3000 veh/hr**,** indicating that many streets operate at moderately high capacity.

A notable number of streets also fall within the 2000–2500 veh/hr range, suggesting a significant cluster of roads with medium flow.

Very high traffic flows (above 4500 veh/hr) are less common but represent major arterial roads or main city connectors.

Lower flow streets (below 1500 veh/hr) are also less frequent, likely corresponding to residential or local access roads.

Overall, this pattern reflects a mixed road network where a few main streets handle very high volumes of traffic, while the majority operate at medium-to-high capacity, highlighting potential congestion hotspots in the 2500–3000 veh/hr range.

4.9.2 Side friction data

The traffic-related data were collected in the study section in mid-block urban road segments. The data on pedestrian and vehicle flow were collected manually from recorded videos in the field. The total hourly volume of vehicles and pedestrians was then calculated.

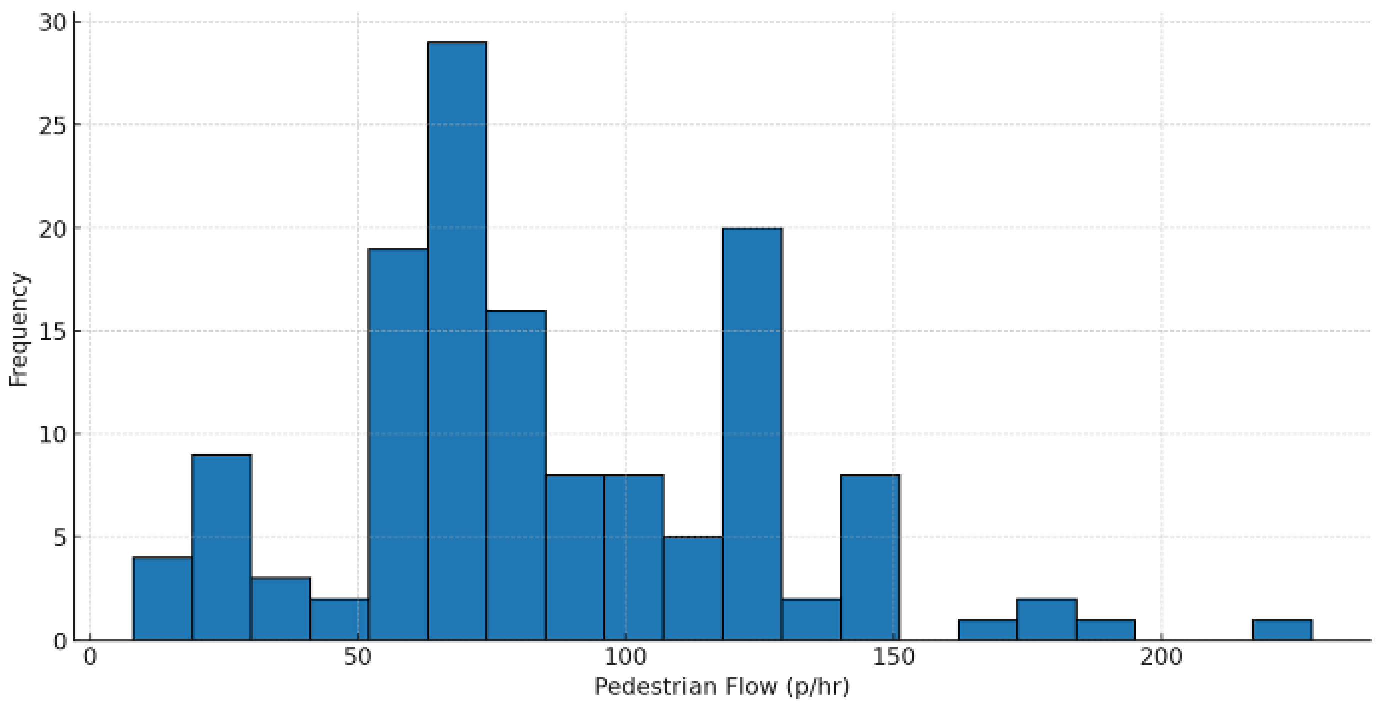


Figure 4.62: Histogram of pedestrian flow (p/hr)

Figure 4.62 histogram illustrates the quantitative distribution of pedestrian flow (pedestrians per hour) across all streets and observed points in the Karbala road network. The horizontal axis represents the different locations or streets, while the vertical axis shows the number of pedestrians per hour.

The chart reveals significant variation in pedestrian flow rates among locations. Some points record very high pedestrian volumes (exceeding 200 people/hour), particularly in areas close to commercial activity hubs or major traffic nodes such as certain streets in Roundabout Sayid Al-Asaar Al-Jameia and Roundabout Mustawsef Hay Al-Hur.

In contrast, other streets show very low pedestrian counts (below 30 people/hour), often located on the city's outskirts or in areas with limited urban activity.

This variation reflects the land-use patterns of the city: dense commercial and service zones attract more pedestrians, whereas remote residential or industrial areas experience lower foot traffic. These findings are valuable for prioritizing pedestrian infrastructure improvements, such as building sidewalks and enhancing crosswalks in high-density areas, as well as implementing strategies to encourage walking in low-density zones to promote urban sustainability.

4.9.3 Air pollution and Nose data

4.9.3.1 Data on air pollution and nose data of Roundabout Al-Tarbiyah

The measurement was conducted in the morning on the selected street in the study area. The gases measured are Carbon dioxide, Carbon monoxide, Nitrogen dioxide, Nitrogen monoxide, and Sulfur dioxide. Table 4.3 illustrate the data measured in Roundabout Al-Tarbiyah. The data was collected from 8:00 AM to 9:00 AM in five-minute intervals. The data collection is being conducted because the device is owned by a government department, which opens slightly before this date.

Additionally, the charging time of the device is limited to one hour, and the high hour was identified based on the traffic flow data. Consequently, the data was collected during this time. With an Ambient pressure of 1019 mbar, wind speed of 2-3 m/s, temperature (8-9 ˚C, and relative humidity of 60-64%.

Table 4-2: Gass emision on Wednesday10 /1/2024 (Roundabout Al-Tarbiyah)

Time / variables	8:00 AM	8:05 AM	8:10 AM	8:15 AM	8:20 AM	8:25 AM	8:30 AM	8:35 AM	8:40 AM	8:45 AM	8:50 AM	8:55 AM	9:00 AM	units
CO2	575.3	576.3	577.3	579.3	560.3	555.3	550.3	535.2	530.2	529.2	514.3	510.3	509.3	ppm
CO	15.55	14.55	13.55	12.55	11.65	10.65	9.65	6.78	7.78	8.78	9.27	9.5	9	ppm
N2O	0.31	0.31	0.31	0.31	0.3	0.299	0.29	0.28	0.284	0.285	0.29	0.29	0.29	ppm
CH4	2.44	2.43	2.42	2.4	2.34	2.33	2.32	2.1	2.09	2.08	2.13	2.14	2.15	ppm
Propane	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Butane	0.95	0.95	0.95	0.95	0.78	0.78	0.78	0.66	0.66	0.66	0.7	0.7	0.7	ppm
Benzene	0.23	0.23	0.23	0.23	0.14	0.14	0.14	0.13	0.13	0.13	0.05	0.05	0.05	ppm
Toluene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Ethyl Benzene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Xylene	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	ppm
Acetic Acid	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Formaldehyde	0.16	0.16	0.16	0.16	0.23	0.23	0.23	0.24	0.24	0.24	0.32	0.32	0.32	ppm
Acetaldehyde	0	0	0	0	0	0	0	0.03	0.03	0.03	0	0	0	ppm
Methanol	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Furan	0.02	0.02	0.02	0.02	0	0	0	0	0	0	0	0	0	ppm
Hydrogen cyanide	0	0	0	0	0.08	0.08	0.08	0.15	0.15	0.15	0.14	0.14	0.14	ppm
Chlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Phosgene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Amm	0.13	0.13	0.13	0.13	0.08	0.08	0.08	0.11	0.11	0.11	0.05	0.05	0.05	ppm

Time / variables	8:00 AM	8:05 AM	8:10 AM	8:15 AM	8:20 AM	8:25 AM	8:30 AM	8:35 AM	8:40 AM	8:45 AM	8:50 AM	8:55 AM	9:00 AM	units
onia														
HCl	0.17	0.17	0.17	0.17	0.11	0.11	0.11	0.11	0.11	0.11	0.08	0.08	0.08	ppm
HF	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
NO2	0.8	0.81	0.82	0.83	0.64	0.6	0.59	0.54	0.5	0.42	0.34	0.3	0.23	ppm
NO	3.54	3.42	3.41	3.3	3.05	3.01	2.99	2.98	2.88	2.76	2.62	2.61	2.6	ppm
SO2	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.8	0.8	0.8	0.62	0.62	0.62	ppm
Temperature	8	8	8	8	8	8	8	8	8	8	9	9	9	C
Wind direction	78.75	78.75	78.75	78.75	67.5	67.5	67.5	45	45	45	33.75	33.75	33.75	Degree
Wind speed	2	2	2	2	2	2	2	2	2	2	2	2	2	Km/hr
RH%	0.6	0.605	0.61	0.612	0.62	0.623	0.625	0.63	0.632	0.635	0.64	0.641	0.642	
Pressure	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	mbar
Noise	80.6	82.5	93.2	79.6	83	92.4	81.2	90.2	89.2	107.1	87.9	81	76.2	dBA
Speed	20-30	20-30	20-30	20-30	24-35	24-35	24-35	30-40	30-40	30-40	40-50	40-50	40-50	Km/h
Flow	4406	3816	3931	3844	3312	3427	3254	3470	3211	4406	3815	2822	2563	Veh/hr

A significant amount of data was collected at various points in the holy city of Karbala, which are the points mentioned previously. All the pollution table data is found in Appendix B, which contains sixteen other tables containing pollution data for the collected points.

4.9.4 Travel time data

A key metric in transportation is travel time, or the time needed to travel a route between any two sites of interest (Turner et al., 1998). The speed is calculated as the segment length divided by the average journey time. According to HCM 2016, the operating characteristics of a street segment, in general, and its LOS can be quantified using ATS for vehicles crossing the segment. The average speed of a car can be used to quantify the impact of traffic regulations. That rate is calculated by dividing the length of the segment by the typical travel time. The time it takes to traverse the street segment, including any delays incurred at stops, is the journey time (HCM, 2016). The most frequently used trip time collection techniques are the test vehicle techniques (also known as "floating car"), which involve sending out a vehicle (or vehicles) to blend in with regular traffic for the sole purpose of gathering data. The segments' travel times were measured using a motor car and the vehicle floating technique (Al Ghanim et al., 2021), which involved multiple iterations of the run to determine the average time as the average trip time. Statistical parameters such as confidence level, standard deviation, and tolerated error should be used to compute the required minimum number of empirical procedures. In the current investigation, six travel time runs were done in each direction and on each leg. The number of runs was calculated for sample sizes of travel time surveys along arterial streets (Turner et al., 1998). Consistent with the times when traffic levels are most reliably monitored.

The trip times were analyzed during the morning rush hour. The speed is often measured as the average through-traffic travel time. Afterwards, the average speeds were calculated for the segments in both directions. Peak-hour delays were taken into account when estimating travel times. In contrast, unexpected events like roadwork, construction, nonrecurring congestion, and accidents were disregarded, and the run was repeated. The segment lengths were measured using the ArcGIS Earth application, and the details are in the Table in the ArcGIS program, as explained in Figure 4.63. The travel time of all streets in Karbala City, including the highway network, is provided in all-time travel time in seconds.

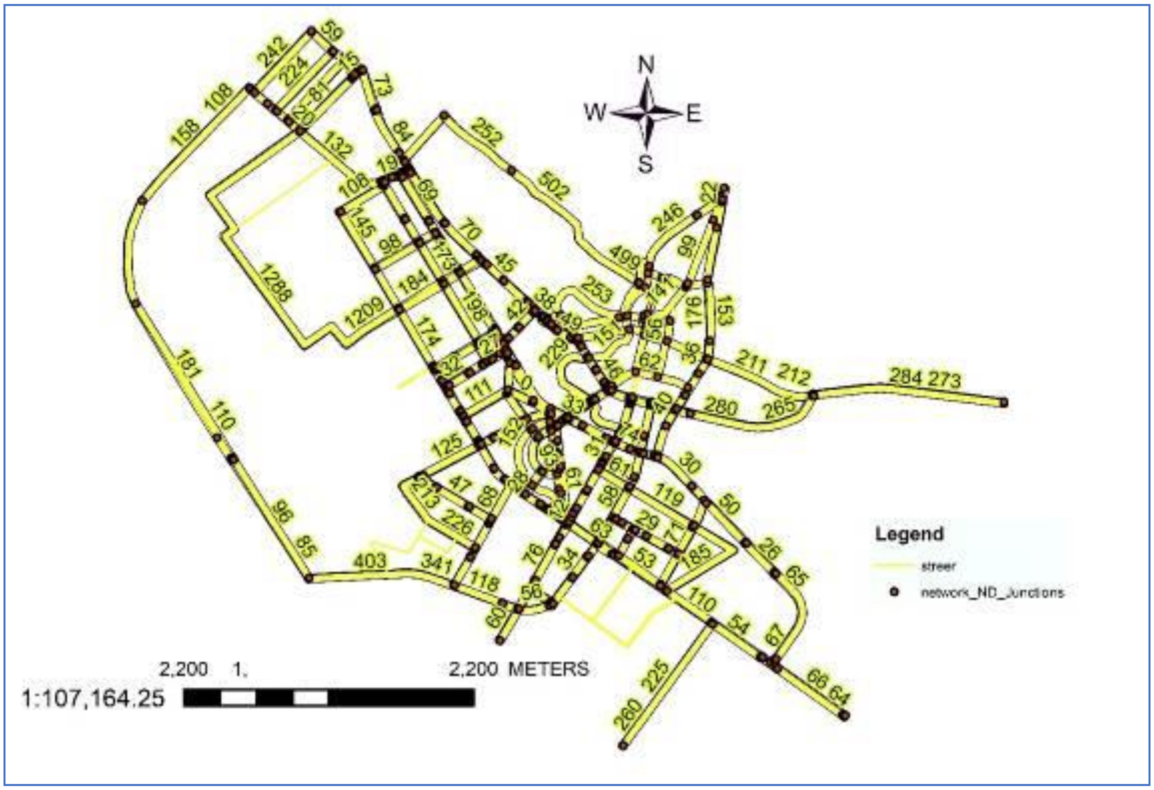


Figure 4.63: Travel time on the second street

4.9.5 Use of environmentally friendly modes

In Karbala, a city known for its religious and historical significance, there has been a push towards adopting sustainable transportation strategies to reduce pollution and improve the quality of life. The city has updated its master plan to include sustainable transportation by providing pedestrian paths and promoting public transportation as the primary mode of movement. Here are some critical points regarding environmentally friendly transportation in Karbala:

-Pedestrian Paths: Emphasizing pedestrian traffic is a significant proposal for the city centre, aiming to facilitate the transfer of visitors to the city centre and reduce reliance on private vehicles. -Public Transport: There are proposals to establish particular public transportation pathways inside residential neighbourhoods to encourage using buses and other public transportation over personal vehicles.

-Non-Motorized Modes: Sustainable transportation prioritizes non-motorized transportation modes such as walking and cycling, which have no polluting emissions and contribute to a healthier urban environment.

-Intelligent Transportation Systems: Intelligent transportation systems are suggested to manage traffic flow and enhance the efficiency of public transportation services.

The strategic shift towards sustainable cities is achieved by applying these sustainable transportation strategies, considering environmental sustainability, economic, and social dimensions. That approach aligns with global trends such as Smart Growth and New Urbanism, which aim to create cities that are not only efficient but also livable and environmentally responsible.

Table 4.3 explains the environmental sources in Karbala. While specific details about the current status of these initiatives are not provided, the strategic plans indicate a commitment to improving the transportation infrastructure in Karbala to make it more sustainable and friendly to residents and visitors.

Table 4-3: Environmentally friendly modes in Karbala.

environmentally friendly modes	In the Transportation of Karbala	Percentage of used%
Pedestrian Paths	Not exactly used	5%
Non-Motorized Modes	Used little	10%
Intelligent Transportation Systems	Not used	0%

Public Transport	Used little	15%

4.9.6 Accidents

Traffic accidents represent a major challenge for urban areas globally, impacting public health, economic stability, and environmental sustainability. In Karbala, a city of cultural and religious significance, traffic accidents pose serious risks, causing loss of life, injuries, and substantial economic costs related to medical care and infrastructure damage. Additionally, accidents contribute to increased traffic congestion and pollution, which negatively affect the city’s sustainability goals.

The study of traffic accidents in Karbala is crucial for identifying high-risk locations and underlying causes such as driver behavior, vehicle conditions, and road infrastructure. Such analysis enables authorities to develop effective safety measures and improve traffic management.

Reducing traffic accidents supports sustainable development objectives, including promoting health and well-being, building resilient infrastructure, and creating sustainable cities. The data used in this study were obtained from the Central Organization for Statistics and Information Technology (COSIT), ensuring reliability and accuracy in assessing accident trends and informing policy decisions. Overall, addressing traffic accidents is essential for enhancing the quality of life and achieving sustainable urban development in Karbala.

Table 4.4 presents the annual Figures for traffic accidents in the city of Karbala over the period from 2015 to 2024. The data shows noticeable fluctuations in the total number of traffic accidents each year, with the highest number recorded in 2023 at 618 accidents, closely followed by 2024 with 600 incidents.

The years 2017 and 2018 also experienced high accident rates, totaling 570 and 587, respectively. On the lower end, 2015 recorded the fewest accidents with 396 cases.

The breakdown of accident types reveals that crashes consistently constitute the largest portion of incidents each year, ranging from 169 in 2021 to 329 in 2024. Runover accidents also represent a significant share, particularly in 2018 and 2019, with over 280 cases annually. Overtura accidents and other types remain relatively low in comparison.

Overall, the data reflect a general upward trend in traffic accidents in Karbala over the recent decade, emphasizing the growing importance of traffic safety interventions and enforcement to reduce risks and enhance public safety.

Table 4-4: Traffic accidents in Karbala(COSIT,2024)

year	The highest traffic accidents	Crash	Overturn	Runover	Other
2024	600	329	15	256	0
2023	618	302	28	286	2
2022	540	286	28	232	0
2021	405	169	22	214	0
2020	409	204	14	191	0
2019	537	246	8	283	0
2018	587	245	21	321	0
2017	570	278	15	277	0
2016	490	195	13	282	0
2015	396	185	15	196	0

4.9.7 Operating Speed in Urban Road Networks

Speed is a critical element in road network performance, directly affecting both safety and mobility. The speed at which a motorist travels is shaped by various aspects, including vehicle capabilities, roadway geometry, weather and lighting conditions, land use context, and, most importantly, the speed limit. Traveling too fast for current conditions can lead to unsafe situations, especially in urban areas where interactions between different road users, vehicles, pedestrians, and cyclists are more complex. In transportation planning, determining safe and context-appropriate speeds is essential to balance the needs for efficient travel and public safety. Urban roads, in particular, often require lower speeds due to limited right-of-way, intersections, and the presence of vulnerable road users.

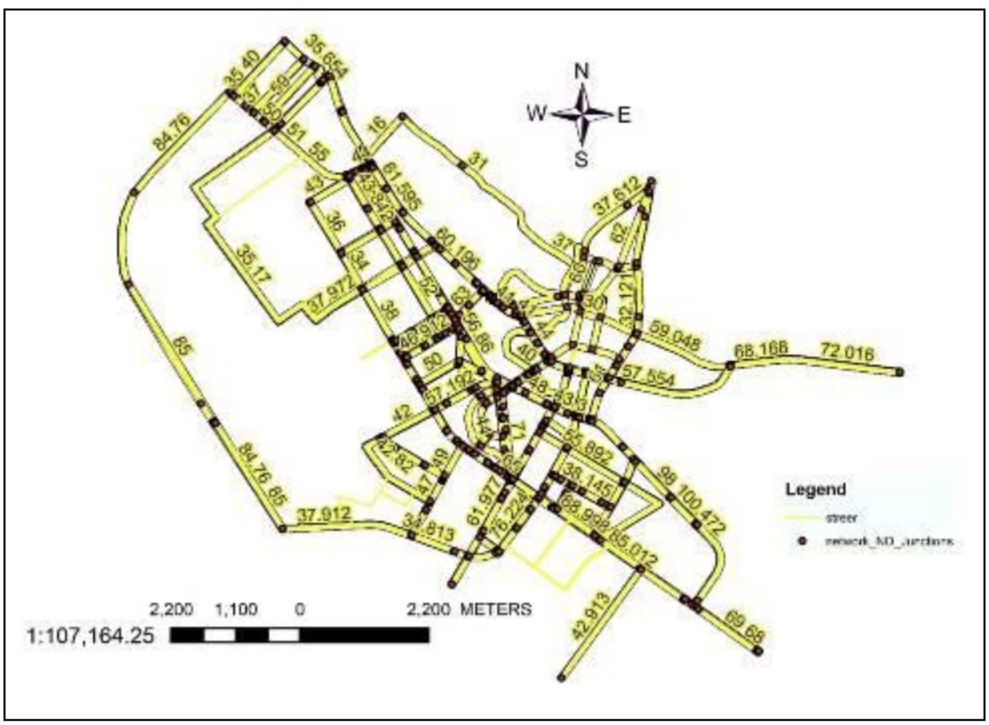


Figure 4.64: Speed of the car road network

Figure 4.64 shows the distribution of vehicle speeds across the urban road network of the study area, as extracted using the Attribute Tool in ArcGIS. The road segments are color-coded with speed values in miles per hour (mph), representing the actual or assigned travel speeds within each section. This map provides insight into how different sections of the network perform in terms of speed and highlights areas where traffic may be flowing more slowly or more quickly based on road design and traffic demand. Understanding these speed patterns is essential for evaluating road performance and identifying sections that may require redesign or revised speed limits. Proper speed management helps ensure that roadways are safe while still enabling effective mobility for all users.

4.9.8 Passenger energy consumption use (min)

Energy consumption rates are often quantified in kilowatt-hours per vehicle-kilometre, passenger kilometre, and seat kilometre (kWh vkm^{-1}, kWh pkm^{-1}, kWh skm^{-1}). Table 4.7 presents the average energy consumption rates for passenger transportation modes correlated with energy consumption parameters like capacity, speed, and occupancy level. Energy consumption includes basic energy usage and the energy expended in fuel production and power delivery (well-to-wheel). The typical energy consumption rates for passenger transportation by vehicle are approximately three times greater than those for transit by bus. Aircraft exhibit an efficiency 23 times inferior to high-speed trains and 16 times inferior to bus travel. The average energy consumption rates of passenger vehicles are determined by analyzing vehicles with low occupancy (36% in regional and intercity trains) to high occupancy rates (exceeding 60% in high-speed trains and aircraft). Other research indicates that autos utilize 2.4 times more energy per passenger-kilometer than buses, while aircraft consume 27 times more than rail transport. Kennedy10 found that the energy intensity of autos is almost three times higher than that of public transit, measured in energy per seat-kilometer. Niedzball and Schmitt11 compared the particular energy requirements of aviation and different vehicle systems, estimating energy consumption rates between 0.35 and 0.47 kWh pkm-1 for passenger cars and 0.72 to 1.98 kWh pkm-1 for airplanes.

Table 4-5: Energy consumption factors and rates for different modes of passenger transport (Pérez-Martínez *et al.*, 2010)

Transportation mode	Seats	Average speed (km h^{-1})	Occupancy (%)	Energy consumption		
				Vehicle (kWh vkm^{-1})	Passenger (kWh pkm^{-1})	Seat (kWh skm^{-1})
Regional train (RT)	724	59	37	35.21	0.13	0.05
Intercity train (IT)	190	71	36	6.28	0.09	0.03
Intercity express train (IET)	189	89	70	10.81	0.08	0.06
High-speed train (HST)	350	160	66	17	0.07	0.05
Middle-class Car (high-low occupation)	5	100	58-35	0.96-0.86	0.33-0.49	0.19-0.17
Standard bus (high-low occupation)	50	45	80-55	4.59-3.61	0.11-0.13	0.09-0.07
Aircraft (high-low occupation)	266	700	80-55	262.17-299.04	1.22-2.03	0.99-1.12
Train (medium-long distance)	190	100	36-31	15.07-16.82	0.23-0.28	0.08-0.09

Karbala street network uses Middle-class cars (high-low occupation). The maximum energy consumption of one car equals 0.96 kWh vkm^{-1} for vehicle energy consumption, 0.49 kWh pkm^{-1} for passenger energy consumption, and 0.19 kWh skm^{-1} for seat energy consumption. Figure 4.65 shows the energy consumption for maximum flow in the network street.

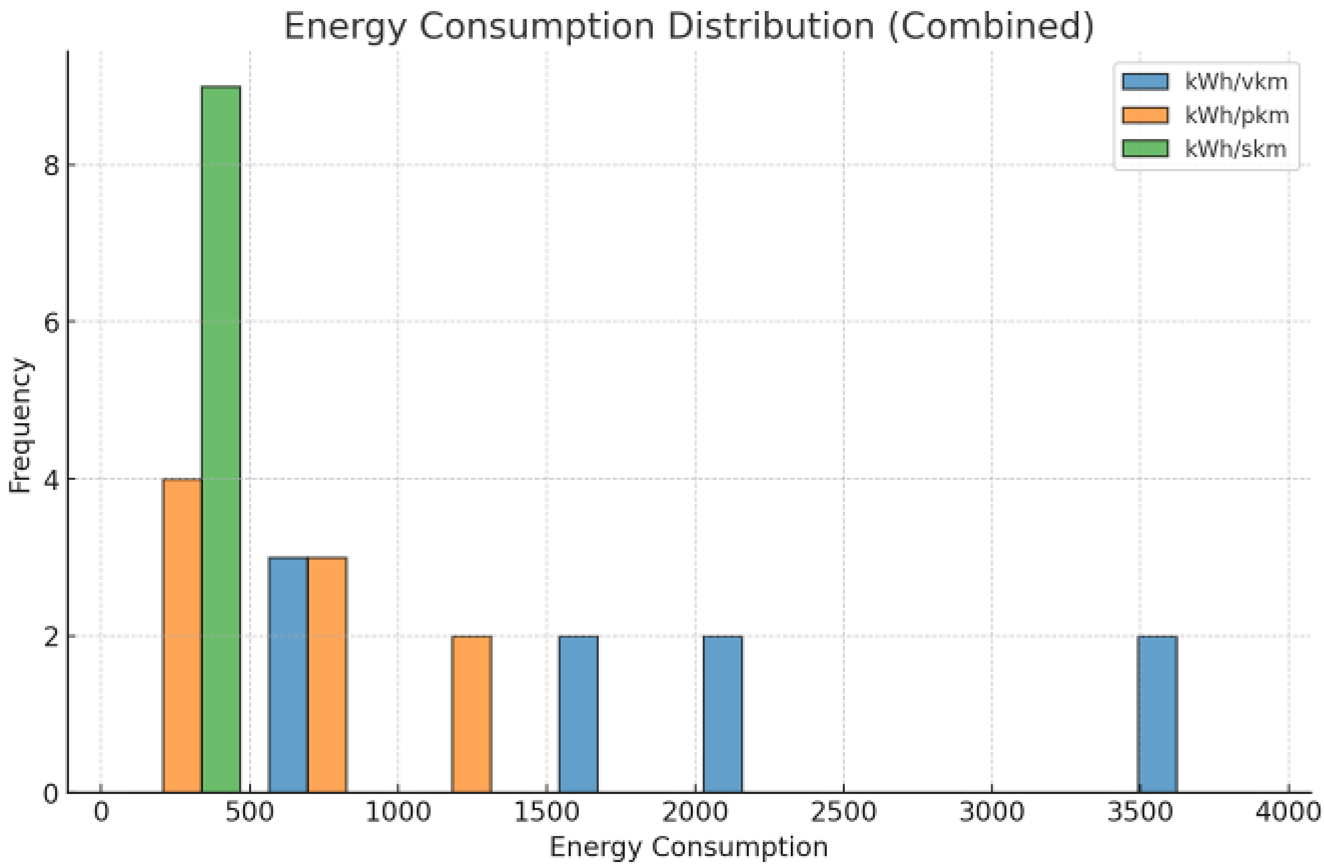


Figure 4.65: Energy consumption distribution

4.10 Summary

Field Surveys: Traffic volume counts, speed measurements, vehicle classification, public transport availability surveys. Environmental Monitoring: On-site measurement of gas emissions and noise levels across selected road segments. GIS-Based Data Collection: Mapping road network characteristics, accident locations, and public transport routes.

Decision-Making Models: AHP was used to prioritize indicators based on expert judgment, and fuzzy logic was applied to model uncertainty in indicator evaluation.

Study Area: The Karbala urban network, including main arterials, collectors, and local streets, was analyzed. Sampling points were chosen to represent diverse traffic and land-use conditions.

Chapter Five: Results and Discussion

5.1 Introduction

This chapter presents a comprehensive analysis of the collected data and the corresponding results. The analysis encompasses several key aspects of urban environmental and transportation performance, including noise levels, air pollution, the share of public transportation within the study area, and the adequacy of pedestrian infrastructure.

The relationship between traffic-related variables was closely examined, particularly the correlation between noise levels and both vehicle speed and traffic flow. Additionally, the impact of traffic flow on air pollution levels was investigated to assess environmental implications.

Moreover, this chapter includes a full assessment of urban sustainability criteria. The relative importance of each sustainability dimension, environmental, social, and economic, was quantified using the AHP. Fuzzy logic was applied to assign accurate weights to these criteria, reflecting the complexity and uncertainty inherent in urban systems.

These results were benchmarked against five major international sustainability rating systems: LEED, Green Star, CASBEE for Urban Development, GSAS Urbanism, and BREEAM Communities. The comparison highlights the gaps and potentials for local urban planning to align with global best practices.

Finally, spatial models were developed using Geographic Information Systems (GIS) to identify and propose optimal interventions aimed at improving the city's overall sustainability performance. These models support strategic decision-making by pinpointing high-impact areas for reform, guiding infrastructure upgrades, and promoting sustainable urban growth.

5.2 Analysis Relationship Between Network Accessibility and Distance from the CBD

The zones within the designated distance were selected to determine how network indices change with the distance to the CBD (buffer radius). The overview of the different characteristic indices inside their corresponding buffer radius is shown in Table 5.1.

The leading network of the study area, as shown in Figure 5.1, was divided into several shapes according to its distance from the previously chosen CBD, with specific distances as shown in Figure 5.2.

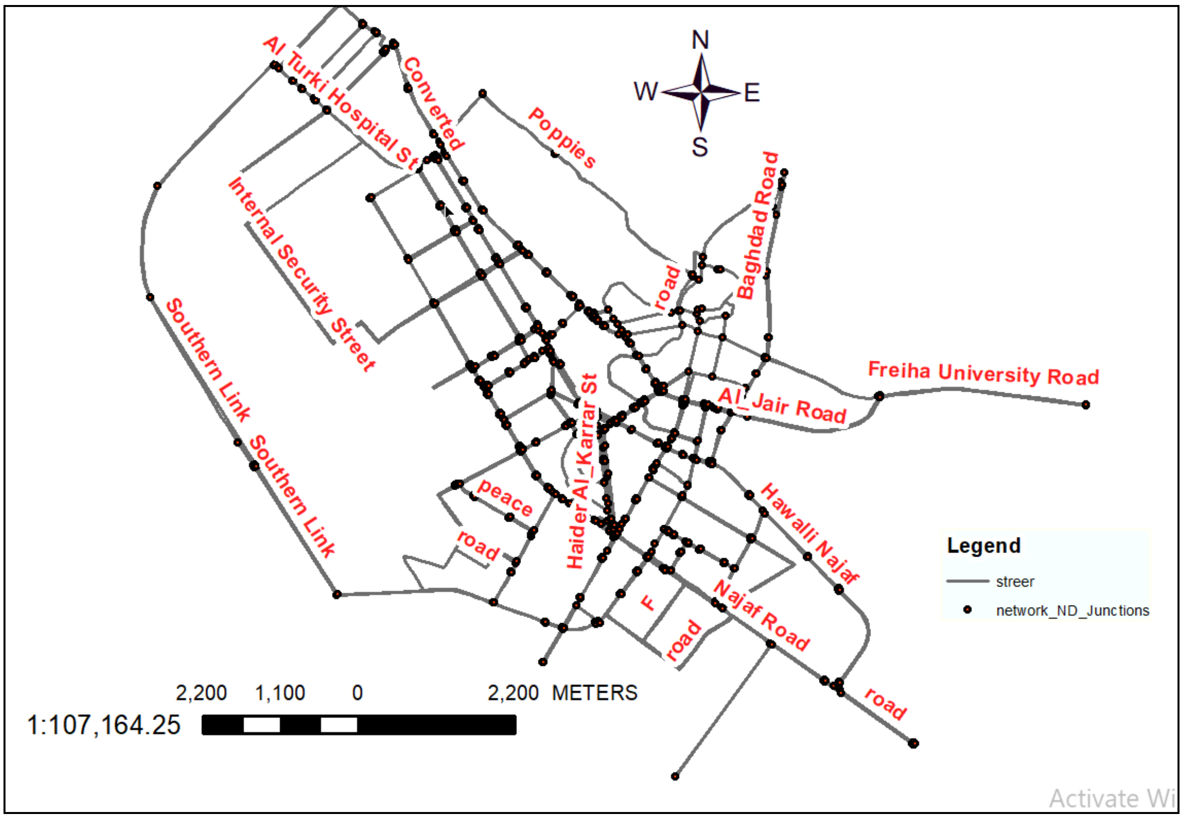


Figure 5.1 Leading street network of Karbala

In Figure 5.2, a 0.5-kilometer radius from the city's central business district was selected as the initial area for analysis. This selection was based on the high levels of traffic congestion and the density of tourist activities in the area. As the city center represents the core of both vehicular movement and economic and touristic activity, it serves as an ideal starting point for the field analysis and the first phase in the urban network evaluation process.

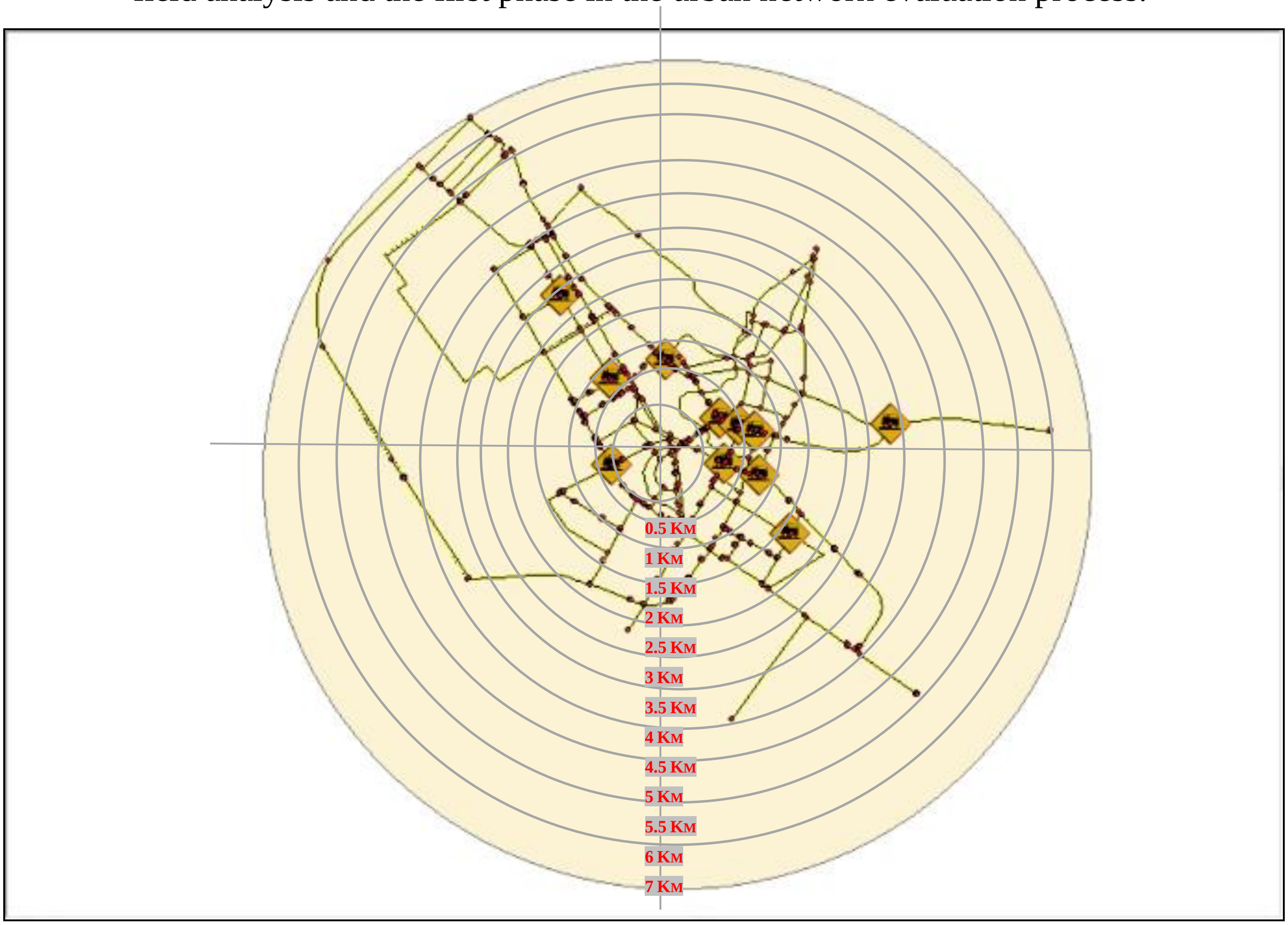


Figure 5.2: Buffer (7Km) from CBD for Karbala Street

Table 5-1: The summary of various characterized indices within respective buffer radius

parameter	0.5 Km buffer	1Km buffer	1.5Km buffer	2 Km buffer	2.5Km buffer	3Km buffer	3.5 Km buffer	4 Km buffer	4.5 Km buffer	5 Km buffer	5.5 Km buffer	6 Km buffer	7.5 Km buffer
No. of node (υ)	21	131	248	378	509	526	570	593	627	675	679	679	741
No. of. link (e)	37	219	349	590	775	800	864	898	945	998	1001	1007	1087
No. of. (p)	0	0	0	0	4	6	5	6	5	4	3	0	0
Alpha	0.432	0.342	0.206	0.282	0.267	0.267	0.263	0.263	0.259	0.243	0.240	0.242	0.234
Beta	0.568	0.598	0.711	0.641	0.657	0.658	0.660	0.660	0.663	0.676	0.678	0.674	0.682
Gamma	0.200	0.201	0.238	0.214	0.219	0.220	0.220	0.221	0.222	0.226	0.227	0.225	0.228
GTP	1.325	0.816	0.469	0.626	0.574	0.572	0.564	0.561	0.552	0.519	0.514	0.524	0.505
∑ L(Km)	16.6	98.5	157	265.5	348.7	360	388.8	404.1	425.2	449.1	450.45	453.15	489.15
A (Km²)	0.785	3.14	7.065	12.56	19.625	28.26	38.465	50.24	63.585	78.5	94.985	113.04	176.625
Eta	0.793	0.752	0.633	0.702	0.685	0.684	0.682	0.681	0.678	0.665	0.663	0.667	0.660
Network density (km per km2)	21.21	31.38	22.22	21.13	17.77	12.73	10.10	8.043	6.688	5.721	4.742	4.009	2.769
I(No. of. intersection)	20	70	82	98	143	153	165	183	188	193	197	205	223
Intersection density(per km2)	25.478	22.293	11.607	7.803	7.287	5.414	4.290	3.643	2.957	2.459	2.074	1.814	1.263
CF	0.105	0.071	0.100	0.105	0.125	0.174	0.220	0.276	0.332	0.388	0.469	0.554	0.802

Table 5.1 presents a comprehensive analysis of network metrics within buffer zones from the CBD, ranging from 0.5 km to 7.5 km. As the buffer distance increases, both the number of nodes and links show a steady

rise, indicating the network's spatial expansion. Initially, values like Alpha and Beta suggest a more cohesive, tightly connected structure, but Alpha decreases with distance, implying a reduction in loop formation and network compactness. Beta and Gamma increase slightly, suggesting an improvement in connectivity efficiency.

The GTP index declines consistently, indicating a drop in topological performance as the network grows. Total link length and area increase, but the network density (measured in km/km^2) declines significantly from 21.21 at 0.5 km to just 2.769 at 7.5 km due to the expanding area outpacing the increase in road length. Intersection count rises, yet its density falls drastically, further confirming a spread-out network. The CF index, however, increases from 0.105 to 0.802, indicating an overall rise in structural complexity and connectivity as the network expands.

The road network's connectedness, density, and accessibility indices are displayed in a box plot variation in Figure 5.15 according to the buffer radius, the distance between the zones, and the central business district.

In Figure 5.3, both the number of nodes and links increase steadily with each buffer zone, reflecting the outward spatial growth of the urban network. In contrast, intersection density and network density decline, indicating a shift from a compact, highly connected core to a more dispersed peripheral layout. The Connectivity Factor (CF) rises consistently with distance, suggesting improved connectivity and structural complexity despite reduced density.

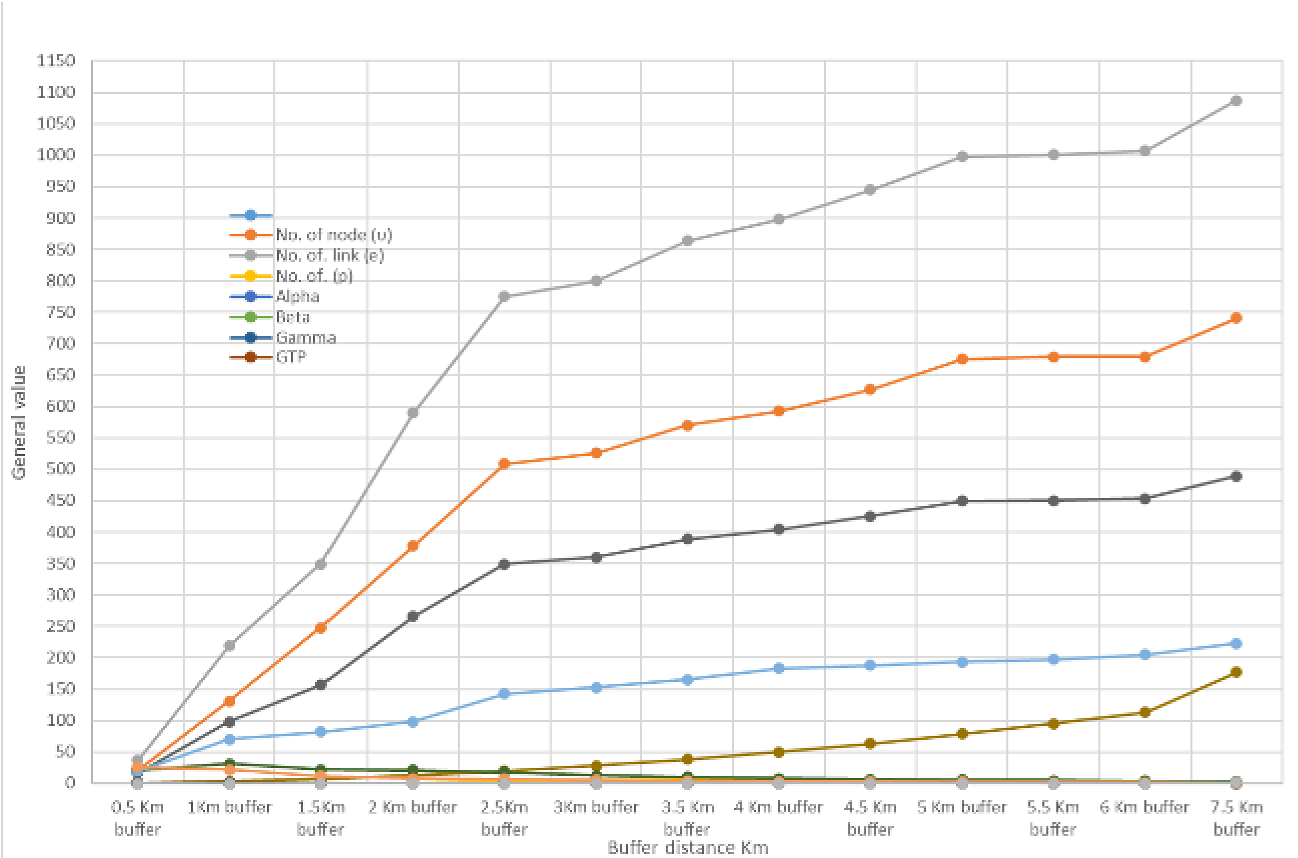


Figure 5.3 Network metrics analysis across buffer zones

As shown in Table 5.2, CF has the strongest correlation with distance from the city center ($R = 0.942$, $R^2 = 0.887$), followed by the number of nodes ($R = 0.926$), number of edges ($R = 0.915$), and network density ($R = 0.927$), all statistically significant ($p < 0.001$). In contrast, the number of parcels (No_of_p) shows a weak, non-significant relationship ($R = 0.189$, $p = 0.537$), indicating minimal influence of distance on this variable.

Building on the previous analysis, Figure 5.4 presents the Relative Neighborhood Graph (RNG) for the study area in Karbala, which was used further to explore the spatial configuration of the urban road network. This method applies a geometric model where roads are abstracted as randomly drawn straight lines, allowing for the evaluation of the relationship between total road length and the number of intersections. The resulting measure, the Connectivity Factor (CF), is detailed in Table 5.2, offering insights into the complexity and integration of the network.

Table 5-2: Model information of the relation between distance buffers

Model the relation between distance-buffer	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
No_of_point_e	0.926	0.857	0.844	0.795003	0.857	66.102	1	11	0.000006
No_of_edge_υ	0.915	0.837	0.822	0.851032	0.837	56.284	1	11	0.000012
No_of_p	0.189	0.036	-0.052	2.066924	0.036	0.407	1	11	0.537
alpha	0.622	0.387	0.331	1.647827	0.387	6.947	1	11	0.023
Beta	0.604	0.365	0.307	1.677811	0.365	6.311	1	11	0.029
Gamma	0.586	0.343	0.283	1.706026	0.343	5.743	1	11	0.035
GTP	0.61	0.372	0.315	1.667359	0.372	6.529	1	11	0.027
Network density	0.927	0.859	0.846	0.789862	0.859	67.109	1	11	0.000005
ETa	0.623	0.389	0.333	1.6458	0.389	6.99	1	11	0.023
Intersection density	0.842	0.708	0.682	1.136963	0.708	26.697	1	11	0.00031
CF	0.942	0.887	0.876	0.709019	0.887	85.936	1	11	0.000002

As illustrated in Figure 5.5 , the computed GTP index and CF values across different buffer zones reflect a gradual transition in network structure as distance from the city center increases. Most of the analyzed zones fall between the geometric patterns of a hexagonal and square RNG, with central areas of Karbala leaning more toward the square form, indicating a more organized and accessible road system.

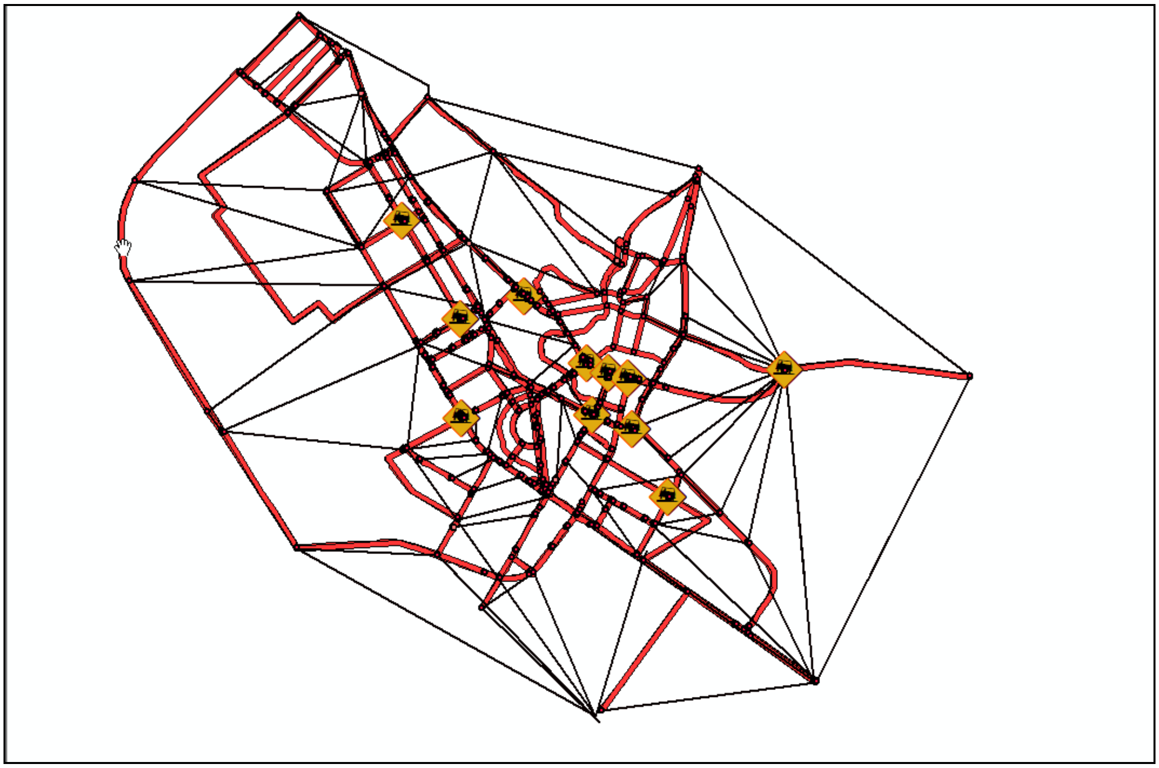


Figure: 5.4 RNG of Karbala

The GTP index, representing the degree of network connectivity, reaches its peak in the 0.5 km buffer (GTP = 1.325), highlighting the high level of connectivity within the urban core. In contrast, the lowest value is found in the 7.5 km buffer (GTP = 0.505), signaling reduced integration in peripheral areas. Similarly, the CF values reinforce this trend: lower CF values indicate denser, more interconnected networks. The smallest CF value is observed at the 0.5 km buffer (CF = 0.105), while the largest is in the 7.5 km zone (CF = 0.802).

These results suggest that the road network becomes increasingly dispersed and less efficient with distance from the city center. The urban core demonstrates the strongest connectivity and density, supporting its selection as the initial focus for spatial and sustainability analysis.

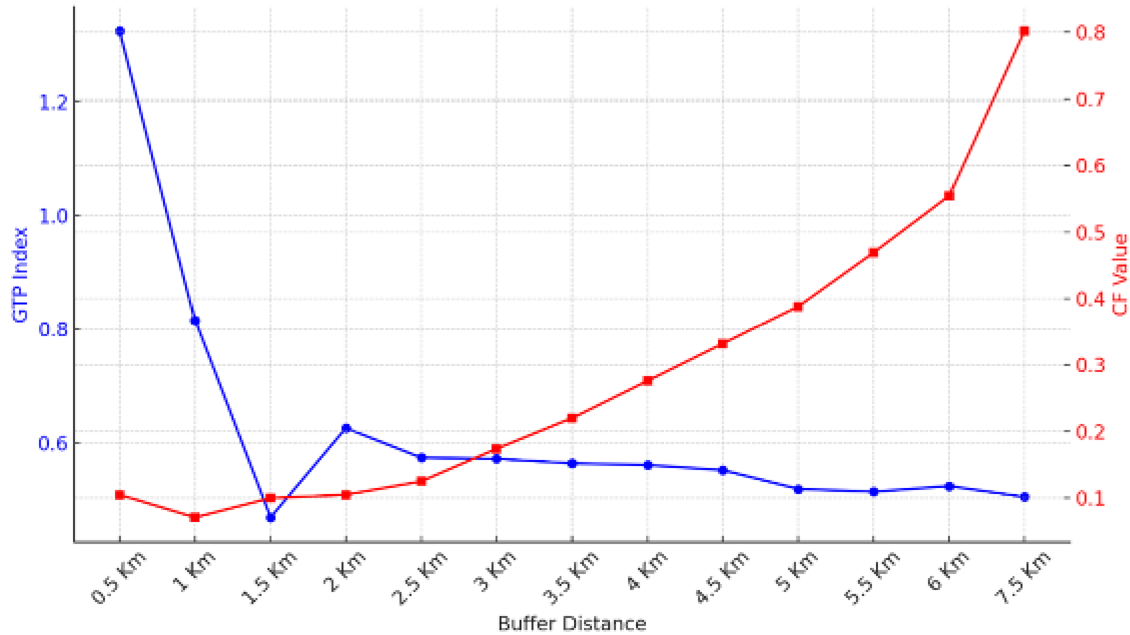


Figure 5.5 Variation of GTP index and CF value with buffer distance

The analysis of the GTP and CF indices across the urban network of Karbala reveals significant spatial trends that align with the theoretical characteristics of two fundamental geometric models: the Hexagonal RNG and the Square RNG.

Theoretical Framework:

Hexagonal RNG represents an idealized, highly efficient network structure characterized by:

High GTP values (typically > 1) indicate strong connectivity.

Low CF values, reflecting high density and well-distributed intersections.

Square RNG, on the other hand, typically exhibits:

Moderate to low GTP values, indicating reduced connectivity.

Higher CF values signify lower intersection density and more dispersed road organization.

In Table 5.3, the buffer distances are explained and classified based on their alignment with either the Hexagonal RNG or the Square RNG network structure.

Table 5-3: Observed Network Patterns in Karbala:

Buffer Distance	GTP	CF	Interpretation
0.5 Km	1.325	0.105	Closely aligned with Hexagonal RNG, featuring very high connectivity and a compact form.
1.0 Km	0.816	0.071	Slight deviation from the hexagonal model, but still within a well-organized structure.
1.5–3.0 Km	0.469–0.572	0.1–0.174	Gradual decline in GTP and increase in CF transition toward a more grid-like (Square RNG) pattern.
3.5–5.5 Km	~0.56	0.22–0.469	Increasing randomness and dispersion characteristics lean toward Square RNG.
6.0–7.5 Km	~0.52	0.554–0.802	The network becomes highly dispersed with lower connectivity approaching a random network configuration.

The highest degree of network efficiency and compactness is observed in the 0.5 km buffer, aligning closely with the Hexagonal RNG structure. As the distance from the city center increases, the network gradually transitions through characteristics of the Square RNG and eventually approaches a randomized pattern, evidenced by a steady increase in CF and a corresponding decline in GTP. This progression highlights the spatial evolution of Karbala's urban form from a well-connected, dense core to a more fragmented and dispersed peripheral structure.

5.3 Evaluating urban street attributes based on tree-like network patterns

To examine whether street network types in different regions exhibit distinguishable characteristics, this study selected various urban street networks within Karbala, each demonstrating distinct spatial forms and configurations. Although the final number of samples chosen may appear limited, the selection is justified by several methodological considerations that support the reliability of the research objectives and findings. As a classification-based study, the primary aim is to identify and analyze the key characteristics of representative or reference networks, rather than to categorize every individual network. An overreliance on large-scale statistical datasets may obscure subtle yet significant network features, as some distinctive attributes can be diluted within vast aggregates of data. Initially, approximately 1,120 road network samples were identified, but after evaluating their boundary definitions and spatial data distributions, samples exhibiting repetitive or highly similar patterns and parameter values were excluded. The remaining samples were selected to preserve variability and distinctiveness. Key structural attributes such as road segment length, functional classification, intersection type, and hierarchy were extracted and used to calculate multiple topological indices. These were then analyzed using ArcGIS software to enable comparative evaluation and to highlight meaningful structural differences across the selected urban networks. Analysis Sample Selection

(1) The samples represent different parts of urban areas: new development zones, cores of downtown districts, ring areas around the city, and outer suburban residential areas.

(2) For convenience of comparison, the Karbala street network was partitioned into four areas to streamline the calculating process and ensure that each portion exhibits some degree of variation, even if only a little.

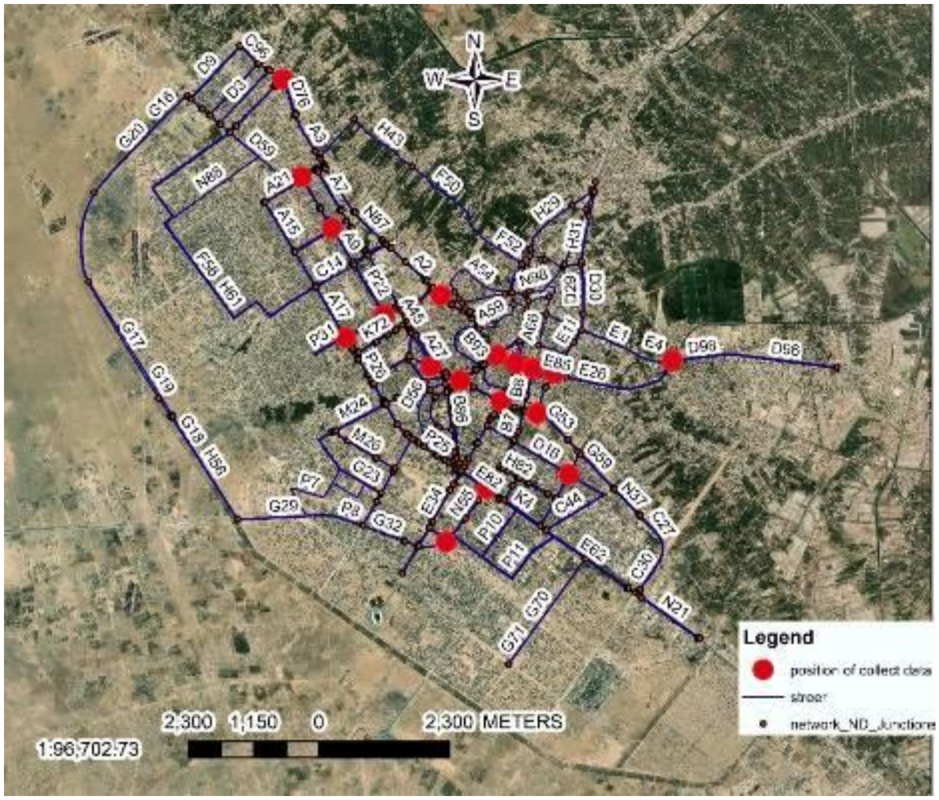


Figure 5.6: Typical street network of Karbala city

The Karbala street network was partitioned into four sections to assess the streets' condition and establish connections based on the classification above. The study revealed that the streets had similar quality levels and were categorized based on Figure 2.3 in Chapter 2.

5.3.1 Analysis Data

The selected samples were categorized into four fundamental street network pattern types, as previously defined: standard rectangular grid, T-type, cul-de-sac-based, and pure tree-like structures (refer to Table 5.4). For each sample, four key indicators were calculated: X-type intersection ratio, T-type intersection ratio, cul-de-sac ratio, and penetrating street ratio, and their values are presented in Table 5.4.

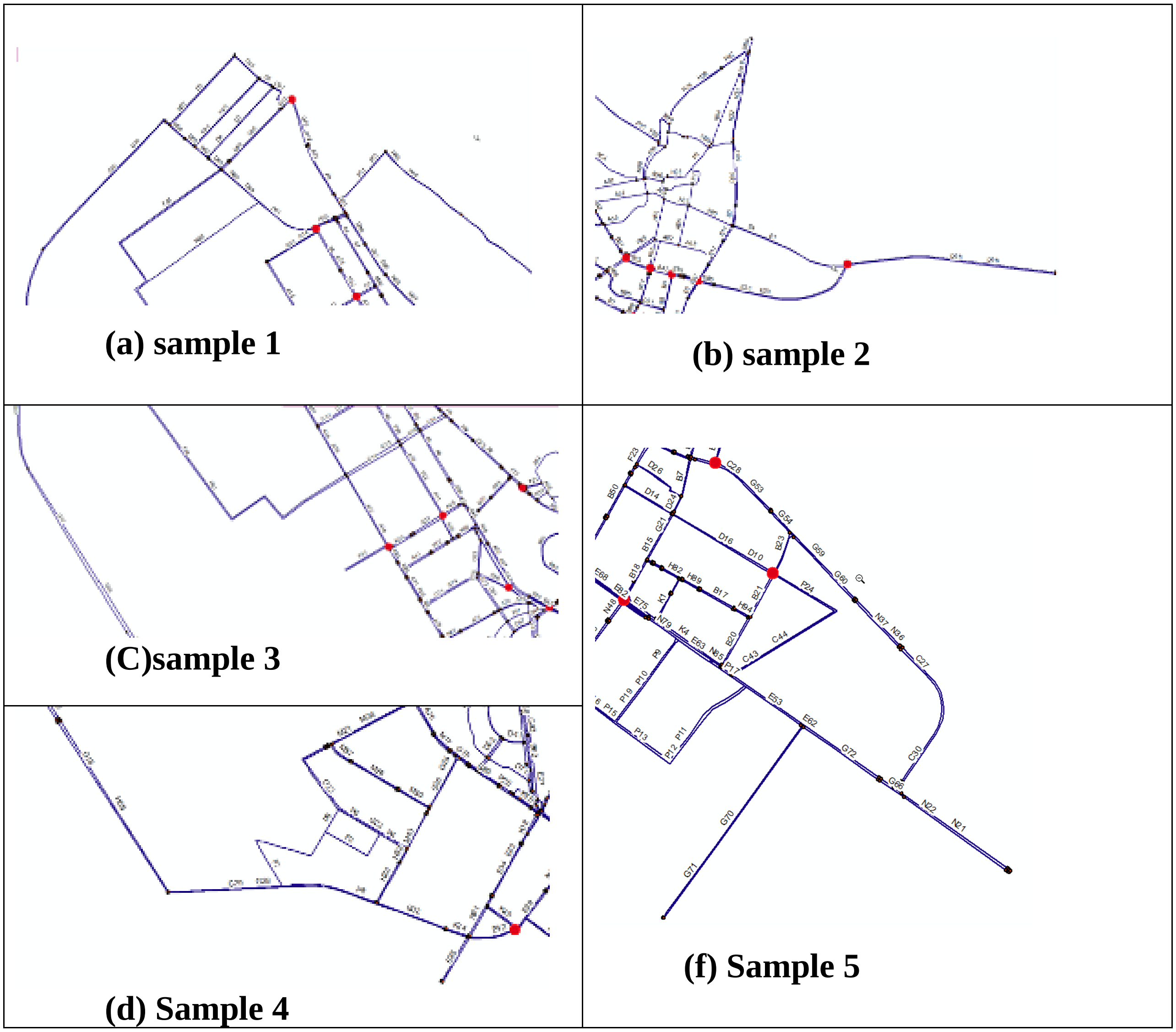


Figure 5.7: Street network diagram for five samples of the city before the calculation process

Analysis of the data revealed a strong correlation between the X-type and T-type intersection ratios and the corresponding network pattern types. In contrast, as illustrated in Figure 5.7, the penetrating street ratio showed a weaker association with either the X-type or T-type ratios. Consequently, the X-type and T-type intersection ratios were identified as the primary indicators for determining the degree of tree-like structure within the street network. The cul-de-sac ratio, however, exhibited limited correlation with overall pattern classification and was therefore deemed less reliable as a distinguishing metric in this context.

Table 5-4: Parameter value of samples

Serial Number	Network samples	Number of joints	X-joint	T-joint	cul-de-sac-joint	X-Type Ratio	T-Type Ratio	Cul-De-Sac Ratio	Penetrating Street Ratio	Type Of Image
1	Sample 1	66	20	32	14	0.30	0.48	0.21	0.58	B
2	Sample 2	83	56	15	12	0.67	0.18	0.14	0.71	A
3	Sample 3	129	61	41	27	0.47	0.32	0.21	0.58	C
4	Sample 4	67	16	38	13	0.24	0.57	0.19	0.61	B
5	Sample 5	77	16	27	34	0.21	0.35	0.44	0.12	D

Note: The road network instances in the table are sorted by type. The types are(A) Pure grid-like network pattern,(B) T-type network pattern,(C) cul-de-sac network pattern, and (D) pure tree-like network pattern.

Figure 5.8 illustrates the relationship between the T-type intersection ratio and the cul-de-sac ratio across all analyzed samples. As shown in Figure 5.9, the T-type ratio exceeds 0.44 in the majority of the sample cities, indicating that T-intersections are a dominant feature in most urban street networks. Conversely, the cul-de-sac ratio in most samples remains below 0.44, implying that dead-end streets are comparatively less frequent and are not a defining characteristic in the majority of the observed networks.

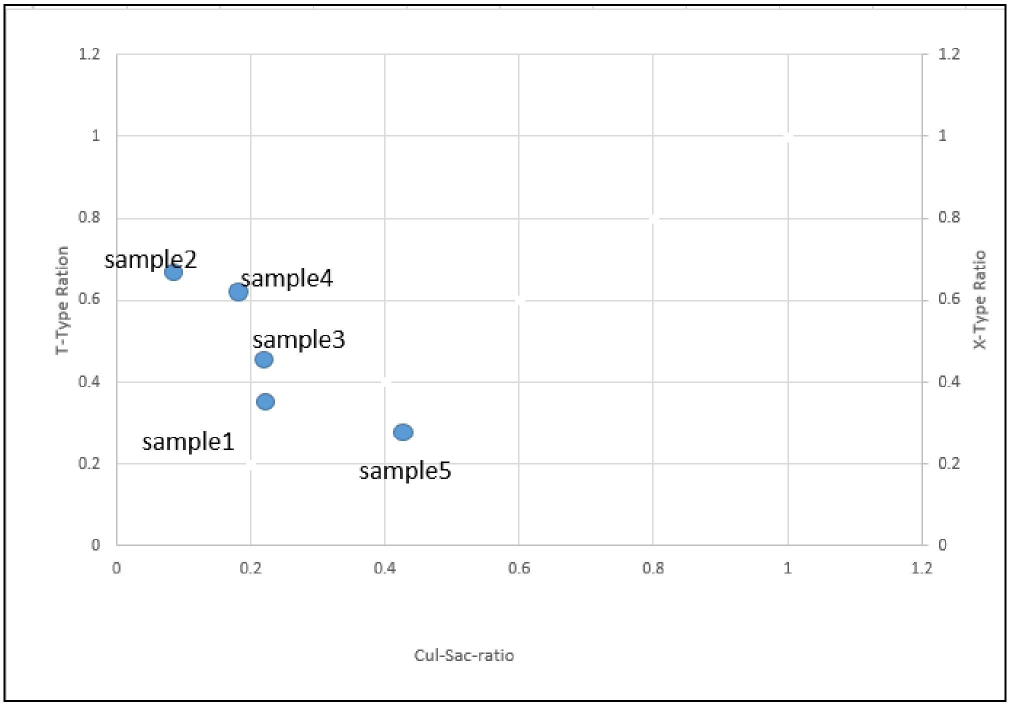


Figure 5.8: Distribution of the sample between three types

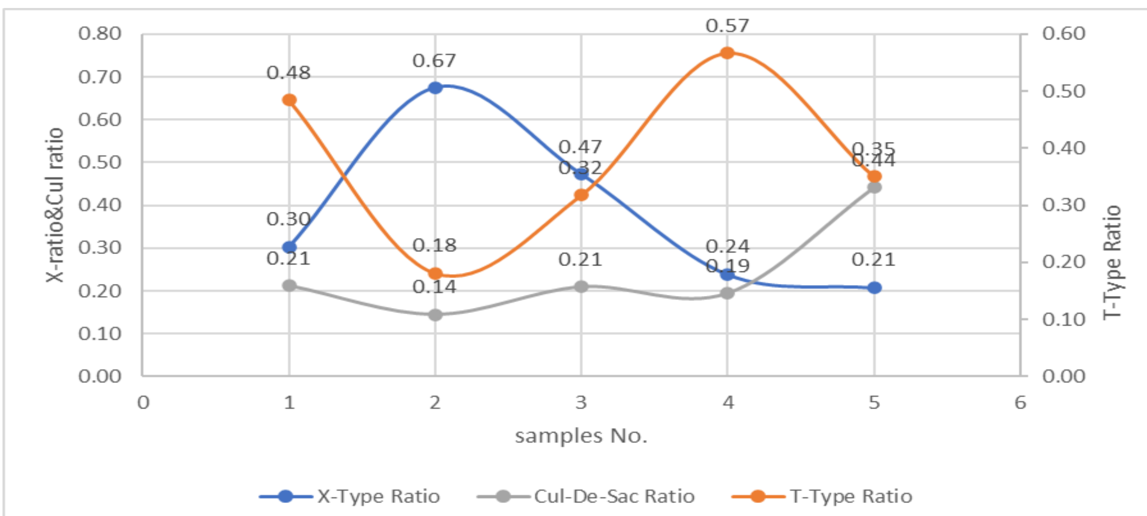
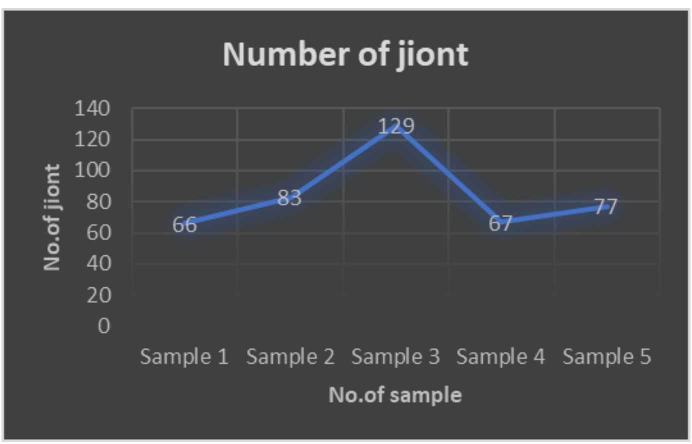


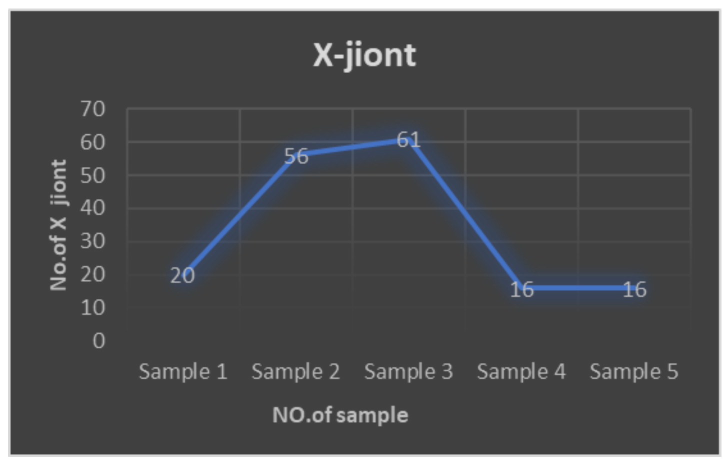
Figure 5.9: Parameter value for each sample

5.3.2 Data Analysis and Interpretation

The results above indicate that the variations in the indicators (such as the ratios of penetrating streets, T-type streets, X-type streets, and cul-de-sacs) can be utilized to determine the structural subtype of a given street network.

• By examining Figure 5.10, it is evident that when the samples are arranged in ascending order based on the T-type ratio, three separate categories can be observed: T-type ratio ∈ [0,0.3), [0.3,0.9), [0.9,1.0]. These three parts correspond to a grid network, a state of transition network, and a tree network. That approach effectively delineates the demarcation between purely tree-like and grid-like road networks. However, due to the proximity of the values of the indicators in the regarding zone, it is challenging to discern any further subdivisions within that regime.





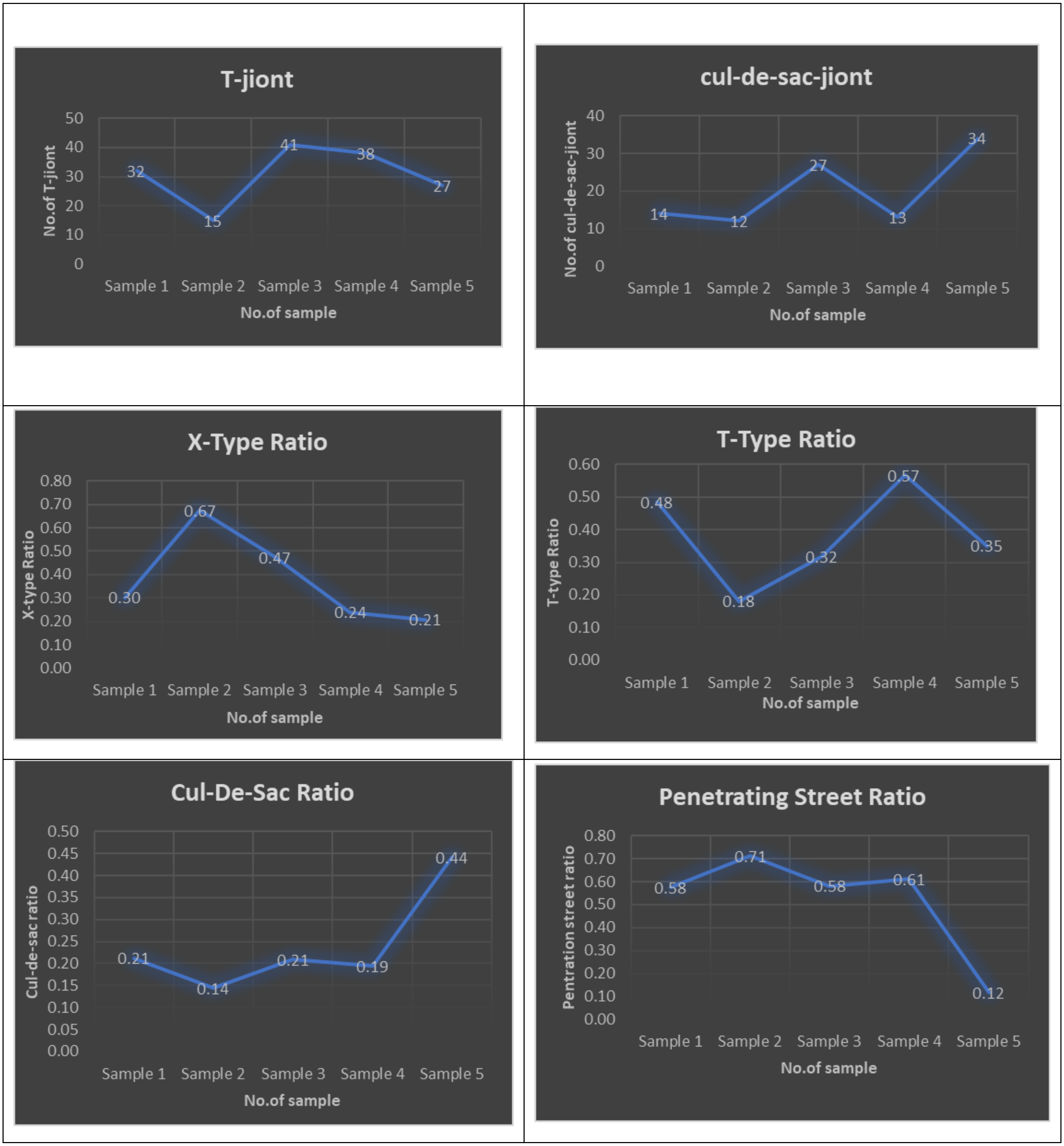


Figure 5.10: Relation between samples of network city and all parameters

Figures 5.11 demonstrate a strong correlation between the penetrating street ratio and the X-type ratio since they exhibit similar trends. If the value exceeds 0.3, it is about to differentiate between a pure grid road network and a rectangular-type street network. Nevertheless, when the value is below 0.3, it is impossible to reliably distinguish between a pure tree-like road network or a T-shaped road network based on these characteristics.

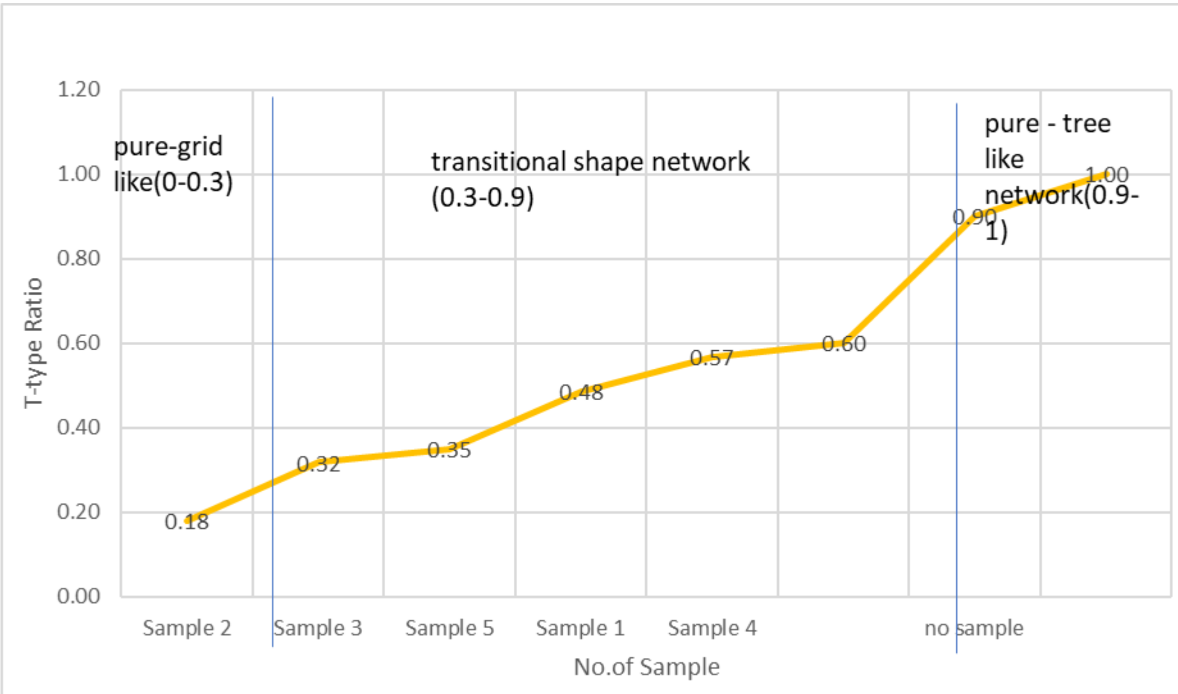


Figure 5.11: Classification of road network samples by type

• Based on Figure 5.12, the cul-de-sac ratio appears to have a trend almost the reverse of the X-type ratio. However, it may have greater effectiveness (i.e., more ability to differentiate) when it is near the area of the tree-like network pattern. When the cul-de-sac ratio is between 0 and 0.3 (inclusive), the network can be anticipated to have either a grid shape or a T-type structure. If the cul-de-sac ratio falls between the range of [0.3, 0.5], the network can be classified as a cul-de-sac type. When the ratio of cul-de-sacs is between 0.5 and 1.0, the network could be completely tree-like.

The penetrating street ratio is a significant and efficient metric for objectively assessing the resemblance of a general network to a tree-like network. Previous analyses have not given it sufficient consideration.

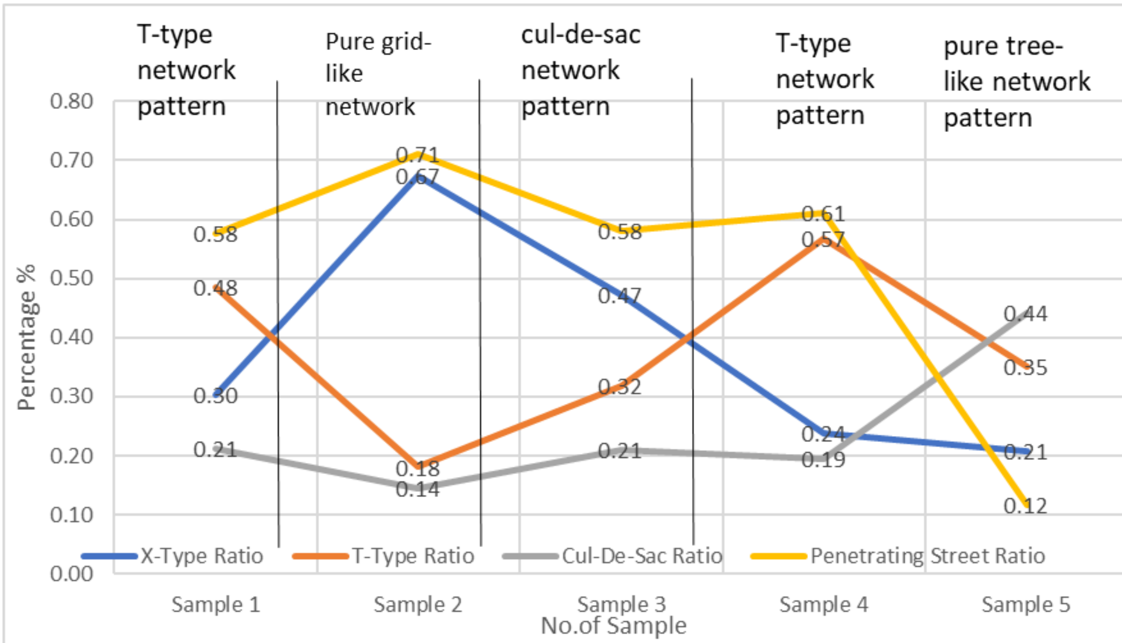


Figure 5.12: Type of network according to four parameters

5.4 Analysis of pollution and noise data

5.4.1 Noise for three positions

Road traffic noise is a significant form of environmental pollution that adversely affects human health (Cai et al., 2020). In this study, noise levels were analyzed concerning traffic flow and vehicle speed over one hour in the selected street network. Measurements were obtained using a handheld noise meter, which was positioned both at the road median and roadside in the study area. The objective was to explore how variations in flow and speed affect noise emissions, as illustrated in Figure 5.13. In roundabout Al-Tarbiya, the highest recorded noise level was 95 dB at 8:00 AM, which coincided with the peak traffic flow (3273 vehicles/hour) and the lowest vehicle speed (25 km/h). As traffic eased over the hour, noise levels gradually declined, reaching 77 dB at 9:00 AM, the lowest reading in the dataset. Vehicle speed showed a steady upward trend, increasing from 25 km/h at 8:00 AM to 50 km/h by 9:00 AM. This increase in speed aligns with the reduction in both traffic flow and noise, indicating a smoother traffic stream and less idling, which typically results in lower noise emissions. Traffic flow peaked at the beginning of the observed period and declined consistently from 3273 vehicles/hour at 8:00 AM to 1460 vehicles/hour at 9:00 AM.

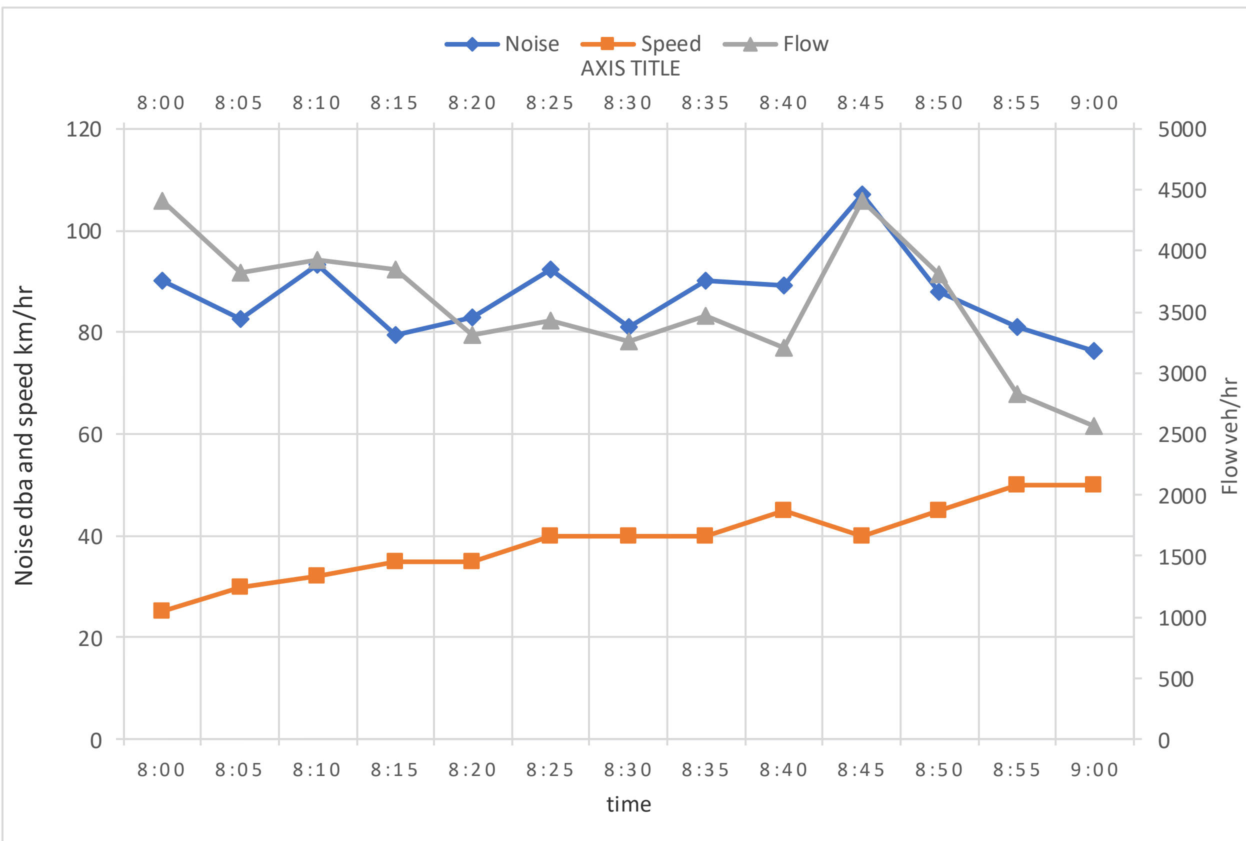


Figure 5.13: Noise chart for Roundabout Al-Tarbiyah

In Figure 5.14, the highest noise was recorded at 8:15 AM (109.3 dB), coinciding with high traffic flow (3187 vehicles/hour) and moderate speed

(35 km/h), indicating severe congestion and aggressive driving behavior. Vehicle flow peaked around 8:15 AM and then gradually declined to 1843 vehicles/hour by 9:00 AM, suggesting a tapering of the morning rush. Speeds increased gradually from 25 km/h at 8:00 AM to 50 km/h by 9:00 AM, showing traffic decongestion. Noise levels were highly variable, but generally declined after 8:15 AM. Elevated noise levels at lower speeds (e.g., 91.6 dB at 25 km/h) confirm that congestion contributes to noise pollution.

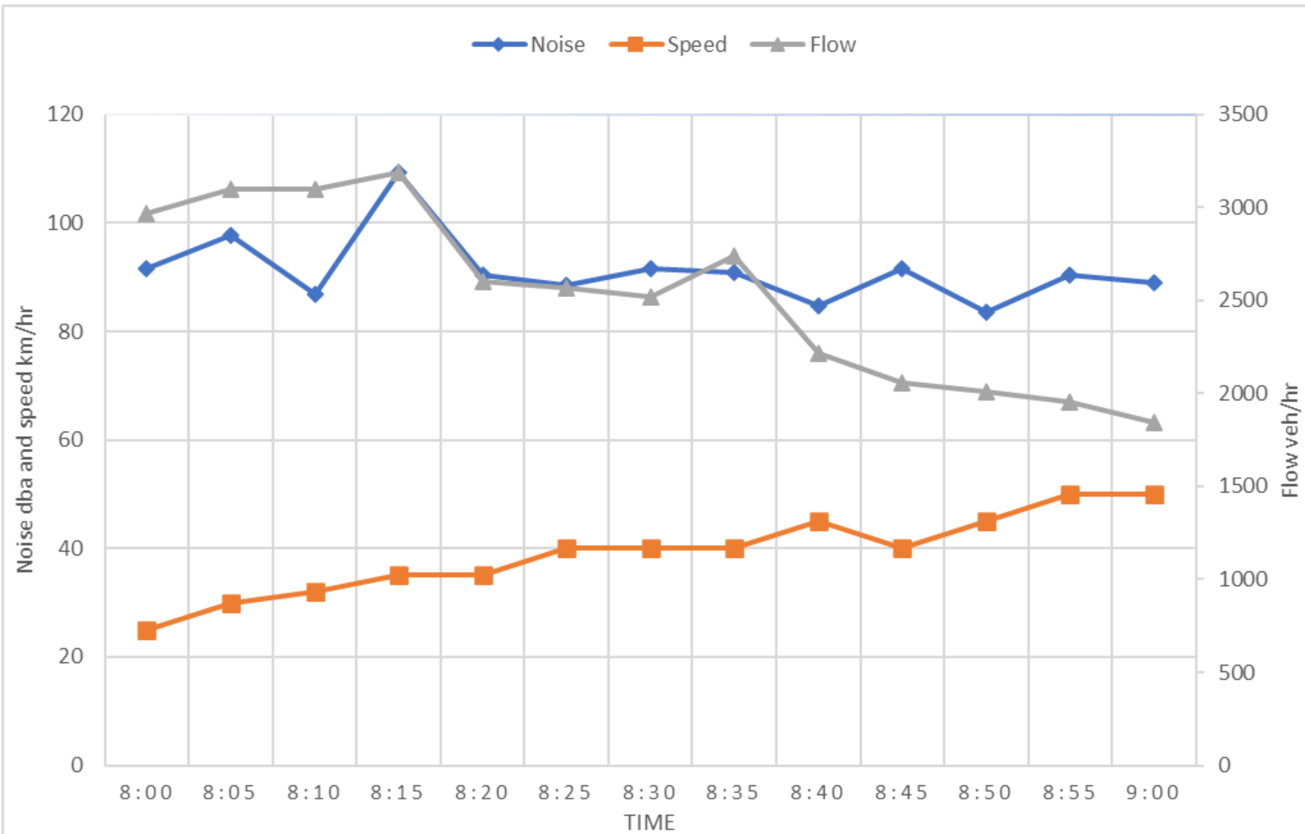


Figure 5.14: Noise chart for Roundabout Saied Joda

In Figure 5.15, the highest noise level (95 dB) was recorded at 8:00 AM, alongside the highest traffic flow (3273 vehicles/hour) and lowest speed (25 km/h), indicating heavy congestion. Vehicle flow gradually decreased from 3273 to 1460 vehicles/hour by 9:00 AM, while speed increased steadily from 25 to 50 km/h, showing traffic decongestion over time. Noise levels generally decreased throughout the hour, reaching 77 dB at 9:00 AM, correlating with reduced congestion and higher speeds.

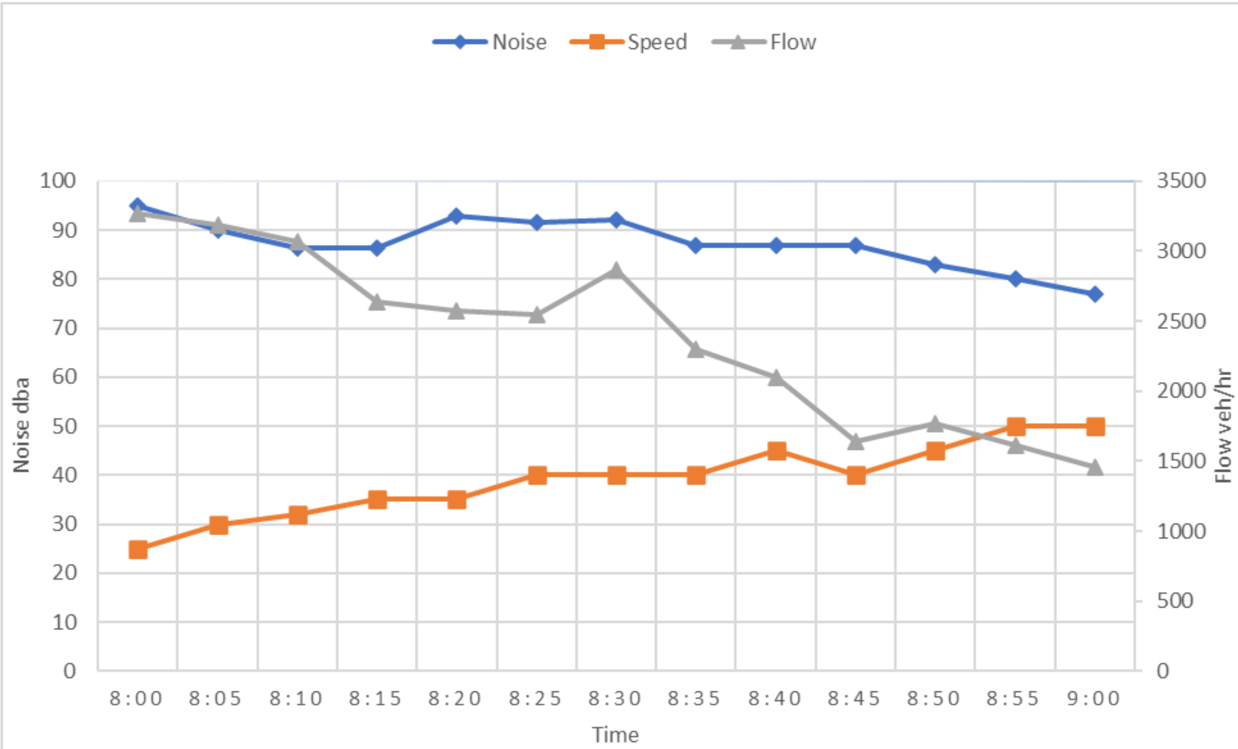


Figure 5.15: Noise chart for Jisr Al-Dariba

Speed vs. Noise: A negative correlation was observed, where higher speeds were associated with lower noise levels, largely due to reduced congestion and smoother flow.

Flow vs. Noise: A positive correlation was identified during peak times; higher vehicle flow at lower speeds contributed to increased noise, especially in the early intervals between 8:00 and 8:15 AM.

The results emphasize the intricate relationship between urban traffic dynamics and environmental noise pollution. As demonstrated, traffic congestion significantly contributes to elevated noise levels, while smoother and faster-moving traffic leads to lower acoustic impact. These findings underscore the importance of implementing effective traffic management strategies to mitigate noise pollution and enhance overall urban livability.

5.4.2 Pollution data for Roundabout Al-Tarbiyah

Following the observation of gases from the location with the instrument above, a correlation was established between the rise in flow and the increase in gas levels. It was observed that dangerous gases are directly correlated with the increase in flow, which is both feasible and natural, as shown in Figure 5.16.

The highest CO_2 concentration (579.35 ppm) occurred at 8:15 AM, corresponding with a high traffic flow (3844 vehicles/hour), indicating a link between traffic volume and emissions. From 8:15 AM onwards, both CO_2 levels and vehicle flow gradually decreased, reaching the lowest CO_2 reading (509.36 ppm) and lowest flow (2563 vehicles/hour) by 9:00 AM. Despite lower CO_2 (529.2 ppm), flow peaked again (4406 vehicles/hour), possibly due to temporary traffic rerouting or increased vehicle efficiency.

The data suggests a general positive correlation between traffic flow and CO_2 emissions. Higher vehicle volumes tend to increase CO_2 concentration. However, occasional deviations hint at other influencing factors such as vehicle type, stop-and-go conditions, or roadway characteristics.

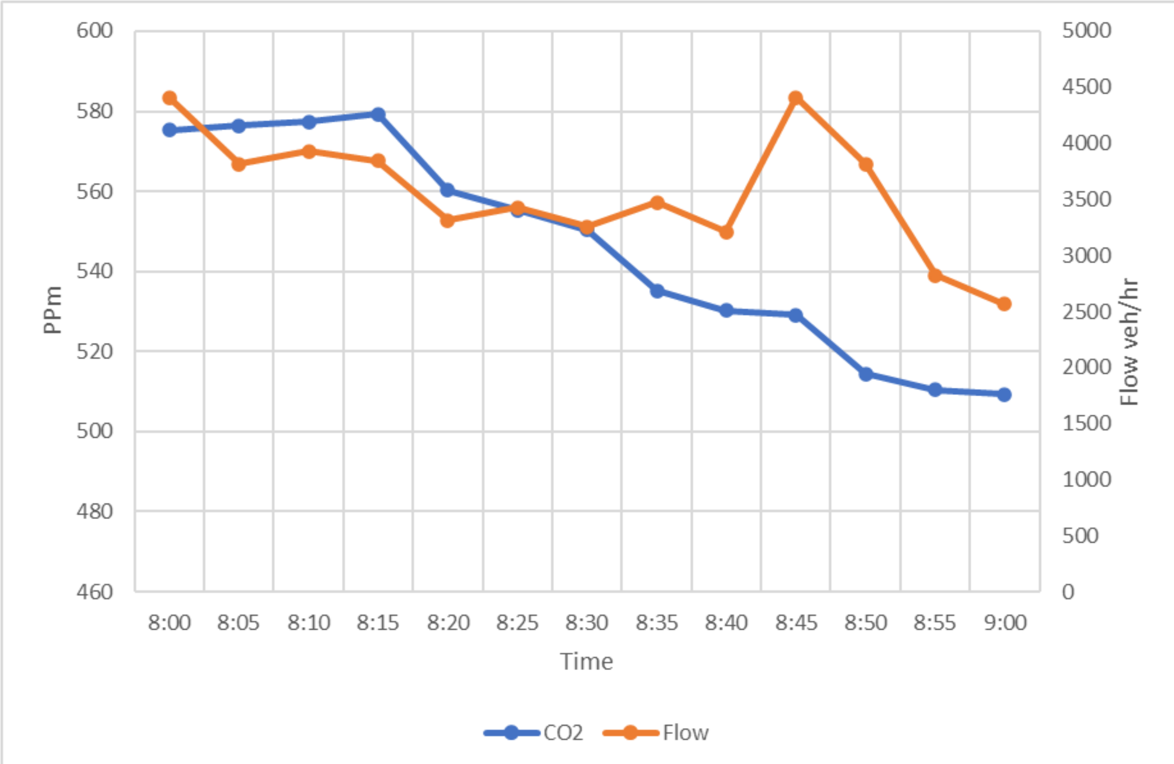


Figure 5.16: CO2 and flow Roundabout Al-Tarbiyah

Figure 5.17 shows a gradual decrease in carbon monoxide (CO) levels from 15.55 ppm at 8:00 AM to a low of 6.78 ppm at 8:35 AM, which aligns with a general reduction in traffic flow during that period. However, an anomalous spike in flow at 8:45 AM (4406 vehicles/hour) is not matched by a significant CO increase, suggesting the presence of more efficient or less polluting vehicles or a change in traffic dynamics. Overall, the data reflects how decreasing congestion and smoother flow reduce CO emissions, supporting the importance of traffic management in urban air quality improvement.

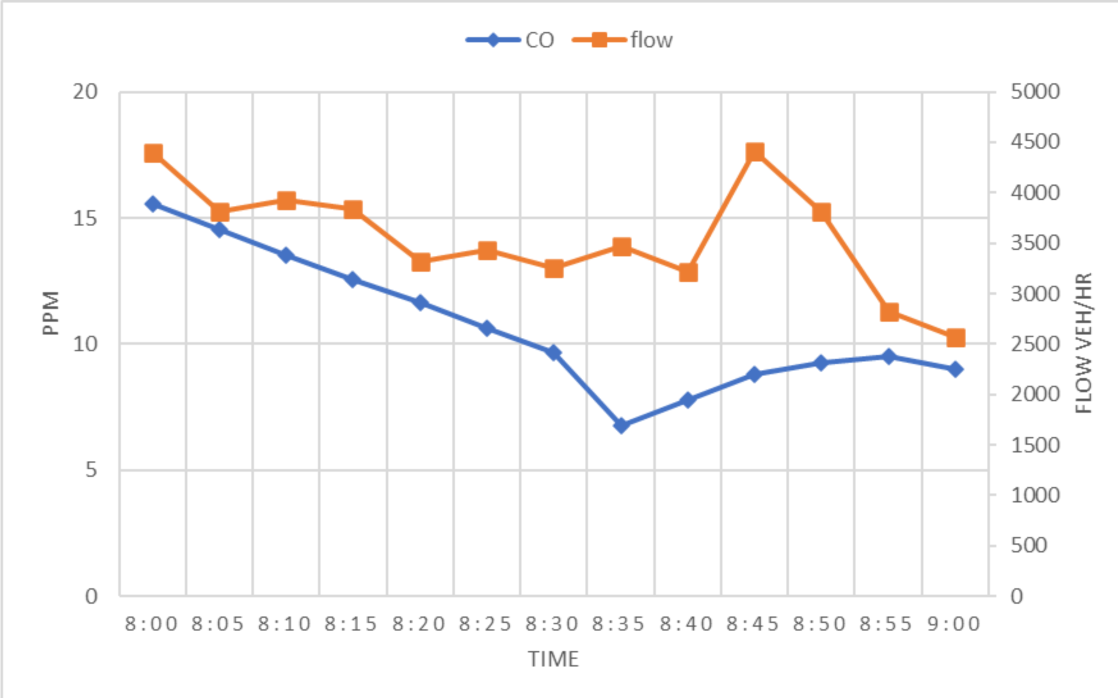


Figure 5.17: CO and flow Roundabout Al-Tarbiyah

Figure 5.18 reflects the concentration levels of various gaseous pollutants, N_2O, CH_4, Propane, Butane, and Benzene concerning traffic flow from 8:00 AM to 9:00 AM. Across the hour, CH_4 and N_2O show a gradual decrease, indicating a general decline in emissions likely due to reduced traffic volumes. Notably, Propane remains at zero throughout, suggesting negligible or no emissions from this compound. Butane and Benzene both decline significantly, especially after 8:20 AM, with Benzene dropping from 0.23 ppm to 0.05 ppm, pointing to improved air quality as traffic eases. Despite a flow spike at 8:45 AM (4406 vehicles/hour), pollutant levels remain relatively low, possibly due to temporary traffic dispersion or better emission controls. Overall, the data suggests a strong link between vehicular flow and emission levels, reinforcing the need for effective traffic and emissions management to improve urban air quality.

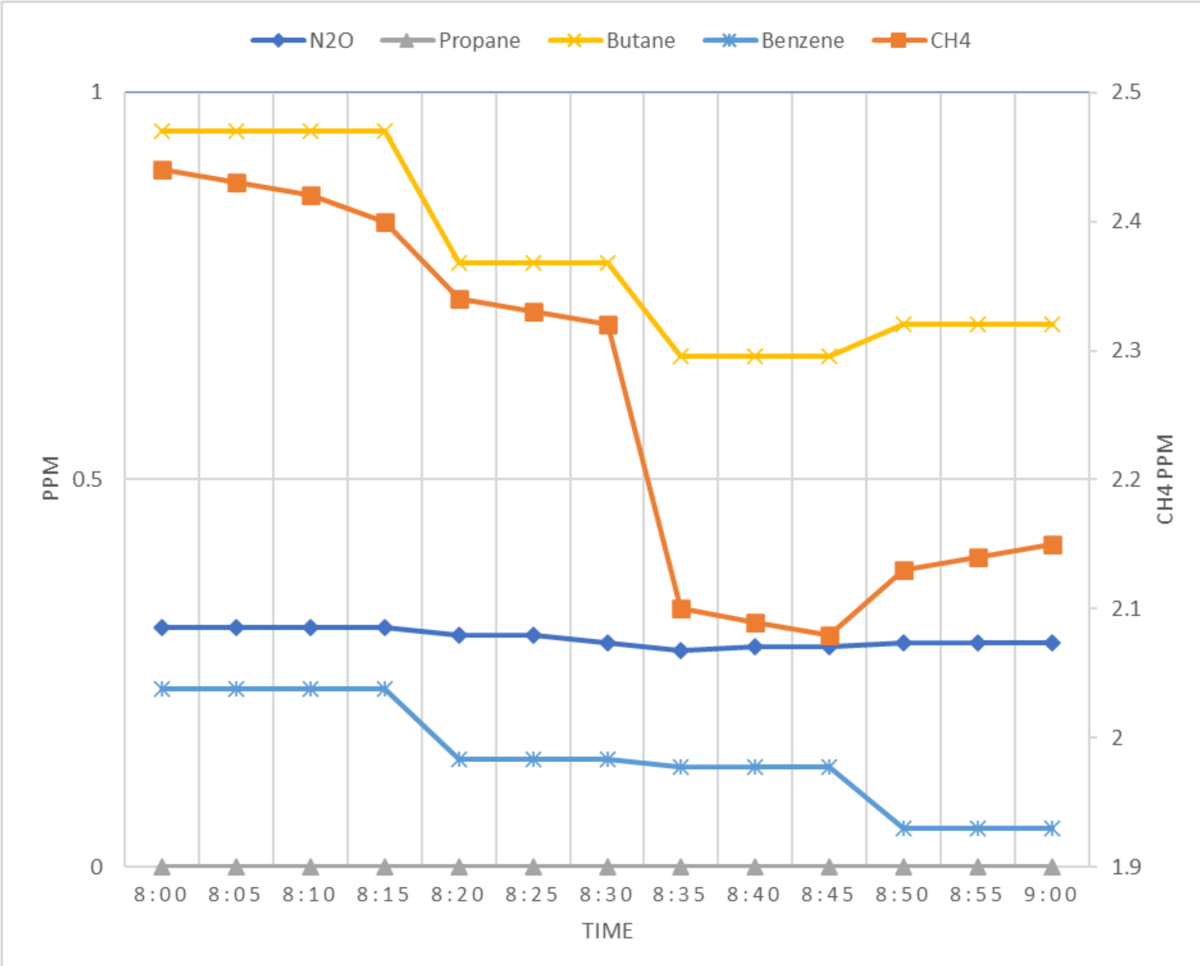


Figure 5.18: Different gases for Roundabout Al-Tarbiyah

From the tables of AQI in Chapter 2, the quantities of maximum gases were determined. After comparing the values according to the international system for measuring the maximum permissible limits for gases, each type of these gases was identified, and it was determined whether these gases had exceeded the allowable limit according to the International System for Measuring the Maximum Permissible Limits. These values were placed in Table 5.5 with an indication of the colours that indicate the danger of these gases, and Figure 5.19 explains the colour of the concentration of gases.

Table 5-5: Maximum gasses according to AQI(WHO,EPA)

variables	Maximum	units	AQI Categories (Index Values)	Colure
CO2	579.35	ppm	Hazardous	Maroon
CO	15.55	ppm	moderate	Yellow
N2O	0.31	ppm	Hazardous	Maroon
CH4	2.44	ppm	unhealthy	Red
Propane	0	ppm	good	Green
Butane	0.95	ppm	unhealthy	Red
Benzene	0.23	ppm	moderate	Yellow
Toluene	0	ppm	good	Green
Ethyl Benzene	0	ppm	good	Green
Xylene	0.1	ppm	moderate	Yellow
Acetic Acid	0	ppm	good	Green
Formaldehyde	0.32	ppm	unhealthy	Red
Acetaldehyde	0.03	ppm	unhealthy	red
Methanol	0	ppm	good	Green
Furan	0.02	ppm	good	Green
Hydrogen cyanide	0.15	ppm	moderate	Yellow
Chlorobenzene	0	ppm	good	Green
Phosgene	0	ppm	good	Green
Ammonia	0.13	ppm	unhealthy	red
HCl	0.17	ppm	unhealthy	red
HF	0	ppm	good	green
NO2	0.83	ppm	unhealthy	Red
NO	3.54	ppm	Hazardous	Maron
SO2	0.8	ppm	unhealthy	Red

This dataset summarizes the maximum observed concentrations of various air pollutants and their corresponding Air Quality Index (AQI) classifications. Several pollutants, including CO_2 (579.35 ppm), N_2O (0.31 ppm), and NO (3.54 ppm), fall under the "Hazardous" category, posing serious health risks and marked by the color Maroon. Gases such as CH_4, Butane, Formaldehyde, Acetaldehyde, Ammonia, HCl, and NO_2 are categorized as "Unhealthy" (Red), indicating adverse effects especially on sensitive groups. Some compounds, including CO, Benzene, Hydrogen Cyanide, and Xylene, fall into the "Moderate" category (Yellow), suggesting limited but notable health concerns. On the positive side, substances like Propane, Toluene, Ethyl Benzene, Acetic Acid, Methanol, Furan, Chlorobenzene, Phosgene, and HF show zero or minimal concentrations, corresponding to "Good" air quality (Green). Overall, the data indicate a complex urban pollution profile, with a significant number of hazardous or unhealthy pollutants, emphasizing the urgency of air quality management and pollution mitigation strategies in urban environments.

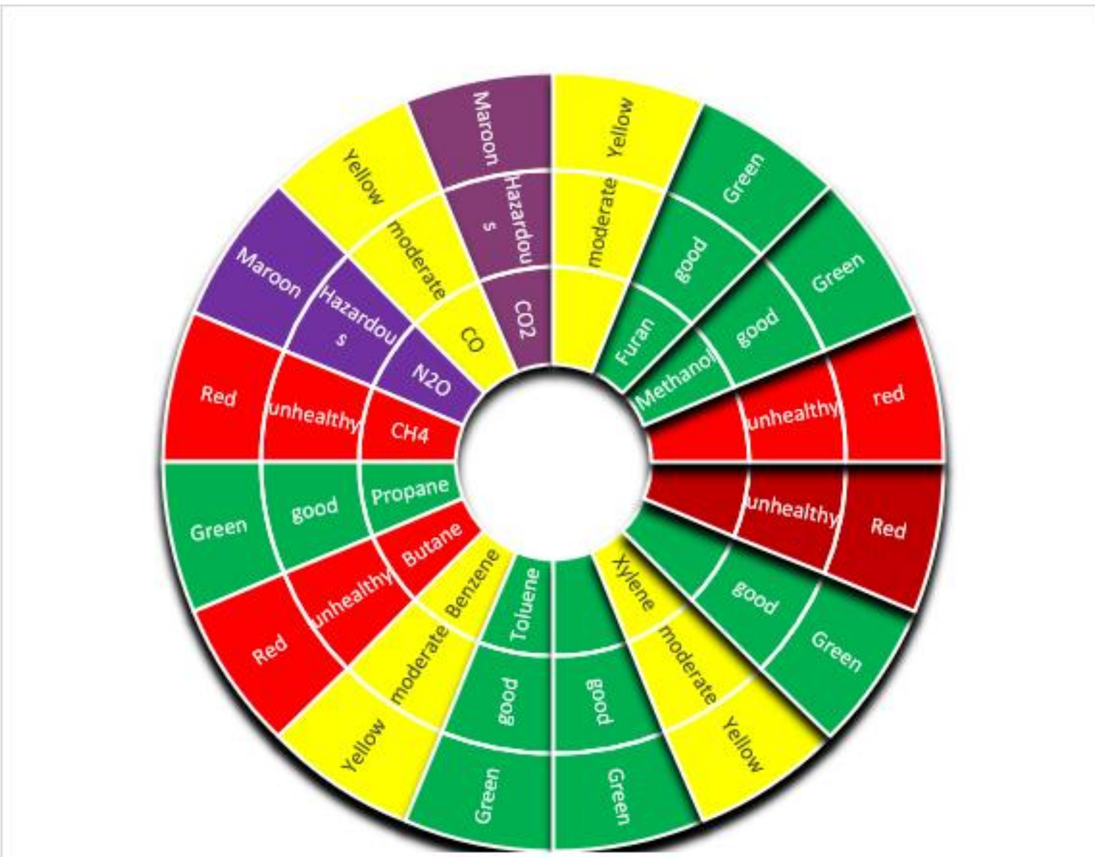


Figure 5.19: Coloured according to gases according to AQI

The analysis covered all data collection sites using the same procedure to ensure consistent results. The outcomes provide a baseline for applying sustainability standards and equations, enabling targeted interventions to enhance traffic flow, safety, and the development of a more efficient, resilient, and environmentally responsible urban transport network.

5.5 Analysis data

The remaining data was analyzed to identify correlations with the street network of Karbala city. The analysis reviewed additional variables that contribute to understanding traffic patterns and safety concerns. These findings will be integrated into the overall evaluation of the road infrastructure in the holy city of Karbala.

5.5.1 Analysis of traffic accident data in Karbala City

Accident data collected in the holy city of Karbala were analyzed, revealing a variation in accidents throughout the year and across different types of accidents. Figure 5.20 illustrates the maximum number of accidents related to crashes, and the lower value represents accidents involving overtaking.

Between 2015 and 2024, traffic accident records show a persistent upward trend, peaking in 2023 with 618 total accidents, the highest in the decade. This rise highlights an escalating risk in the urban traffic environment. Crash-type accidents consistently represented the largest share, reaching a peak of 329 in 2024, suggesting ongoing vehicle-to-vehicle conflict as a major concern.

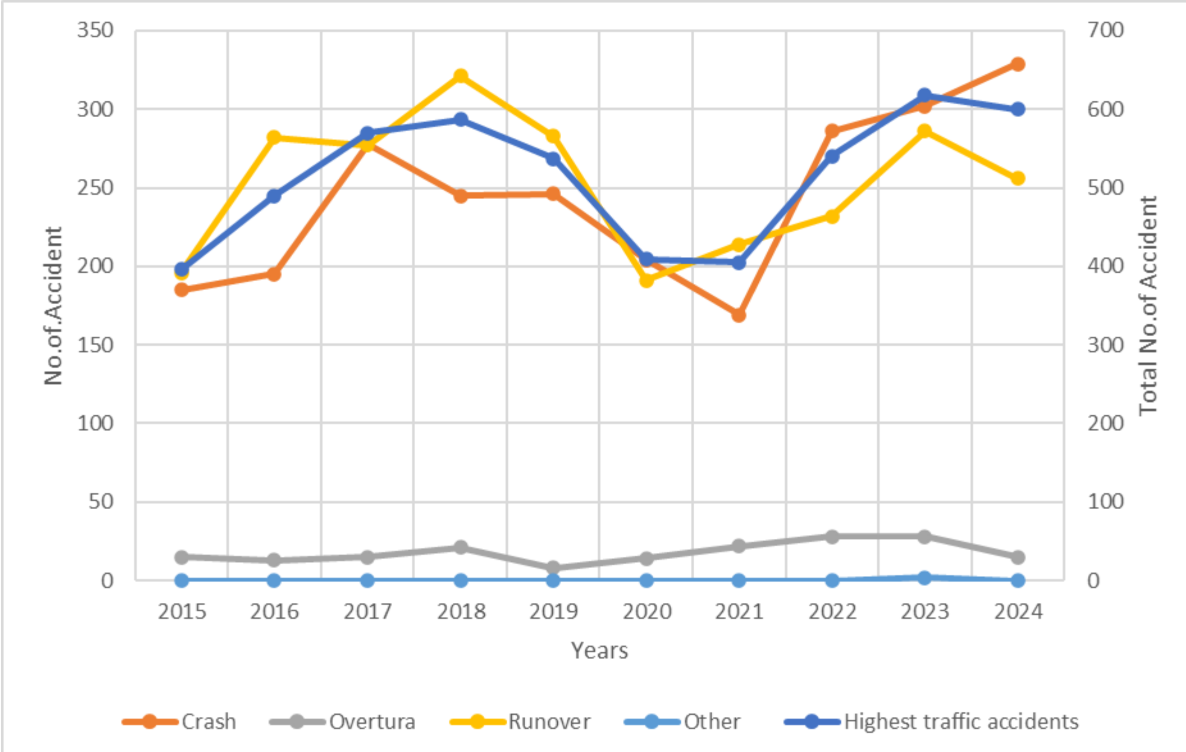


Figure 5.20: Traffic accidents in Karbala

Run-over incidents showed noticeable fluctuations, with the highest number in 2018 (321), followed by another surge in 2023 (286). These Figures underscore the continued vulnerability of pedestrians and the need for enhanced pedestrian safety infrastructure.

Overturning accidents, while numerically smaller, increased gradually over time, peaking at 28 in both 2022 and 2023, indicating rising issues related to vehicle stability or driver control.

Overall, the data emphasizes critical areas for intervention: managing high-speed collisions, protecting pedestrians, and improving vehicle stability measures. The consistent rise in total accident calls for urgent urban traffic planning reforms and improved enforcement strategies.

5.5.2 Analysis of environmentally friendly modes

The percentage of alternatives to cars in the streets of Karbala city is almost non-existent, largely due to the prevalence of fossil-fueled vehicles on the roads, which are not environmentally friendly. Thus, the city streets acquire an unsustainable characteristic due to the lack of use of these means.

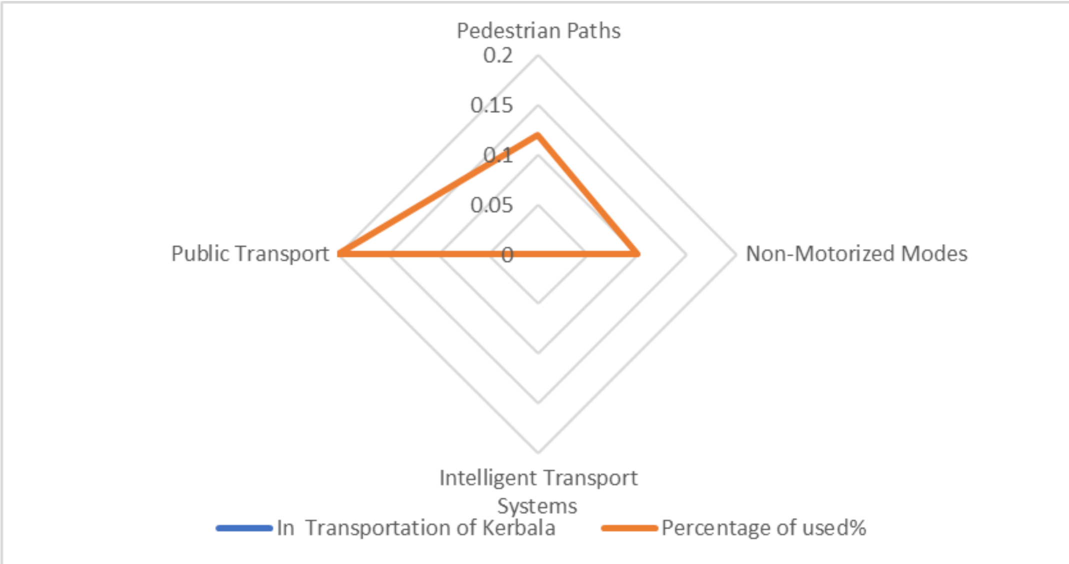


Figure 5.21: Sketch of environmentally friendly modes

Note from Figure 5.21 that the percentages of pedestrian use with the most appropriate use of public transportation and the use of transportation mechanisms that do not contain fossil fuels, such as bicycles, are tiny, and the distribution of these percentages is in the form of an unequal triangle and that the dependence of each type on the other achieves sustainability for the streets in small percentages. If a rate for a fourth type has been added that achieves sustainability, the distribution of these percentages would give good indicators of the sustainable direction of the streets. Still, unfortunately, the city streets do not achieve a sustainable balance in the development of roads and cities.

5.5.3 Level of Service (LOS) evaluation based on traffic discharge analysis

This section analyzes traffic discharge data to assess the Level of Service (LOS) for roadway segments by comparing actual vehicular flow rates to estimated capacities. The results show high LOS (A–C) in certain bridges, tunnels, and low-volume residential streets, where adequate capacity and limited pedestrian interference support smooth flow. Moderate LOS (D–E) appears on streets nearing capacity limits, indicating emerging congestion. Severe LOS (F) dominates in major roundabouts and corridors, with volume-to-capacity ratios exceeding 1.0 sometimes reaching 2.45 reflecting extreme congestion and infrastructure strain. Multi-entry roundabouts perform worst due to complex interactions and limited capacity, while bridges and tunnels generally fare better. These findings highlight the need for targeted measures such as road widening, signal optimization, roundabout redesign, and improved pedestrian management to alleviate critical bottlenecks.

As illustrated in Figure 5.22, the Levels of Service (LOS) for the surveyed streets indicate that approximately 46% of the roads operate at LOS F**,** reflecting severe congestion and poor traffic conditions. LOS C accounts for around 18%, followed by LOS B at 15%**,** LOS D at 6%, and LOS E at 2%. Notably, none of the streets achieved LOS A, indicating that optimal traffic flow is not present on any surveyed roadway. This data highlights that a significant portion of the main streets are experiencing serious traffic congestion, underscoring the urgent need for effective traffic management strategies and infrastructure improvements in the urban road network of Karbala.

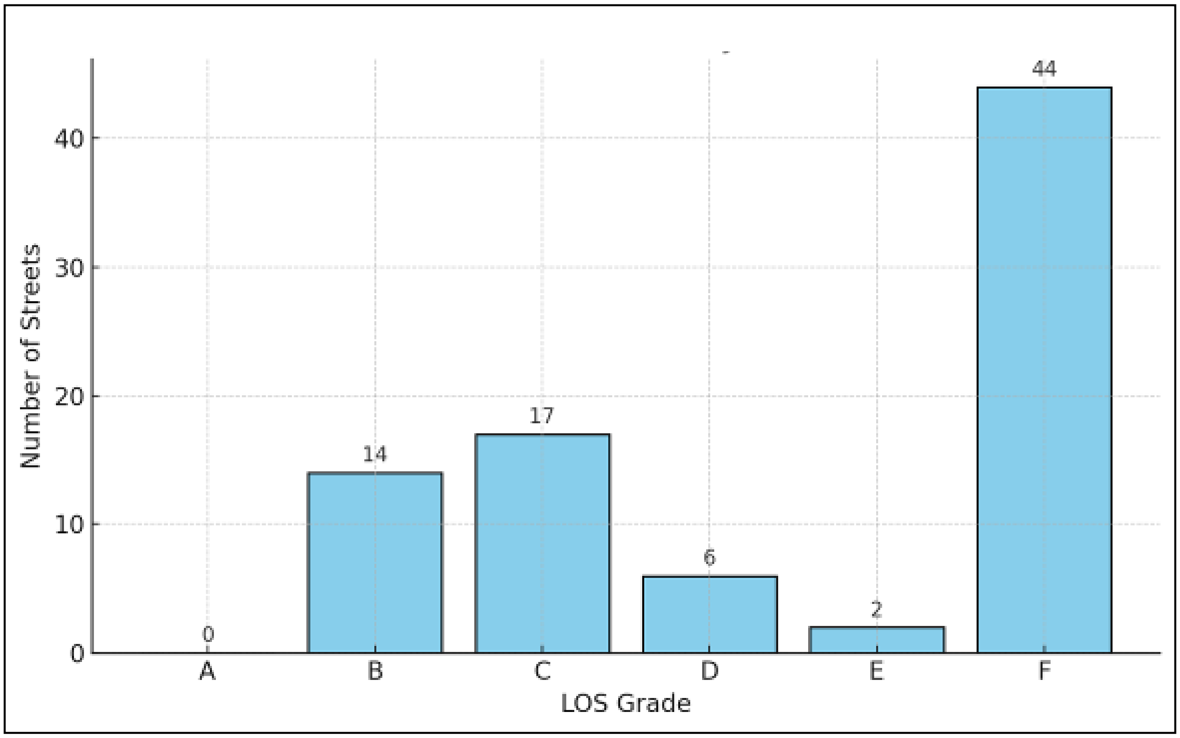


Figure 5.22: LOS distribution in the city of Karbala

5.5.4 PVCI Analysis for Urban Planning

The interaction between pedestrians and vehicles plays a vital role in urban traffic safety and performance. In Karbala, where pedestrian movement is significant due to commercial and religious activity, assessing the Pedestrian-Vehicle Conflict Index (PVCI) offers valuable insights into traffic dynamics. This study investigates conflict levels across the city's main streets, identifying high-risk zones and supporting efforts to improve street design, traffic control, and pedestrian safety.

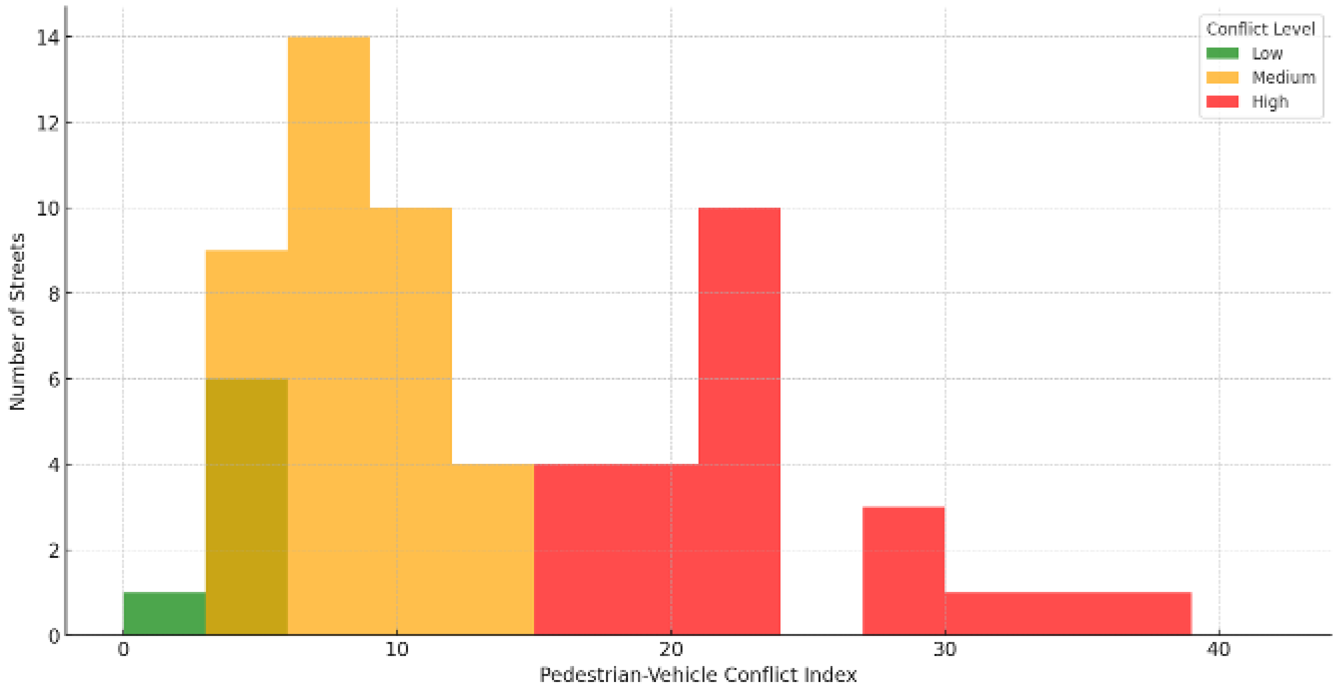


Figure 5.23: Histogram of pedestrian-vehicle conflict index in Karbala by conflict level

Figure 5.23 shows the histogram of the Pedestrian–Vehicle Conflict Index (PVCI) in Karbala, categorized into low, medium, and high conflict levels. Most streets fall within the medium range, indicating frequent pedestrian–vehicle interaction without sufficient safety measures. A notable share is in the high-conflict category, reflecting serious safety risks that require urgent interventions such as protected crossings and traffic calming. Few streets have low conflict, highlighting the need for targeted urban planning to improve pedestrian safety and reduce conflicts.

5.5.5 Analysis of Passenger Energy Consumption Use

Energy consumption in urban road networks is a key indicator of traffic efficiency and environmental impact. It reflects how vehicle movement, passenger flow, and spatial distribution contribute to overall energy demand.

Overall, the analysis revealed significant variation in energy consumption levels across different areas of the city. Some roundabouts and major streets recorded high values, largely due to heavy traffic volumes and high vehicle density. In contrast, areas with lower traffic activity or specialized usage patterns showed considerably lower consumption. The results also suggest that certain main roads intersect multiple zones, leading to repeated high values, while bridges and tunnels generally displayed lower energy usage.

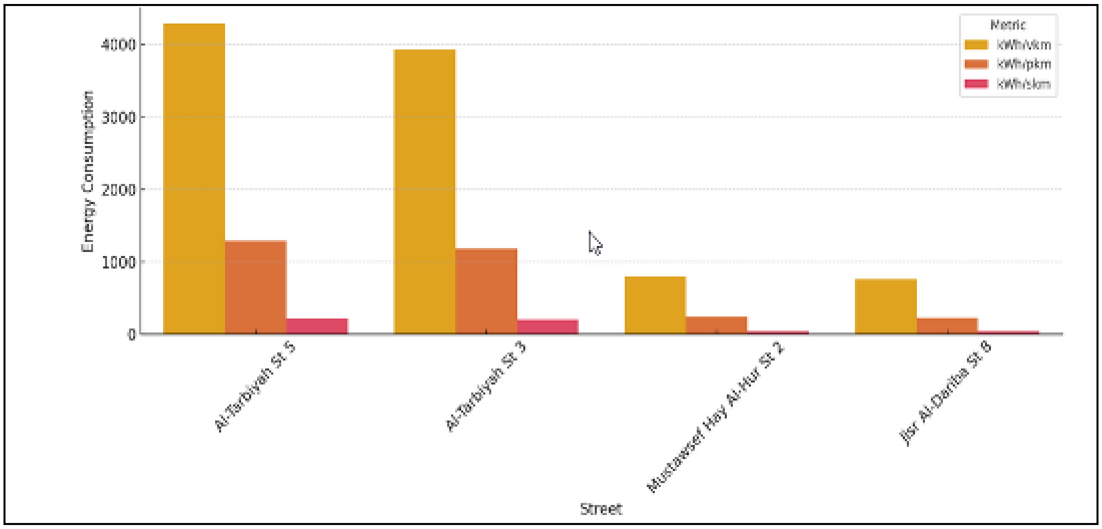


Figure 5.24: Maximum and minimum energy consumption for the road

Figure 5.24 illustrates energy consumption across selected streets at different roundabouts in Karbala, measured in three categories: per vehicle-kilometer (kWh/vkm), per passenger-kilometer (kWh/pkm), and per square kilometer (kWh/skm). Streets linked to the Al-Tarbiyah roundabout exhibit the highest energy consumption across all metrics, especially Street 5 and Street 3, indicating heavy traffic or high vehicle intensity. In contrast, streets like those at Jisr Al-Dariba and Mustawsef Hay Al-Hur show the lowest energy usage, suggesting lower traffic volumes or more efficient vehicle flow. This comparison highlights key differences in traffic dynamics and energy efficiency between various urban intersections.

5.6 Evaluating criteria by the Analytic Hierarchy Process (AHP)

After collecting the three main criteria environmental, social, and economic the remaining sub-criteria for each main criterion were collected. However, these criteria differ in their importance and impact at varying rates. A questionnaire was created, and the weight of each criterion was obtained from (1-9) through a group of experts. These questionnaires are placed in Appendix D. Subsequently, a statistical model, the hierarchical model, as shown in Table 5.10, was created to represent the environmental criterion.

Table 5-6: AHP modelling for environment criteria

Criteria	(1-9)	Air pollution impact(min)	Passenger energy use (min)	Noise pollution impacts(min)	Climate change due to emitted gases	Renewable energy usage(max)	Carbon footprint(min)	Use of natural resources(min)	Use of environmentally friendly modes(max)	Vibration level(min)
Air pollution impact(min)	6	1.00	1.50	1.20	0.67	0.86	0.75	0.86	1.00	1.50
Passenger energy use (min)	4	0.67	1.00	0.80	0.44	0.57	0.50	0.57	0.67	1.00
Noise pollution impacts(min)	5	0.83	1.25	1.00	0.56	0.71	0.63	0.71	0.83	1.25
Climate change due to emitted gases	9	1.50	2.25	1.80	1.00	1.29	1.13	1.29	1.50	2.25
Renewable energy usage(max)	7	1.17	1.75	1.40	0.78	1.00	0.88	1.00	1.17	1.75
Carbon footprint(min)	8	1.33	2.00	1.60	0.89	1.14	1.00	1.14	1.33	2.00
Use of natural resources(min)	7	1.17	1.75	1.40	0.78	1.00	0.88	1.00	1.17	1.75
Use of environmentally friendly modes(max)	6	1.00	1.50	1.20	0.67	0.86	0.75	0.86	1.00	1.50
Vibration level(min)	4	0.67	1.00	0.80	0.44	0.57	0.50	0.57	0.67	1.00

Upon implementing the hierarchical model, the percentage for each criterion was derived, as seen in Table 5.11, which presents the percentage of each environmental criterion. The consistency value was verified and must be below 0.1 explained in Chapter 2.

Table 5-7: A percent and consistency for the environment criteria

Criteria	Percent%	Consistency
Air pollution impact(min)	11.00%	0.11
Passenger energy use (min)	7.14%	0.00
Noise pollution impacts(min)	8.93%	0.02
Climate change due to emitted gases	16.07%	6.13
Renewable energy usage(max)	12.50%	0.50
Carbon footprint(min)	14.29%	1.89
Use of natural resources(min)	12.50%	0.50
Use of environmentally friendly modes(max)	10.71%	0.11
Vibration level(min)	7.14%	0.00
Sum	1.00	1.03
CI=1,RCI=-0.67<0.1		

Table 5.12 illustrates the use of the hierarchical model in allocating the social criterion, including 13 factors.

Table 5-8: AHP modelling for social criteria

Criteria	(1-9)	Protection against accidents(max)	Health impacts(min)	Speed of transportation service (max)	Equity & social inclusion(max)	Traffic clogging(min)	Efficient pricing(max)	Road transportation accidents(min)	Protection against thefts(max)	Ease of reaching central location(max)	Stakeholder participation (max)	Suitability to disabled customers(max)	Private car replacement(max)	Protection against danger and risk(max)
Protection against accidents(max)	9	1.00	1.13	1.80	1.29	2.25	1.80	1.00	1.50	1.50	1.50	1.29	1.50	1.13
Health impacts(min)	8	0.89	1.00	1.60	1.14	2.00	1.60	0.89	1.33	1.33	1.33	1.14	1.33	1.00
Speed of transportation service (max)	5	0.56	0.63	1.00	0.71	1.25	1.00	0.56	0.83	0.83	0.83	0.71	0.83	0.63
Equity & social inclusion(max)	7	0.78	0.88	1.40	1.00	1.75	1.40	0.78	1.17	1.17	1.17	1.00	1.17	0.88
Traffic clogging(min)	4	0.44	0.50	0.80	0.57	1.00	0.80	0.44	0.67	0.67	0.67	0.57	0.67	0.50
Efficient pricing(max)	5	0.56	0.63	1.00	0.71	1.25	1.00	0.56	0.83	0.83	0.83	0.71	0.83	0.63

Road transportation accidents(min)	9	1.00	1.13	1.80	1.29	2.25	1.80	1.00	1.50	1.50	1.50	1.29	1.50	1.13
Protection against thefts(max)	6	0.67	0.75	1.20	0.86	1.50	1.20	0.67	1.00	1.00	1.00	0.86	1.00	0.75
Ease of reaching central location(max)	6	0.67	0.75	1.20	0.86	1.50	1.20	0.67	1.00	1.00	1.00	0.86	1.00	0.75
Stakeholder participation (max)	6	0.67	0.75	1.20	0.86	1.50	1.20	0.67	1.00	1.00	1.00	0.86	1.00	0.75
Suitability to disabled customers(max)	7	0.78	0.88	1.40	1.00	1.75	1.40	0.78	1.17	1.17	1.17	1.00	1.17	0.88
Private car replacement(max)	6	0.67	0.75	1.20	0.86	1.50	1.20	0.67	1.00	1.00	1.00	0.86	1.00	0.75
Protection against danger and risk(max)	8	0.89	1.00	1.60	1.14	2.00	1.60	0.89	1.33	1.33	1.33	1.14	1.33	1.00

Table 5.13 presents the percentage of each social criterion, and the consistency among them has been verified.

Table 5-9: A percentage and consistency for social criteria

Criteria	Percentage%	Consistency
Protection against accidents(max)	10.47%	77.21
Health impacts(min)	9.30%	16.70
Speed of transportation service (max)	5.81%	0.04
Equity & social inclusion(max)	8.14%	2.94
Traffic clogging(min)	4.65%	0.00
Efficient pricing(max)	5.81%	0.04
Road transportation accidents(min)	10.47%	77.21
Protection against thefts(max)	6.98%	0.40
Ease of reaching central location(max)	6.98%	0.40
Stakeholder participation (max)	6.98%	0.40
Suitability to disabled customers(max)	8.14%	2.94
Private car replacement(max)	6.98%	0.40
Protection against danger and risk(max)	9.30%	16.70
Sum	100%	15.03
CI=0.16,RCI=0.074<0.1		

The hierarchical model for the last criterion, the economic criterion, was also developed in Table 5.14. The weights of these criteria were derived from Table 5.15, and the consistency value was validated.

Table 5-10: AHP modelling for economic criteria

Criteria	(1-9)	Cost of operating a transportation mode (min)	System economic efficiency (max)	Profit for the transportation operator (max)	Operator productivity (max)	The cost incurred by not serving on time (min)	Project viability (max)	System reliability (max)	Speed and ease of service (max)	System independence (max)	Transportation intensity (max)	A positive attitude toward transportation (max)
Cost of operating a transportation mode (min)	9	1.00	1.13	1.13	1.29	1.29	1.50	1.50	1.70	1.70	2.00	2.50
System economic efficiency (max)	8	0.89	1.00	1.00	1.14	1.14	1.33	1.33	1.60	1.60	2.00	2.67
Profit for the transportation operator (max)	8	0.89	1.00	1.00	1.14	1.14	1.33	1.33	1.60	1.60	2.00	2.67
Operator productivity (max)	7	0.78	0.88	0.88	1.00	1.00	1.17	1.17	1.40	1.40	1.75	2.33
The cost incurred by not serving on time (min)	7	0.78	0.88	0.88	1.00	1.00	1.17	1.17	1.40	1.40	1.75	2.33
Project viability (max)	6	0.67	0.75	0.75	0.86	0.86	1.00	1.00	1.20	1.20	1.50	2.00
System reliability (max)	6	0.67	0.75	0.75	0.86	0.86	1.00	1.00	1.20	1.20	1.50	2.00
Speed and ease of service (max)	5	0.56	0.63	0.63	0.71	0.71	0.83	0.83	1.00	1.00	1.25	1.67
System independence (max)	5	0.56	0.63	0.63	0.71	0.71	0.83	0.83	1.00	1.00	1.25	1.67
Transportation intensity (max)	4	0.44	0.50	0.50	0.57	0.57	0.67	0.67	0.80	0.80	1.00	1.33
A positive attitude toward transportation (max)	3	0.33	0.38	0.38	0.43	0.43	0.50	0.50	0.60	0.60	0.75	1.00

Table 5-11: A percentage and consistency for economic criteria

Criteria	Percentage%	Consistency
Cost of operating a transportation mode (min)	12.81%	68.02
System economic efficiency (max)	11.82%	28.18
Profit for the transportation operator (max)	11.82%	28.18
Operator productivity (max)	10.34%	6.49
The cost incurred by not serving on time (min)	10.34%	6.49
Project viability (max)	8.87%	1.19
System reliability (max)	8.87%	1.19

Speed and ease of service (max)	7.39%	0.16
System independence (max)	7.39%	0.16
Transportation intensity (max)	5.91%	0.01
A positive attitude toward transportation (max)	4.43%	0.00
Sum	100.00%	12.73
CI=0.17,RCI=0.091<0.1		

After figuring out the sub-criteria for the main criteria in the tables above, the weights were also shared among the basic criteria, which vary in importance; the environmental criterion is seen as the most important, followed by the social criterion, and lastly, the economic criterion, based on the questionnaire in Appendix D. Consistency was also confirmed in how the percentages for these criteria were distributed. Also, consistency was confirmed between the distribution of percentages for these criteria.

Table 5-12: AHP modeling for three main criteria with a percentage

Dimension	(1-9)	Environmental	Social	Economic	A percentage	Consistency
Environmental	8	1	1.7	2.2	48.95%	3.74
Social	6	0.588235	1	1.3	28.84%	0.76
Economic	5	0.454545	0.769231	1	22.22%	0.35
Sum					100.00%	1.62
	CI=0.11, RCI=0.1=0.1					

After the weights are obtained, they will be used to determine the value and importance of each criterion.

5.7 Evaluated fuzzy logic for the criteria

Fuzzy logic will be used to interpret each sustainability criterion as a value with a higher and lower limit. It shall analyze each criterion based on its indications. The top values will be minimal if the criterion suggests lower values that should not be surpassed. Higher numbers will be viewed as small values and lower values as large values, and vice versa, depending on the magnitude of the reality outcome of this criterion. The fuzzy logic formulations for each criterion are listed in Table 5.17.

Table 5-13: Fuzzy logic values for each criterion

	Criterion	Objective	Low	Medium	High
environment	Air pollution impact	Minimize	0.6-1	0.3 - 0.6	0-0.3
	Passenger energy use	Minimize	0.5-1	0.2 - 0.5	0-0.2
	Noise pollution impacts	Minimize	0.7-1	0.4 - 0.7	0-0.4
	Climate change due to	Minimize	0.6-1	0.3 - 0.6	0-0.3
	Emitted gas	Minimize	0.55-1	0.25 - 0.55	0-0.25
	Renewable energy usage	Maximize	0 - 0.4	0.4 - 0.7	0.7 - 1
	Carbon footprint	Minimize	0.6-1	0.3 - 0.6	0-0.3
	Use of natural resources	Minimize	0.6-1	0.3 - 0.6	0-0.2
	Use of environmentally friendly modes	Maximize	0 - 0.4	0.4 - 0.7	0.7 - 1
	Vibration level	Minimize	0.5-1	0.2 - 0.5	0-0.2
	Criterion	**Objective**	**Low**	**Medium**	**High**
social	Protection against accidents	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Health impacts	Minimize	0.5-1	0.2 - 0.5	0-0.2
	Speed of transportation service	Maximize	0 - 0.4	0.4 - 0.7	0.7 - 1
	Equity & social inclusion	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Traffic clogging	Minimize	0.5-1	0.2 - 0.5	0-0.2
	Efficient pricing	Maximize	0 - 0.4	0.4 - 0.7	0.7 - 1
	Road transportation accidents	Minimize	0.5-1	0.2 - 0.5	0-0.2
	Protection against thieves	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Ease of reaching the central location	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Stakeholder participation	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Suitability for disabled customers	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Private car replacement	Maximize	0 - 0.4	0.4 - 0.7	0.7 - 1
	Protection against danger and risk	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Criterion	**Objective**	**Low**	**Medium**	**High**
economic	Cost of operating a transportation mode	Minimize	0.6-1	0.3 - 0.6	0-0.3
	Transportation intensity	Maximize	0 - 0.4	0.4 - 0.7	0.7 - 1
	Profit for the transportation operator	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Speed and ease of service	Maximize	0 - 0.4	0.4 - 0.7	0.7 - 1
	System economic	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1

	Criterion	Objective	Low	Medium	High
	efficiency				
	A positive attitude toward transportation means	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	System independence	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	System reliability	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Project viability	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	Operator productivity	Maximize	0 - 0.3	0.3 - 0.6	0.6 - 1
	The cost incurred by not serving on time	Minimize	0.5-1	0.2 - 0.5	0-0.2

5.8 Evaluating sustainable indicators for the road

After collecting the data, information about sustainability indicators was obtained. Different rates of achievement were found for all sustainability indicators. However, in general, the achievement rates in Karbala are almost non-existent. Some indicators are present in small quantities. Researchers must not have considered them. Despite the weakness of these indicators, a small percentage has been achieved. However, in most cases, these rates are nonexistent compared to the rest of the indicators.

Table 5-14: Evaluating sustainable indicators for road

Dimension	objective	Criterion	Indicator	Fuzzy logic	Note
Environmental	Air pollution impact(min)	Air pollution	Air pollution from transportation (	High (0.2)	The percentage of the gas from good to hazardous for all streets, according to AQI(EPA), must be less than 400ppm; in Tarbiya, 597ppm, Table D-1
	Passenger energy use (min)	Energy consumption	The ratio of passenger-km to respective	Medium (0.45)	Related to the flow max 1287 in Al-Tarbiya,

Dimension	objective	Criterion	Indicator	Fuzzy logic	Note
			energy consumption(max)		less than the limit 2496 **(IEA, DOE)** Table D-3
	Noise pollution impacts(min)	Noise	Noise pollution [dB levels]	High (0.15)	which exceeds the CPCB standards, the EPA, and the WHO recommendations max(70dB) in Tarbiya 107 from Table 4.27, Table D-4
	Climate change due to Emitted gas	GHG emissions	Emission intensity of GHG [CO2 eq/pkm]	Medium (0.6)	Based on the data gathered and compared to the minimum limits, Iraq (Karbala) does not present a greenhouse gas threat. Refer to Appendix D. Table D-5, D-6, D-7
	Renewable energy usage(max)	Renewable energy	Share of renewables in overall energy consumption [%]	Low (0.09)	The percentage of this criterion is so little (0.5-1.5) %(IRENA>**29 %),** Table D-8
	Carbon footprint(min)	CO2 emissions	CO2 emission from fossil fuel consumption [ton/person CO2]	High (0.25)	In Iraq, 4 tons/person Exceed 2 tons/person according to the global carbon budget principle, Table D-10
	Use of natural resources(min)	Natural resource consumptio	Degree of depletion of natural	High (0.1)	According to **General sustainability**

Dimension	**objective**	**Criterion**	**Indicator**	**Fuzzy logic**	**Note**
		n	resources [%]		**literature, not exceeding 100% in Iraq = 470%** Table D-11
	Use of environmentally friendly modes(max)	Non-motorized modes	Share of non-motorized trips in overall trips [%]	**Low (0.1)**	In Karbala, the rate is 20%, according to World Bank Urban Mobility Guidelines (20-35)%, which is considered **moderate.** Table D-13
	Vibration level(min)	Vibration	Vibration level [Hz]	High (0.2)	According to the study record, 100 Hz exceeds the limit in Appendix D (80Hz), Table D-15
Social	Protection against accidents(min)	Safety	The ratio of injured people to Km traveled per mode (per day) (min)	High (0.1)	1.3 accidents per million km in Karbala exceed the Global Safety Standards of 0.5 to 1 injury per million kilometers. Table D-20, D-21
	Health impacts(min)	Health	Injury severity level [-]	Medium (0.4)	The approximate average ISS score for all cases in Karbala (2023) is ≈ 10-12 **Consider Moderate Injuries: ISS 9–15,** Table D-23

Dimension	**objective**	**Criterion**	**Indicator**	**Fuzzy logic**	**Note**
	Speed of transportation service (max)	Travel time	Average speed in city[km/h]	Medium (0.5)	**Karbala's average transportation speed is within this range, ranging from 30 to 40 km/h. Moderate Speed Speed: Ranges from 20 to 50 km/h,** Table D-26
	Equity & social inclusion(max)	Accessibility	Mental accessibility [-]	Low (0.15)	**Mental accessibility in Karbala (less than 50%) CRPD WHO ADA,** Table D-28
	Traffic clogging(min)	Congestion	Time spent traveling under congested conditions [minutes]	Medium (0.4)	Related to congestion-related LOS Travel Time Index (TTI) and Planning Time Index (PTI), Table D-29
	Efficient pricing(max)	Affordability	The ratio of user cost for transportation to household income [%] (min)	Medium (0.59)	Questionnaires for experiment **(0.59)**
	Road transportation accidents(min)	Accidents	Accident rate from traffic, including injuries and fatalities [-]	High (0.05)	100,000 population, 44 accidents annually in Karbala

Dimension	**objective**	**Criterion**	**Indicator**	**Fuzzy logic**	**Note**
					According to (WHO (15 per 100,000 population in 2021, Table D-30
	Protection against thefts(max)	Security	Share of the population feeling safe against thefts & violation [%]	Medium (0.47)	Questionnaires for experiment (**0.47)**
	Ease of reaching central location(max)	Reachability	Time to get to next transportation mode [minutes] (min)	High (0.71)	Questionnaires for experiment (**0.71)**
	Stakeholder participation (max)	Participation	Share of steps with public involvement in transportation planning in all steps [%]	Medium (0.59)	Questionnaires for experiment (**0.59)**
	Suitability to disabled customers(max)	Equality	Share of citizens with physical access to overall citizens [%]	Medium (0.54)	Questionnaires for experiment (**0.54)**
	Private car replacement(max)	Fewer private cars	Number of private cars replaced [-]	Low (0.04)	Currently, there are no strategies in Karbala to replace private transportation with public transportation. Table D-32
	Protection against danger and risk(max)	Risk and danger	Perceived risks and danger [-] (min)	Medium (0.5)	There is a degree of protection from street risks, such as setting annual security plans for the Arbaeen pilgrimage. Table D-32
Economic	Cost of operating a transportation	Operation cost	Operational, maintenance,	Medium (0.59)	Questionnaires for experiment

Dimension	**objective**	**Criterion**	**Indicator**	**Fuzzy logic**	**Note**
	made(min)		and fuel costs [Dinar Iraqi]		(**0.59)**
	Transportation intensity(max)	Occupancy	Overall system capacity utilization rate [%]	Medium (0.59)	Questionnaires for experiment (**0.59)**
	Profit for the transportation operator(max)	Revenues	The ratio of revenues to cost (investment or operational) [%]	Medium (0.5)	Questionnaires for experiment (**0.5)**
	Speed and ease of service(max)	Quality	The time needed to handle customer complaints queries [day] (min)	Medium (0.6)	Questionnaires for experiment (**0.6)**
	System economic efficiency(max)	Investment cost	Capital cost [Dinar Iraqi] (min)	Medium (0.59)	Questionnaires for experiment (**0.59)**
	A positive attitude toward transportation means(max)	Demand	Number of (potential) users	High (0.71)	Questionnaires for experiment (**0.71)**
	System independence(max)	Subsidy	The sum of public expenditures, investment, and subsidies [Dinar Iraqi] (min)	Medium (0.54)	Questionnaires for experiment (**0.54)**
	System reliability(max)	Reliability	Availability of transportation mode (on time) [%]	Low(0.04)	It depends on public transportation and the public transportation networks dedicated to the city. In Karbala, public transportation accounts for only 15%, whereas the international standard requires more than 95%, as

Dimension	**objective**	**Criterion**	**Indicator**	**Fuzzy logic**	**Note**
					outlined in the ISO 9001 system. Table D-32
	Project viability(max)	Technical feasibility	The ratio of benefit to risk [-]	High (0.74)	Questionnaires for experiment (**0.74**)
	Operator productivity (max)	Productivity	The ratio of output (users served) to input (paid labor hours) [-]	High (0.71)	Questionnaires for experiment (**0.71**)
	The cost incurred by not serving on time(min)	Cost of delay	Opportunity cost for potential customers not served [Dinar Iraqi]	Low (0.5)	Questionnaires for experiment (**0.5**)

The fuzzy logic theory was used to determine the criteria's value after each criterion's weight was determined from Table 5.18; however, as previously mentioned, the weights of the criteria were determined by an Analytical Hierarchy Process (AHP). The criteria's final weight was determined and will be compared to worldwide systems to determine whether or not Karbala's streets are sustainable.

Table 5-15: Determining the final weight of the criterion

Dimension	Percentage of dimension %(A1)	Criterion	Fuzzy number (A2)	Percentage of criterion%(A3)	Weight of criterion(A1XA2XA3)
Environmental	48.95%	Air pollution	0.2	11.00%	0.0108
		Energy consumption	0.45	7.14%	0.0157
		Noise	0.15	8.93%	0.0066
		GHG emissions	0.6	16.07%	0.0472
		Renewable energy	0.09	12.50%	0.0055
		CO2 emissions	0.25	14.29%	0.0175

		Natural resource consumption	0.1	12.50%	0.0061
		Non-motorized modes	0.4	10.71%	0.0210
		Vibration	0.02	7.14%	0.0007
Social	28.84%	Safety	0.6	10.47%	0.0181
		Health	0.4	9.30%	0.0107
		Travel time	0.5	5.81%	0.0084
		Accessibility	0.15	8.14%	0.0035
		Congestion	0.4	4.65%	0.0054
		Affordability	0.59	5.81%	0.0099
		Accidents	0.05	10.47%	0.0015
		Security	0.47	6.98%	0.0095
		Reachability	0.71	6.98%	0.0143
		Participation	0.59	6.98%	0.0119
		Equality	0.54	8.14%	0.0127
		Fewer private cars	0.04	6.98%	0.0008
		Risk and danger	0.5	9.30%	0.0134
Economic	22.22%	Operation cost	0.59	12.81%	0.0168
		Occupancy	0.59	11.82%	0.0155
		Revenues	0.6	11.82%	0.0158
		Quality	0.5	10.34%	0.0115
		Investment cost	0.6	10.34%	0.0138
		Demand	0.71	8.87%	0.0140
		Subsidy	0.54	8.87%	0.0106
		Reliability	0.04	7.39%	0.0007
		Technical feasibility	0.74	7.39%	0.0122
		Productivity	0.71	5.91%	0.0093
		Cost of delay	0.5	4.43%	0.0049
The total percentage of sustainability					38%

The final ratio of the sustainability criteria, as shown in Table 5.19, was obtained by multiplying all of the ratios for the sustainability criteria that were calculated in Table 5.18. Additionally, this procedure was carried out for every site from which data was gathered(Appendix C), as indicated in Table 5.20, which lists the study regions along with their sustainability ratio.

Table 5-16: Evaluating sustainable indicators for all roads

No	Name of position	sustainability criteria%	LEED	BREEAM Communities	Green Star	CASBEE for Urban Development	GSAS – Urbanism
1	Roundabout of AL-Tarbiyah	38%	failed	pass	failed	failed	failed
2	Roundabout of Alsafina	39%	failed	pass	failed	failed	failed
3	Roundabout of Al-Jameia	39%	failed	pass	failed	failed	failed
4	Roundabout of Al-Mualimin	39%	failed	pass	failed	failed	failed
5	Roundabout of Mustawsaf	37%	failed	pass	failed	failed	failed
6	Roundabout of Al-Mulhak	36%	failed	pass	failed	failed	failed
7	Roundabout of Amel Alnazafa	35%	failed	pass	failed	failed	failed
8	Roundabout of Al-Baladia	37%	failed	pass	failed	failed	failed
9	Roundabout	34%	failed	pass	failed	failed	failed

	of Al-Muhafadha						
10	Roundabout of Qantarat Alsalam	33%	failed	pass	failed	failed	failed
11	Intersection of Fatimat Al-Zahraa	38%	failed	pass	failed	failed	failed
12	Intersection of Al-Abbas	38%	failed	pass	failed	failed	failed
13	Roundabout of Al-Thawra	32%	failed	pass	failed	failed	failed
14	Roundabout of Hay Ramadan	35%	failed	pass	failed	failed	failed
15	Roundabout of Tariq Alhure	31%	failed	pass	failed	failed	failed
16	Roundabout of Al-Kawthar	29%	failed	failed	failed	failed	failed
17	Intersection of Al-Emam Ali	35%	failed	pass	failed	failed	failed
18	Roundabout of Al-Gader	29%	failed	failed	failed	failed	failed

Table 5.20: The UK's BREEAM system received a passing grade out of the five global systems (LEED, BREEAM, Communities Green Star, CASBEE for Urban Development, and GSAS – Urbanism). A sustainability rating of greater than 30 % is deemed passing. According to the data gathered and examined, this indicates that the city's roadways passed none of the systems.

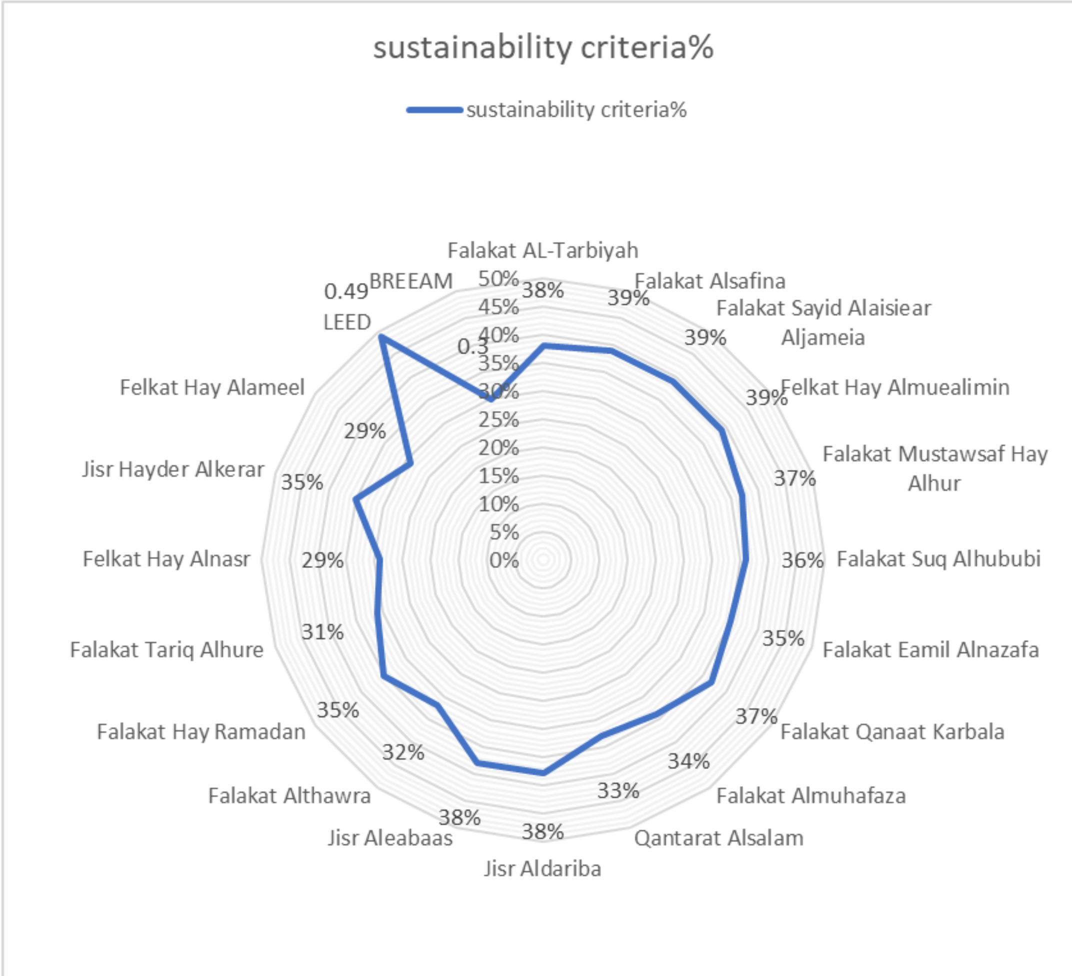


Figure 5.25: Percentage of sustainability criteria inroads

. Figure 5.25 illustrates the distribution of percentages related to the attainment of sustainability standards based on the points analyzed in the study and their subsequent further examination.

5.9 Urban road sustainability comparison: Karbala and global cities

Understanding how Karbala's urban road network performs in terms of sustainability requires benchmarking it against global standards. Figure 5.45 presents a comparative overview with selected leading cities, revealing critical gaps and opportunities for policy enhancement.

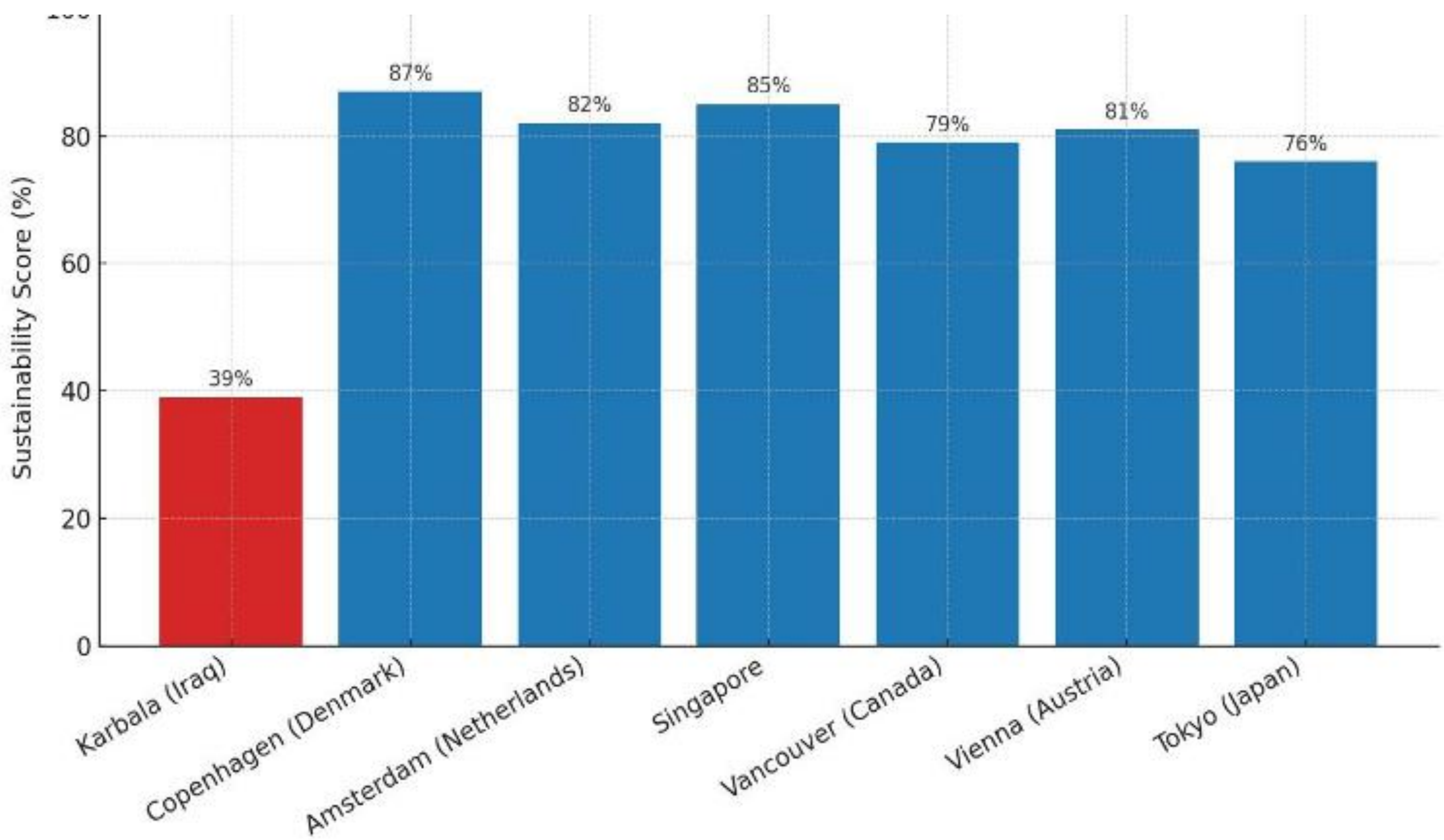


Figure 5.26: Urban road sustainability comparison

Figure 5.26 presents a comparative analysis of urban road sustainability between Karbala (Iraq) and several globally recognized cities. Karbala records a sustainability score of only 39%, highlighting a substantial disparity when compared to leading international cities. For instance, Copenhagen achieves the highest score at 87% (OECD, 2022), followed by Singapore at 85% (World Bank, 2023), Amsterdam at 82% (European Commission, 2021), Vienna at 81% (UITP, 2022), Vancouver at 79% (UN-Habitat, 2023), and Tokyo at 76% (JST, 2021). These Figures reflect the effectiveness of sustainable transport strategies and integrated urban planning adopted by these cities. In contrast, the significantly lower score of Karbala underscores systemic challenges such as heavy reliance on private vehicles, underdeveloped cycling and pedestrian infrastructure, and a lack of regulatory frameworks promoting sustainable mobility. This comparison provides not only a benchmark for evaluating Karbala's current status but also a strategic foundation for implementing urban policies aligned with international sustainability standards.

5.10 Modelling of the Road

Modeling roads within a GIS framework** follows four main stages: data acquisition, processing, spatial analysis, and visualization. Data are collected from satellite imagery, aerial photos, GPS, and surveys, stored in vector or raster formats. Processing includes error correction and dataset integration. Spatial analysis applies methods such as buffering (proximity), overlay (layer relationships), network analysis (connectivity and flow), and surface analysis (terrain features). These support environmental and urban models for assessing ecological impacts, transportation, and infrastructure planning. Finally, visualization through maps, graphs, and 3D models communicates results effectively, aiding road design, planning, and management.

5.10.1 Distribution of gas emissions

A GIS-based spatial model was applied using the Kernel Density tool to transform gas measurement points into a continuous density surface. Results indicated that intersections recorded the highest gas concentrations, largely due to congestion and vehicle idling, while mid-street segments showed lower levels. Some roadways with elevated drainage exhibited unexpectedly high densities, likely influenced by topographic and microclimatic conditions. Distinct spatial patterns were also observed for

CO, NO_2, and SO_2, reflecting variations in traffic intensity and land use, with Figures (5.28–5.40) illustrating the critical hotspots for mitigation.

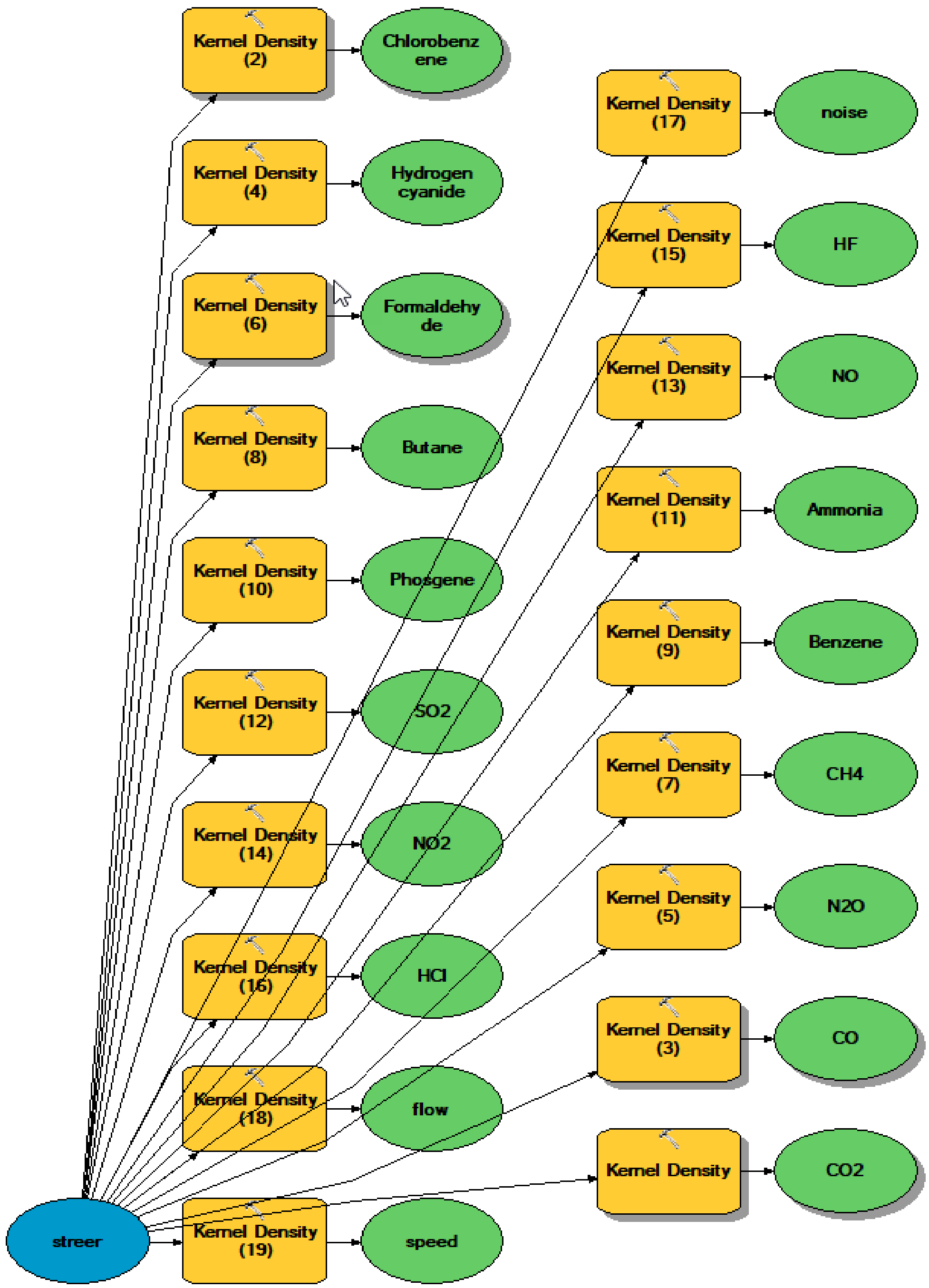


Figure 5.27: Model in GIS of the distribution of the density of gas emission

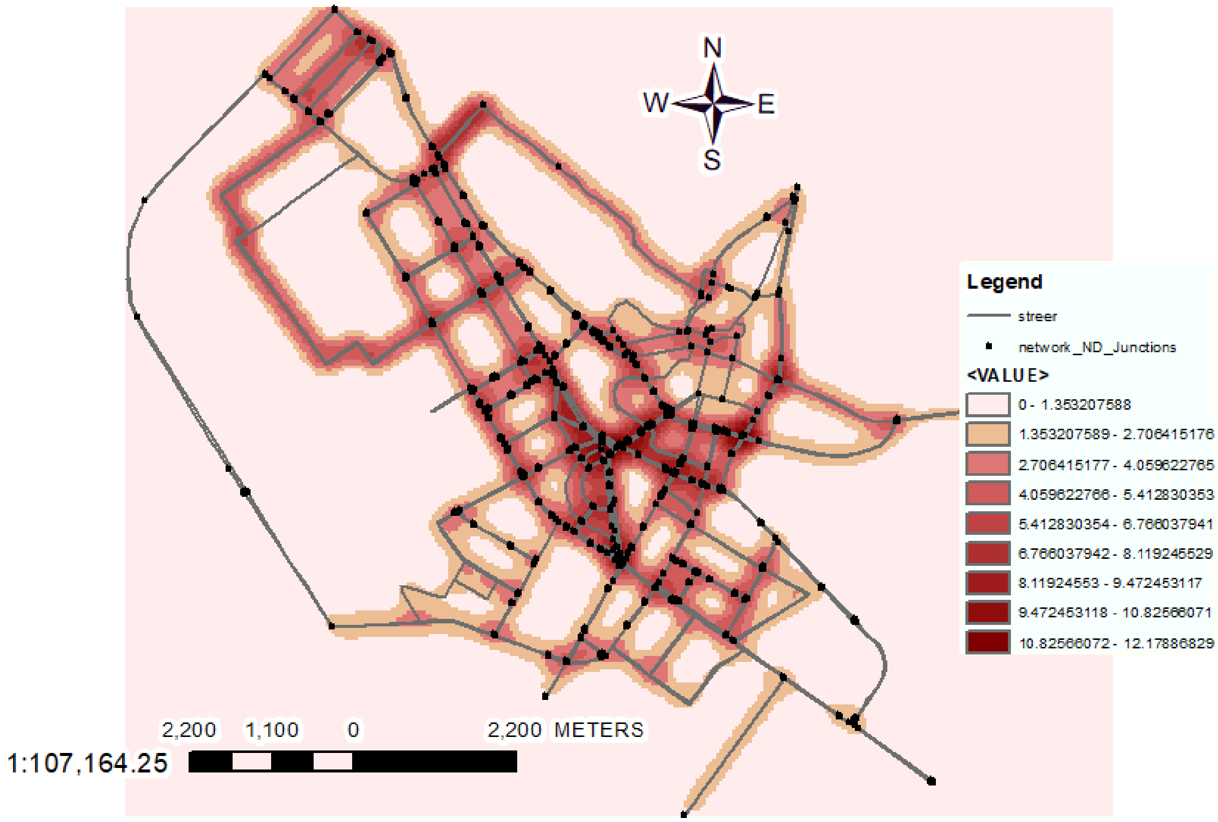


Figure 5.28: Carbon Dioxide (CO_2) Concentration in Karbala streets

Figure 5.28 illustrates the spatial distribution of CO_2 gas emissions across the street network of Karbala city. The map uses a color gradient to represent emission intensity, with lighter shades indicating low CO_2 levels and darker red to brown tones signifying higher concentrations. The highest emissions are concentrated in the central areas of the city, likely corresponding to zones with heavy traffic, major intersections, and commercial activities. The black lines represent the street network, while the black dots denote junction points. This spatial analysis is useful for identifying pollution hotspots and can support urban planning decisions aimed at reducing vehicular emissions and improving air quality.

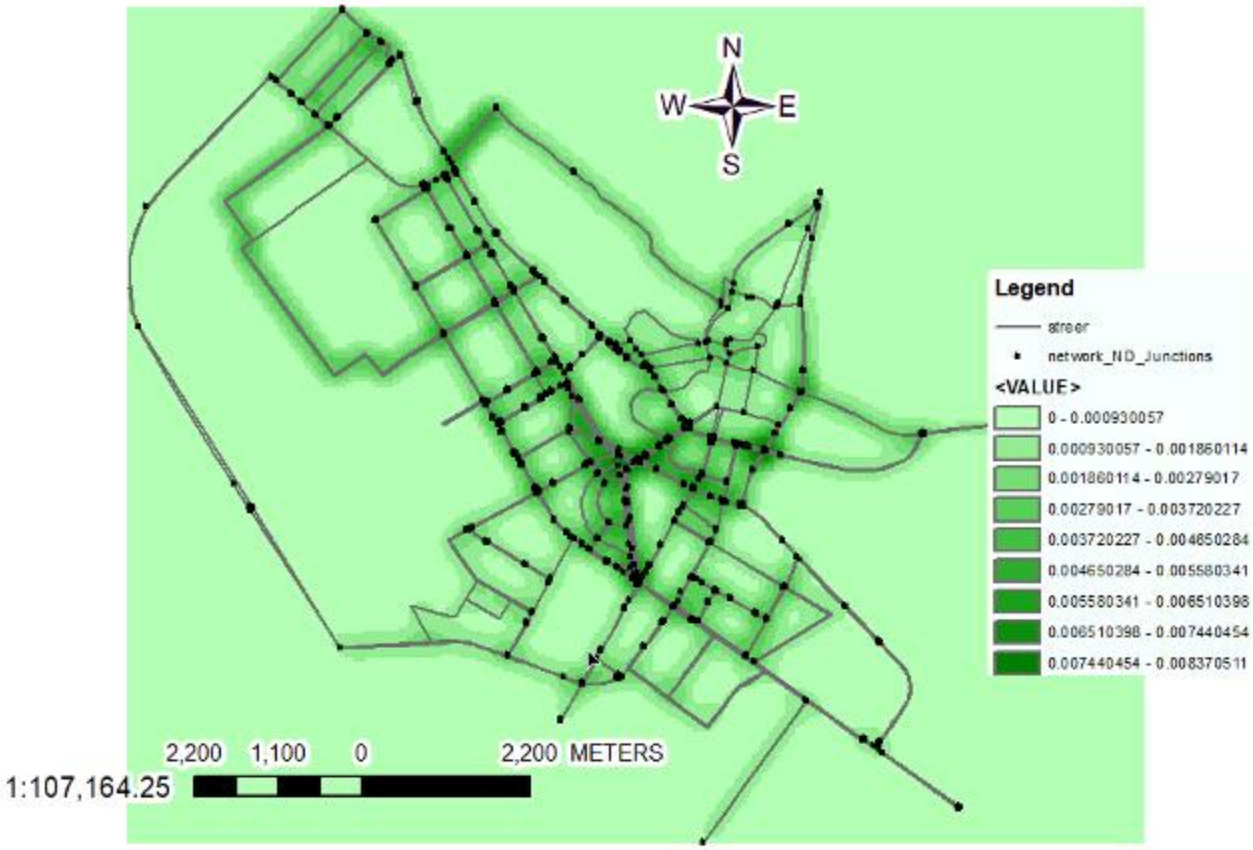


Figure 5.29 : Butane gas Concentration in Karbala streets

Figure 5.29 illustrates the spatial distribution of butane gas concentrations across the street network of Karbala city using GIS software. The map employs a range of green shades to represent varying levels of butane presence, where lighter tones indicate lower concentrations and darker green tones signify higher levels. The black dashed lines denote the street network, while the black dots indicate junction points. The concentration patterns suggest that certain areas, especially toward the central and northeastern parts, exhibit higher levels of butane, possibly due to increased activity or infrastructure. This analysis provides valuable insights for urban environmental management and public safety planning.

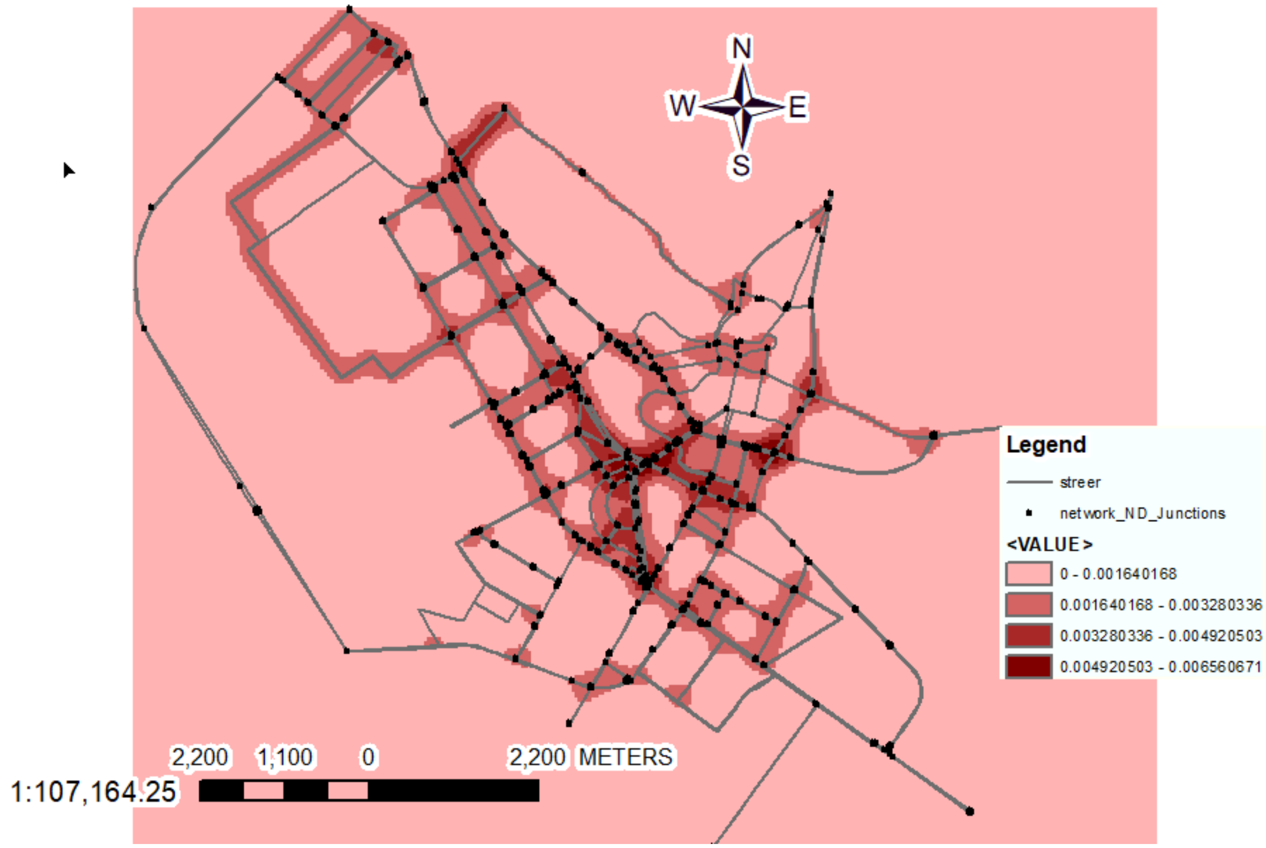


Figure 5.30: Formaldehyde gas Concentration in Karbala streets

Figure 5.30 presents the spatial distribution of formaldehyde gas concentrations across the street network of Karbala, generated using GIS software. Formaldehyde is a toxic and volatile organic compound (VOC) commonly released from vehicle emissions, industrial processes, and combustion activities. It poses significant health risks, including eye, nose, and throat irritation, respiratory issues, and is classified as a human carcinogen with prolonged exposure. The map highlights areas with elevated formaldehyde levels, particularly in zones with dense traffic or limited ventilation. This spatial analysis is essential for identifying pollution hotspots and informing strategies to mitigate exposure and enhance urban air quality.

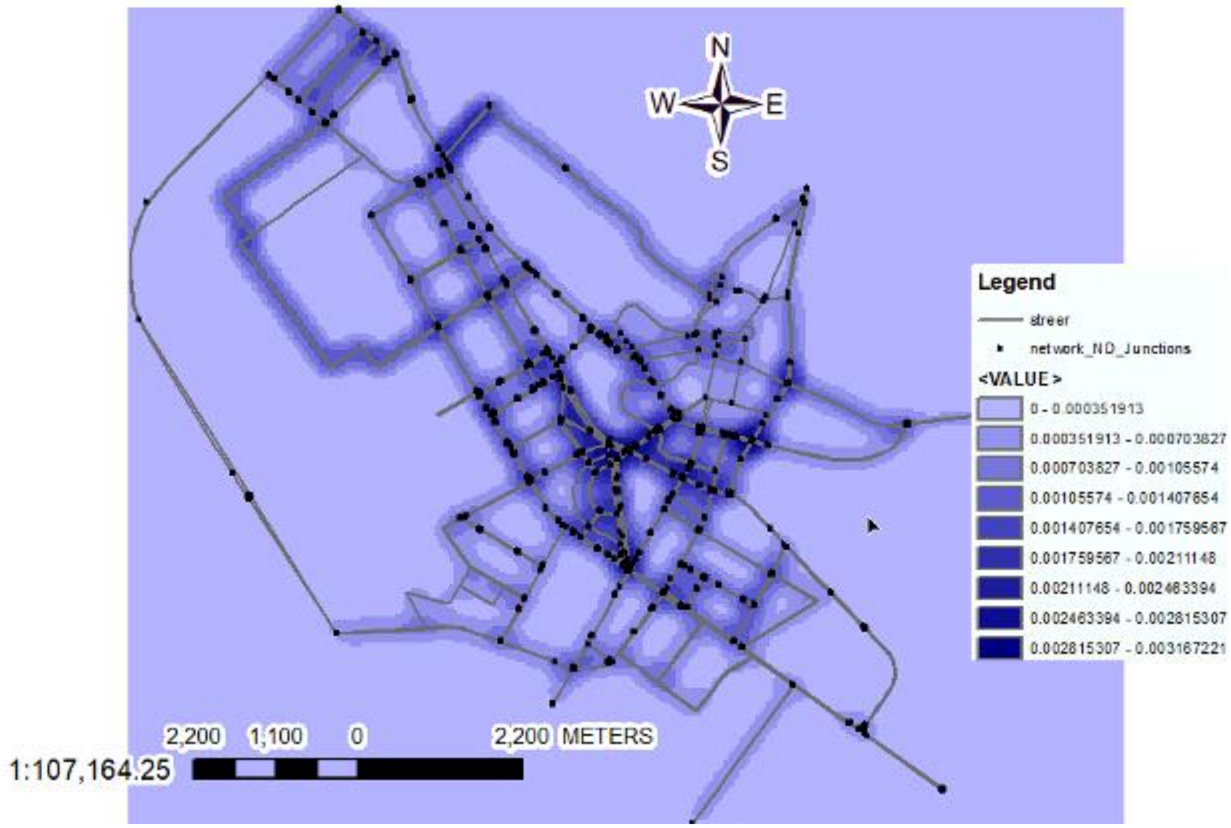


Figure 5.31: Phosgene gas Concentration in Karbala streets

Figure 5.31 shows the spatial distribution of phosgene gas concentrations across the street network of Karbala, based on GIS analysis. Phosgene is a highly toxic and colorless gas that was historically used as a chemical weapon and can be released from industrial processes or the combustion of certain chlorinated compounds. Even at low concentrations, phosgene can cause serious respiratory damage, including coughing, chest tightness, and delayed pulmonary edema, making it extremely hazardous to human health. The map reveals specific urban zones where phosgene levels are elevated, possibly due to traffic emissions or nearby industrial activities. This data is crucial for environmental monitoring, emergency response planning, and protecting public health.

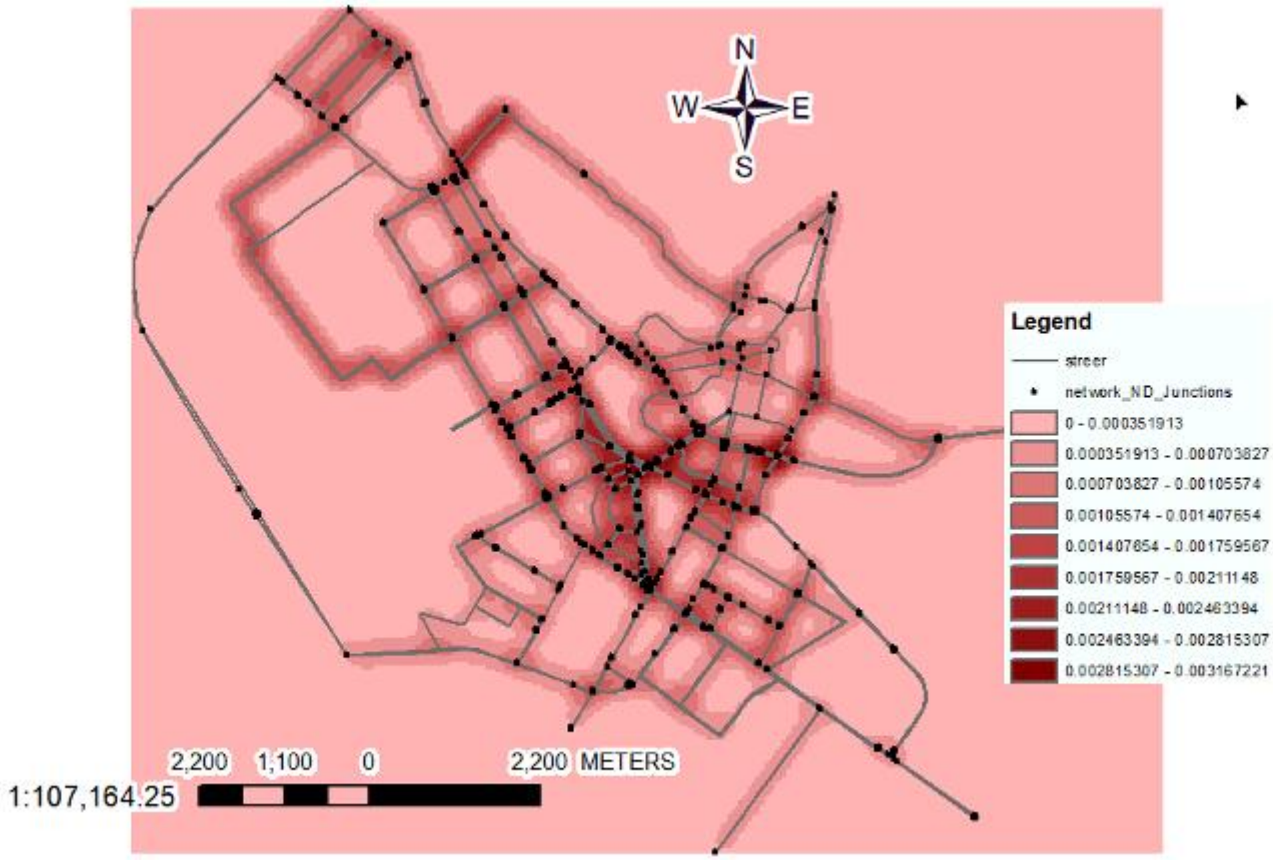


Figure 5.32: SO2 gas Concentration in Karbala streets

Figure 5.32 illustrates the spatial distribution of sulfur dioxide (SO_2) gas concentrations across the street network of Karbala, as mapped using GIS tools. SO_2 is a harmful air pollutant primarily produced by the combustion of fossil fuels in vehicles and industrial activities. Exposure to sulfur dioxide can irritate the eyes, nose, and throat, and can severely affect the respiratory system, especially in children and individuals with asthma. High concentrations of SO_2 can also contribute to the formation of acid rain, which damages buildings, vegetation, and water sources. The GIS map identifies areas with elevated SO_2 levels, highlighting zones that may require air quality management and pollution control measures.

Figure 5.33: HCL gas Concentration in Karbala streets

Figure 5.33 presents the spatial distribution of hydrogen chloride (HCl) gas concentrations across the streets of Karbala, derived using GIS software. HCl is a corrosive and highly irritating gas that can be released from industrial emissions, combustion of plastics, or chemical processes. Inhalation of HCl vapors can cause severe irritation of the respiratory tract, coughing, choking, and even chemical burns to the eyes, nose, and throat. Prolonged or high-level exposure may lead to long-term lung damage. The map highlights zones with elevated concentrations, potentially linked to traffic congestion or nearby sources of industrial waste. This data is critical for assessing environmental risks and developing strategies for air pollution control and public health protection.

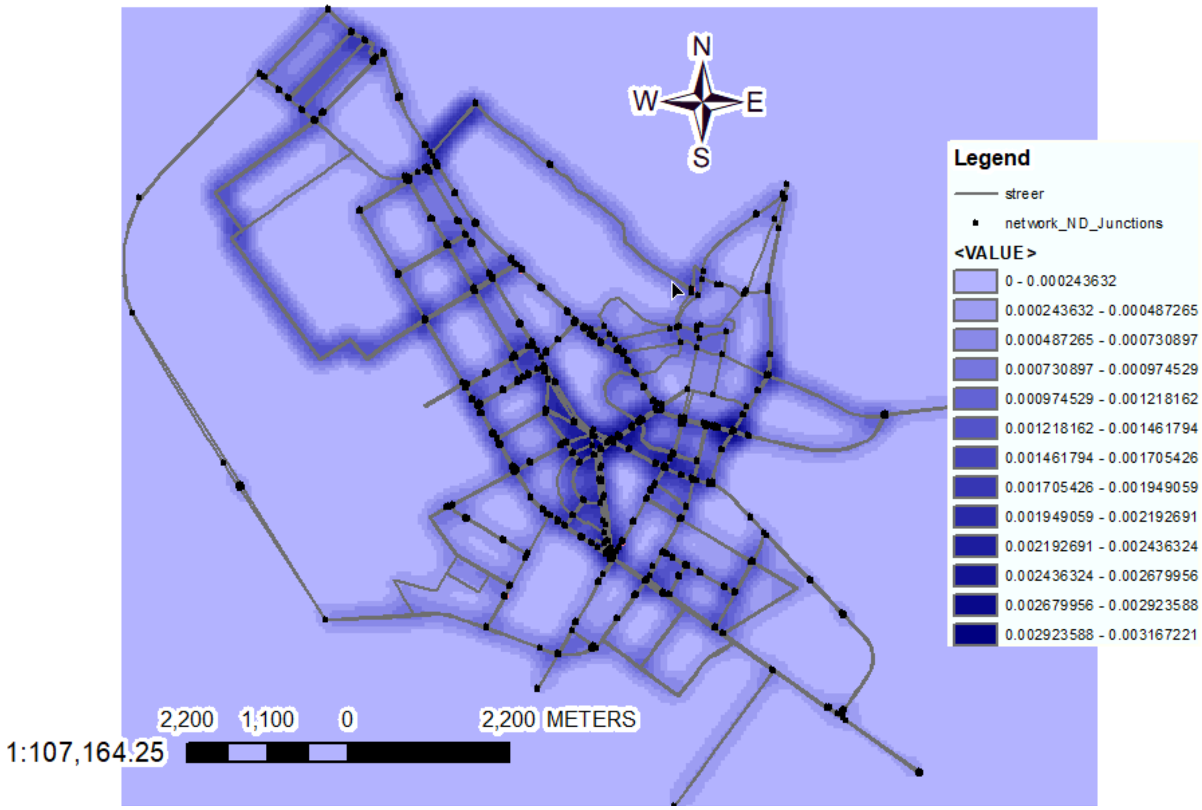


Figure 5.34: HF gas Concentration in Karbala streets

Figure 5.34 displays the spatial distribution of hydrogen fluoride (HF) gas concentrations in the streets of Karbala, based on GIS mapping.HF is an extremely toxic and corrosive gas that poses serious health risks even at low concentrations. Exposure to hydrogen fluoride can cause severe irritation of the eyes, skin, and respiratory system, and in high doses, it can lead to deep tissue damage, bone deterioration, and life-threatening systemic toxicity. Due to its ability to penetrate tissues deeply, HF is considered one of the most dangerous industrial chemicals. The GIS map identifies areas with detectable HF concentrations, indicating potential sources such as vehicular emissions or improper waste combustion. This information is vital for environmental monitoring, emergency planning, and ensuring public safety in urban spaces.

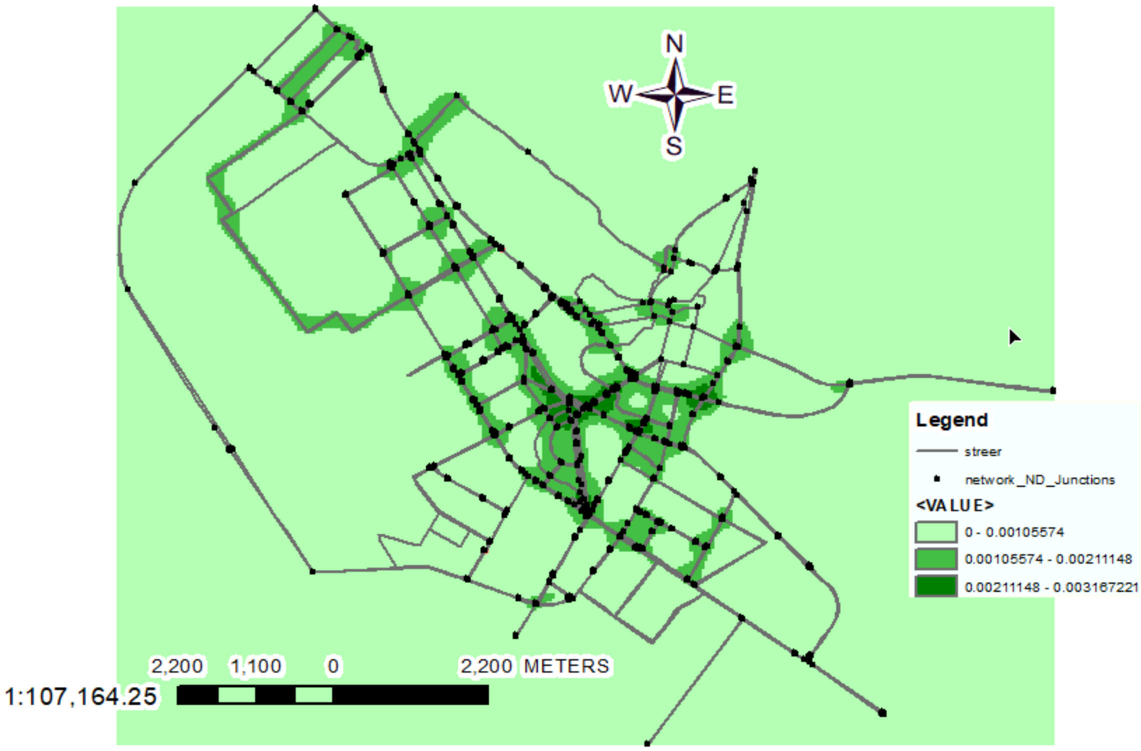


Figure 5.35: NO gas Concentration in Karbala streets

Figure 5.35 displays the spatial distribution of Nitric Oxide (NO) gas concentrations in the streets of Karbala, based on GIS mapping. NO is a harmful air pollutant primarily produced from vehicle emissions and industrial activities. Although it is less toxic than some other nitrogen oxides, NO can still pose serious health risks, particularly for individuals with respiratory conditions. Prolonged exposure may contribute to the development or worsening of asthma and other lung diseases. Moreover, NO reacts in the atmosphere to form nitrogen dioxide (NO_2) and ground-level ozone, both of which are harmful to human health and the environment. The GIS map highlights specific areas in Karbala where elevated concentrations of NO have been detected, suggesting localized emission sources. This data is essential for air quality assessment, urban planning, and the implementation of pollution control strategies to protect public health.

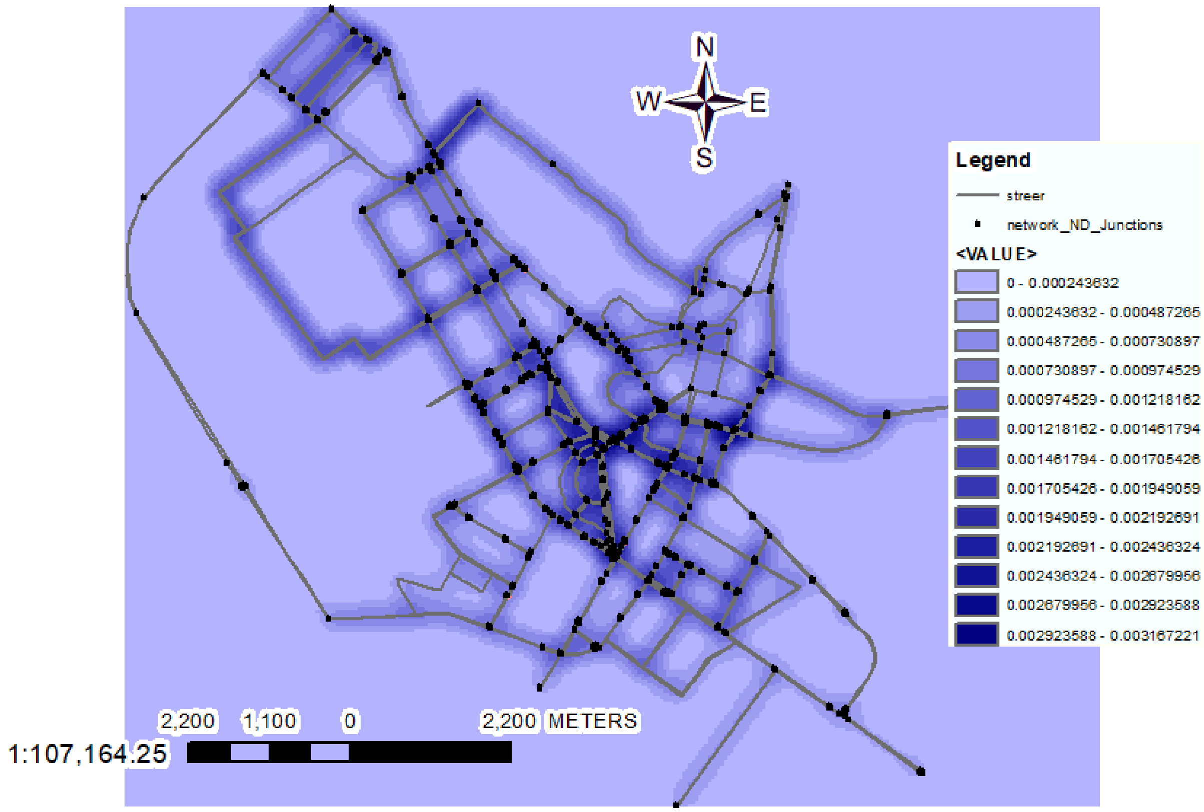


Figure 5.36: Ammonia gas Concentration in Karbala streets

Figure 5.36 shows the spatial distribution of ammonia (NH_3) gas concentrations in the streets of Karbala using GIS mapping. Ammonia is a pungent, colorless gas commonly used in agriculture and industry, but its presence in urban environments can be harmful. Even at relatively low concentrations, ammonia can irritate the eyes, nose, throat, and lungs, particularly affecting vulnerable groups such as children, older people, and individuals with respiratory conditions. At higher concentrations, it can cause serious health issues, including respiratory distress and chemical burns. The GIS map highlights specific areas in Karbala where elevated ammonia levels were detected, potentially linked to sources such as traffic emissions, sewage leaks, or industrial activity. These findings are crucial for urban air quality assessment, environmental health planning, and the development of strategies to reduce exposure and protect public well-being.

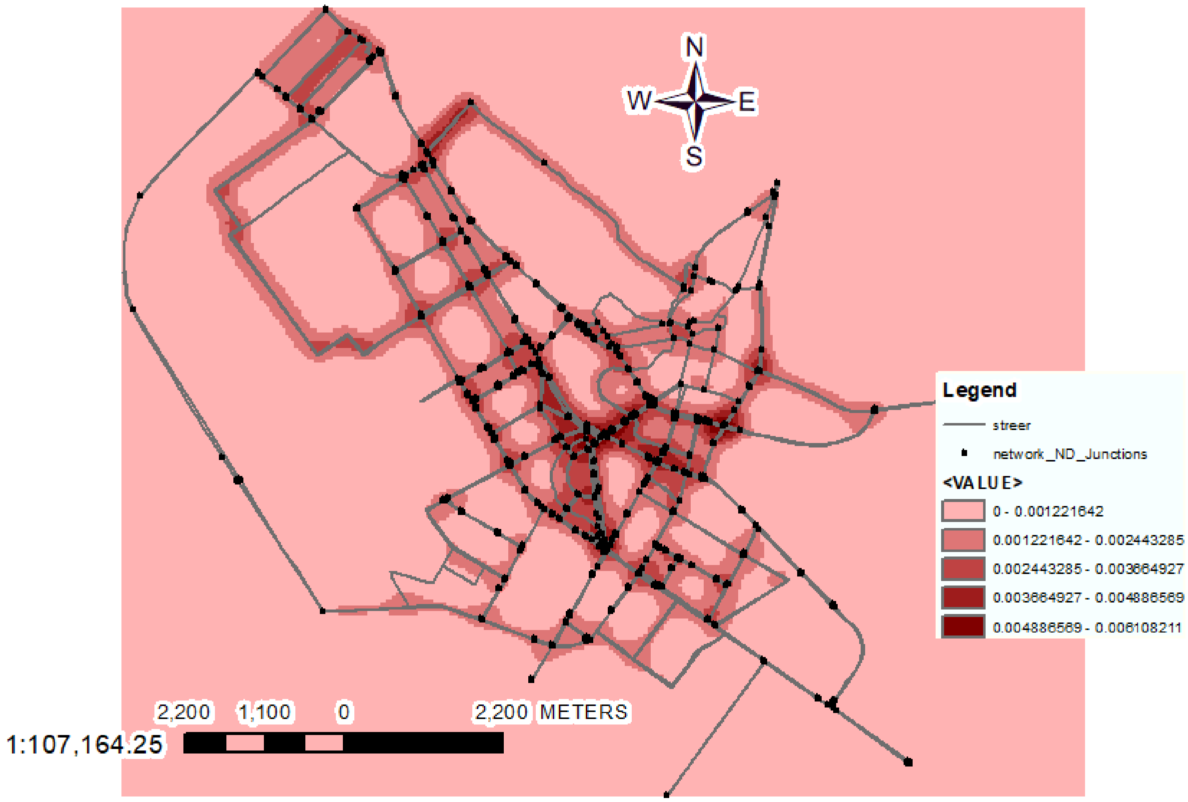


Figure 5.37: Benzen gas Concentration in Karbala streets

Figure 5.37 presents the spatial distribution of benzene gas concentrations in the streets of Karbala, as visualized through GIS mapping. The map reveals varying levels of benzene concentrations across the city, with darker areas indicating higher values. Notably, central and more densely trafficked zones exhibit elevated concentrations, likely due to vehicular emissions, fuel evaporation, and industrial activities.

Benzene is a highly toxic and volatile organic compound (VOC) known for its carcinogenic properties. Long-term exposure to benzene can lead to serious health effects, including damage to bone marrow, decreased red blood cell production, and increased risk of leukemia. Even short-term exposure at high levels can cause dizziness, headaches, and respiratory irritation. The GIS-based identification of benzene hotspots in Karbala is essential for assessing environmental risks, guiding public health policies, and implementing effective air quality control measures to protect residents and urban workers from harmful exposure.

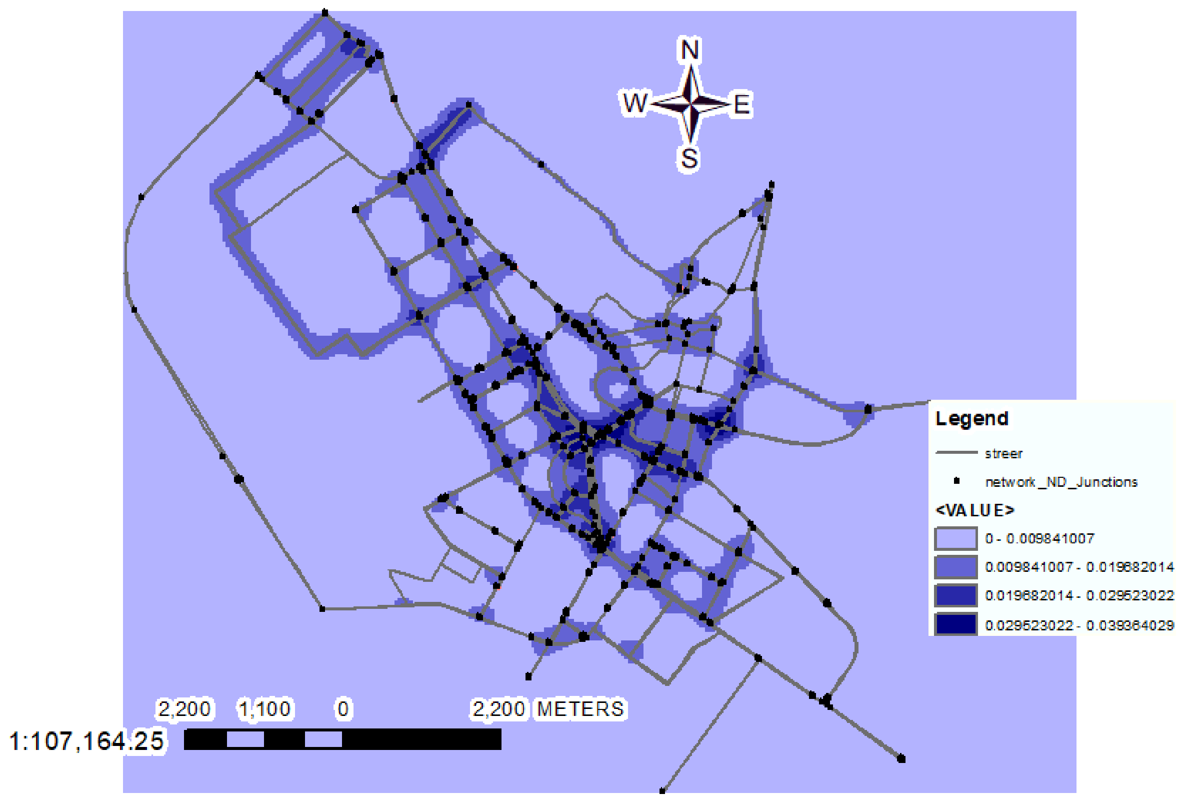


Figure 5.38: CH4 gas Concentration in Karbala streets

Figure 5.38 illustrates the spatial distribution of methane (CH_4) gas concentrations in the streets of Karbala using GIS mapping techniques. The map uses a gradient of blue shades to represent varying concentration levels, with darker regions indicating higher values. The central and southeastern parts of the city appear to have more elevated CH_4 concentrations, which may be associated with factors such as traffic congestion, landfill emissions, sewage systems, or gas leaks.

Methane is a colorless and odorless gas that, while not highly toxic to humans at low concentrations, poses significant environmental and safety risks. It is a potent greenhouse gas with a global warming potential many times greater than carbon dioxide, contributing to climate change. In urban settings, methane accumulation in enclosed or poorly ventilated areas can also present an explosion hazard. Monitoring methane concentrations through GIS allows for early detection of risk zones, supports urban planning efforts, and helps reduce both environmental impacts and potential threats to public safety.

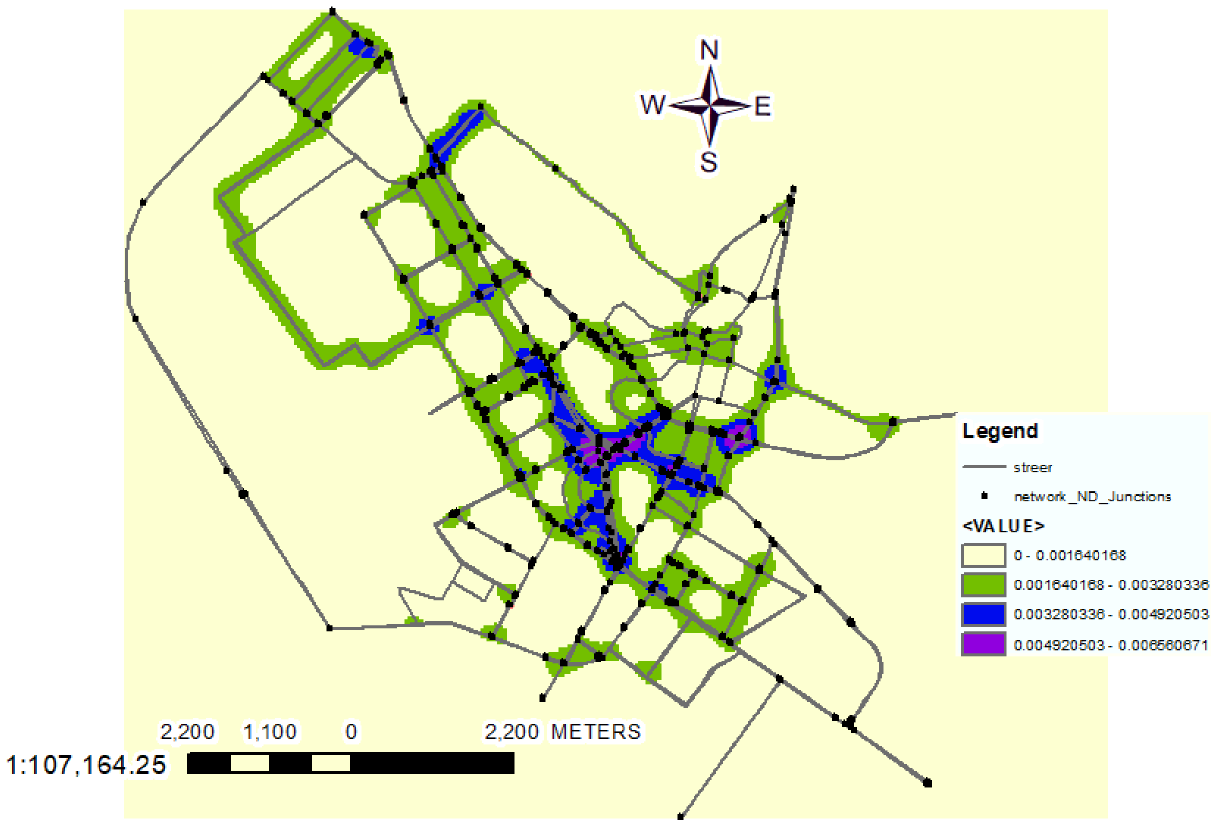


Figure 5.39: N2O gas Concentration in Karbala streets

Figure 5.39 illustrates the spatial distribution of nitrous oxide (N_2O) concentrations in Karbala using GIS-based mapping. Elevated levels were observed in central and traffic-dense zones, indicating emissions from vehicles, industrial activities, and waste systems. N_2O, with a global warming potential nearly 300 times higher than CO_2, poses both environmental and health risks, including ozone layer depletion and neurological effects from prolonged exposure. Identifying these hotspots through GIS supports evidence-based strategies for emission control and urban air quality management.

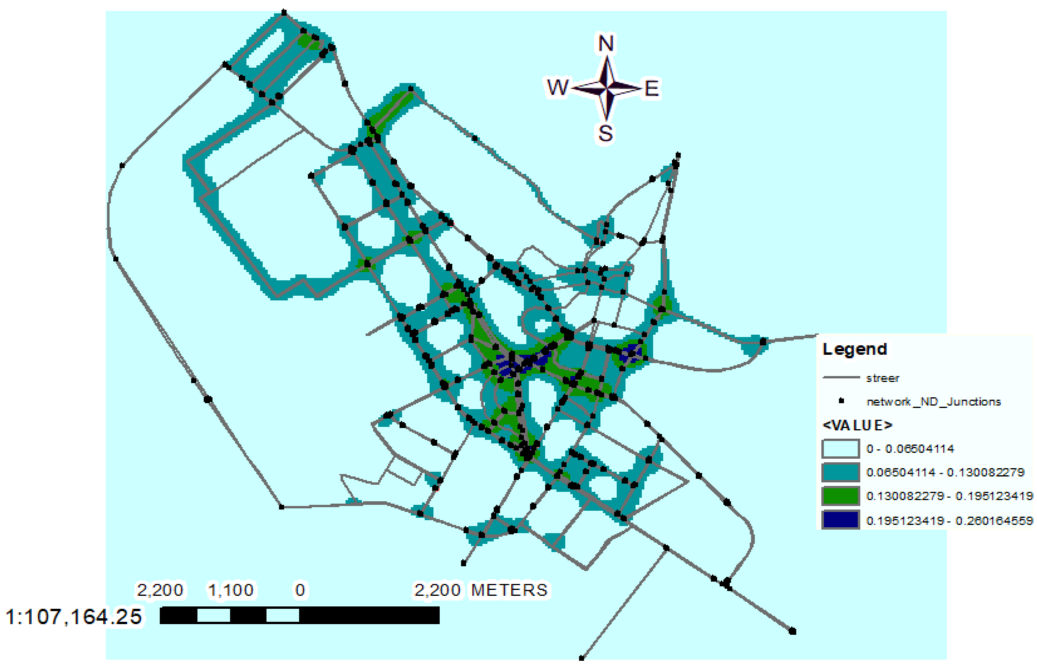


Figure 5.40: CO gas Concentration in Karbala streets

Figure 5.40 illustrates the spatial distribution of carbon monoxide (CO) gas concentrations in the streets of Karbala, as analyzed through GIS mapping. Though the specific map is not shown here, such maps typically highlight concentration gradients, with darker shades indicating higher CO levels. In urban environments like Karbala, elevated CO concentrations are often found in densely populated and high-traffic areas due to vehicle emissions, inefficient fuel combustion, and industrial sources.

Carbon monoxide is a colorless, odorless, and highly toxic gas that poses serious health risks, especially in enclosed or poorly ventilated spaces. Even at low concentrations, CO can bind with hemoglobin in the blood more effectively than oxygen, reducing oxygen delivery to vital organs. Symptoms of exposure include headaches, dizziness, confusion, and at high levels, it can lead to unconsciousness or death. Mapping CO levels across city streets is essential for identifying risk zones, informing public health strategies, and improving air quality through urban planning and emission control measures.

5.10.2 Method for Making Model Suggestions for More Sustainable Streets

Multiple models were developed in the GIS program to identify the optimal solution for addressing traffic congestion on the streets while implementing a sustainable strategy. All data about sustainability indicators was input into a designated layer for roads inside the GIS, as previously referenced in the preceding paragraph, which discusses the development of a model to evaluate data on the Karbala Governorate map. Several models were developed.

5.10.2.1 The first method:

The GIS application was directed to identify the optimal path for alleviating traffic congestion. A suggestion was received to include streets in the routes delineated in the map, as seen in Figure 5.41, which depicts the suggested additions to the defined regions. The implementation of this concept is hindered by the complexities of street growth, which is constrained by several economic and social issues.

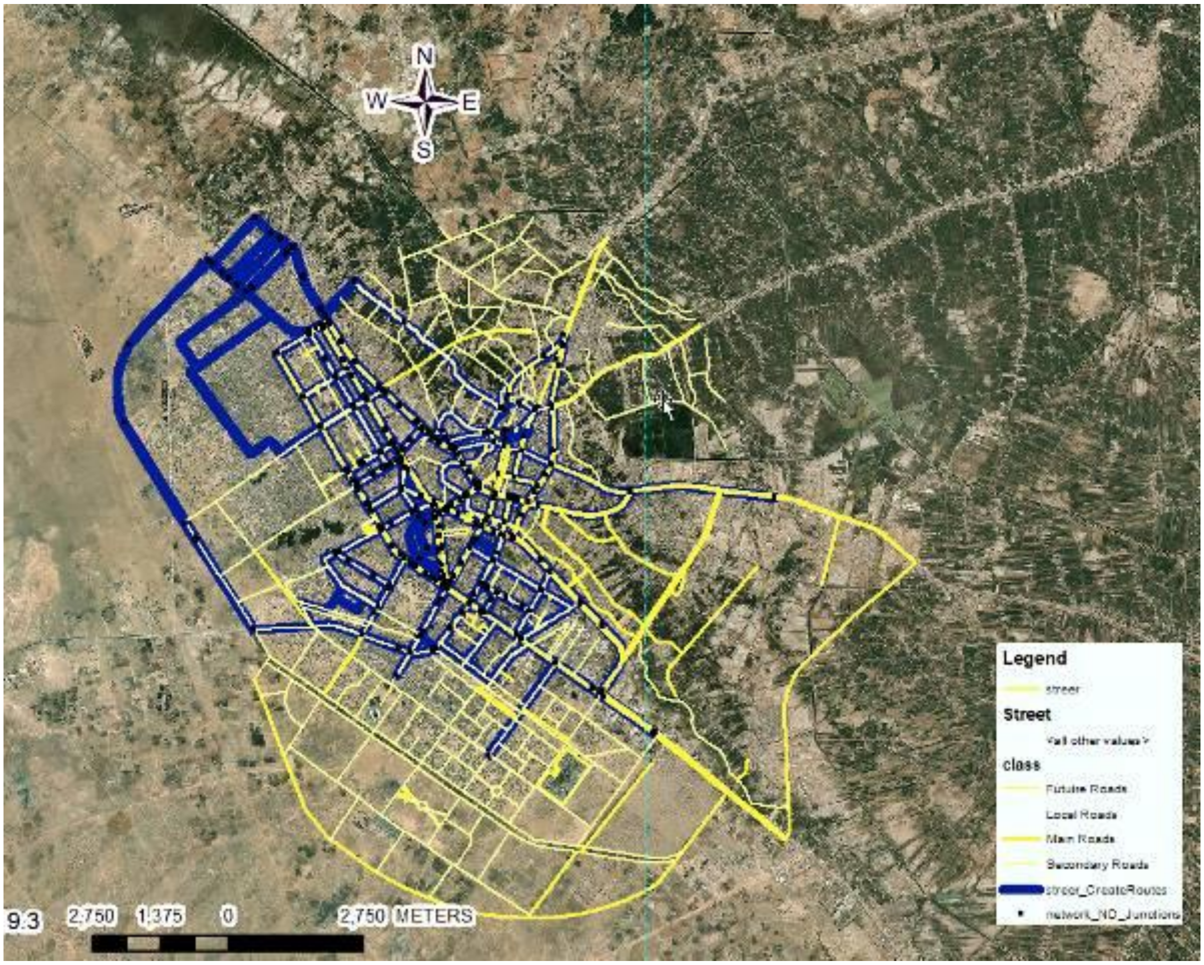


Figure 5.41: Model of CreateRoutes

5.10.2.2 The second method:

Figure 5.42 illustrates that the derived model indicates the movement defect of vehicles along the shown oval, suggesting the feasibility of installing connecting connections in this region to enhance the transportation process. The ongoing rebuilding efforts in Karbala indicate an extension of the main urban thoroughfares, demonstrating that the program has yielded outcomes aligned with the city's actual conditions, as shown by the predominant activity in this manner for the streets. For implementing a new street design in the city of Karbala, it is essential to evaluate it against all the facts offered in this thesis.

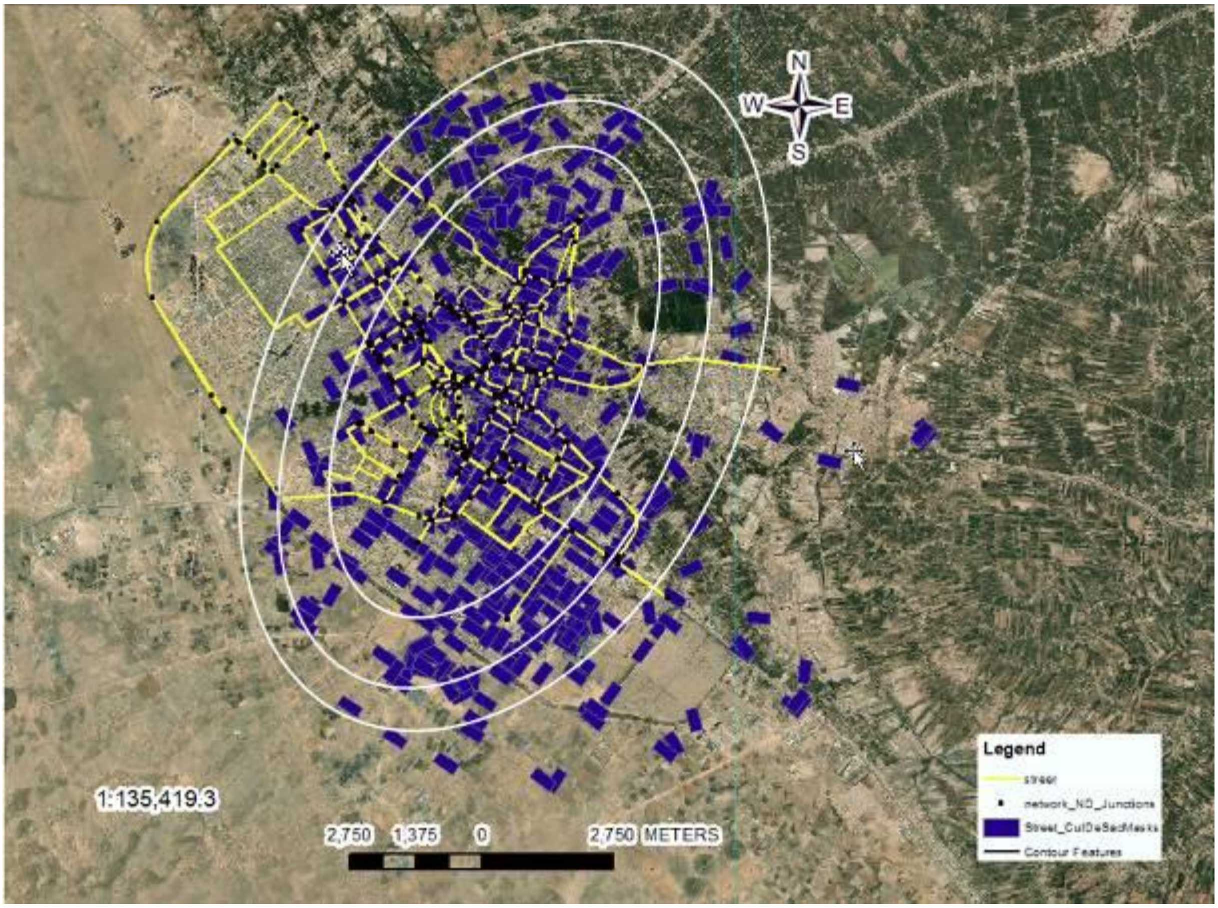


Figure 5.42: Model of Cul_DeSag mask

5.10.2.3 The third method:

This model, shown in Figure 5.43, illustrates the regions affected by high pollution and traffic volumes, as well as areas with potential for future road development. Additionally, it represents the wide range of data distributions that may be found on the streets. These designs or the model that was developed might be valuable in the construction of roads, and they are also regarded to be indications for the design of streets.

Figure 5.43: Model of flow and gas

5.11 Summary

Traffic Performance: Many arterial roads operate near or over capacity during peak hours, with LOS dropping to E or F in congested corridors. Environmental Quality: CO_2 emissions and noise levels exceeded World Health Organization (WHO) recommended limits in several locations, particularly near commercial centers and main intersections.

Safety Concerns: Accident data indicated high rates of traffic collisions in areas with poor geometric design, insufficient pedestrian crossings, and inadequate signage. Public Transport: Limited coverage and low frequency of public buses contribute to increased private car dependency. AHP results ranked environmental indicators, particularly air pollution, as the most critical dimension, followed by safety and accessibility. Fuzzy logic modeling allowed for nuanced classification of roads into different sustainability categories.

Chapter Six: Suggested Sustainable Improvements

6.1 General

The need to incorporate sustainability principles into urban (re)development policy through urban design expertise has grown significantly in recent years (Chan and Lee, 2008). Metropolitan regions are frequently unhealthy places to live due to the environmental harm caused by human activity, as well as the noise, pollution, and heavy traffic they experience. However, there are approaches to dealing with these difficulties. As a result, the concept of "healthy cities" is popular and in demand (Mottaeva, 2018).

6.2 Suggest suitable

6.3 improvements for a network:

6.3.1 Create a ring road outside of the city

To facilitate movement from the southern governorates, for example, to the northern governorates without having to go through the streets of Karbala city, the first improvement that is proposed to be made to the street network is to create a ring road outside of the city that connects the entrances to the external governorates Figure 6.1. This road is referred to as the external road. Additionally, bridges and diversions will be constructed. Because of this, the congestion that exists inside the city is reduced, traffic flow is improved, and connectivity is enhanced.

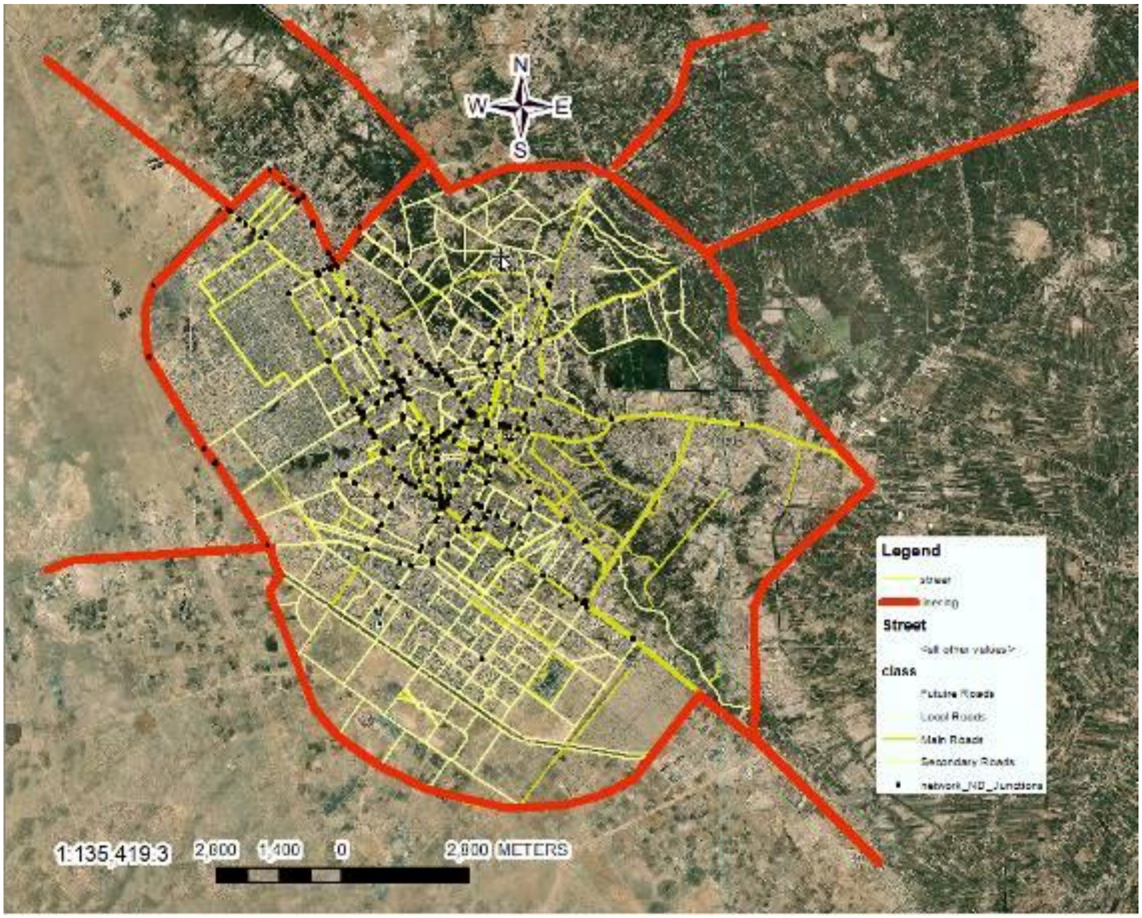


Figure 6.1: Ring road outside of the city that connects the entrances to the external governorates

6.3.2 Add streets to improve the functionality of the street network.

Improving the functionality of the street network by adding new streets can significantly enhance connectivity, reduce congestion, and improve overall traffic flow. Effective strategies include grid pattern expansion, where the existing grid is extended by adding streets parallel and perpendicular to current ones, maintaining consistent block sizes for uniformity and easier navigation (Sevtsuk, 2016). Another approach is connecting dead-ends and cul-de-sacs by converting them into through streets and creating additional links to nearby arterial and local roads to strengthen network integration (Distel, 2015). The construction of bypass roads around densely populated or congested areas can divert through traffic, with designs capable of handling high volumes while linking major highways and arterial streets (Nyongesa, 2018). Additionally, developing secondary roads to connect residential areas with main roads, and tertiary roads to provide internal neighborhood access, helps reduce dependency on major routes for local travel (Mitchell, 2014).

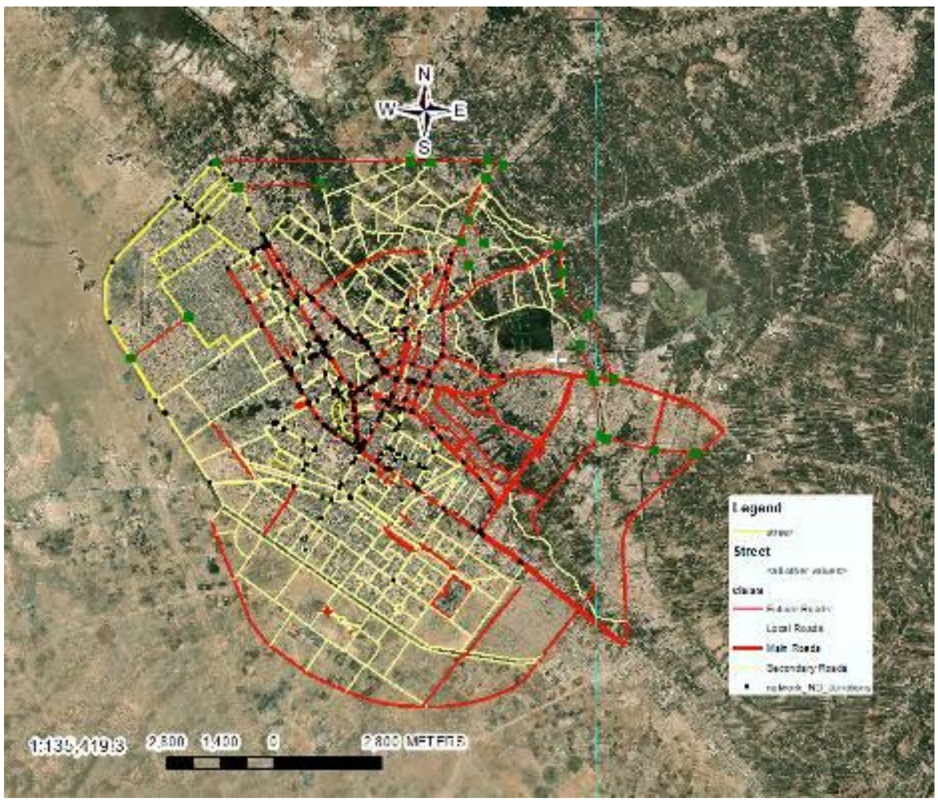


Figure 6.2: Adding new streets parallel and perpendicular to existing ones

6.3.3 Closing Network Gaps and Improving Urban Mobility

In Figure 6.3, several new roads have been added to address existing gaps and enhance overall connectivity within the network. Specifically, a new road has been proposed to link the northwestern edge of the network directly with the routes leading toward the city center, thereby improving accessibility for peripheral areas and reducing travel distances. Additionally, a set of cross-linking roads has been introduced in the southwestern region to break the prevailing pattern of elongated, linear roadways. These new connections are designed to facilitate lateral movement, enabling smoother east-west travel and reducing dependency on a limited number of primary routes. Overall, the addition of these streets aims to create a more cohesive and integrated road network, promoting efficient circulation and supporting balanced urban development.

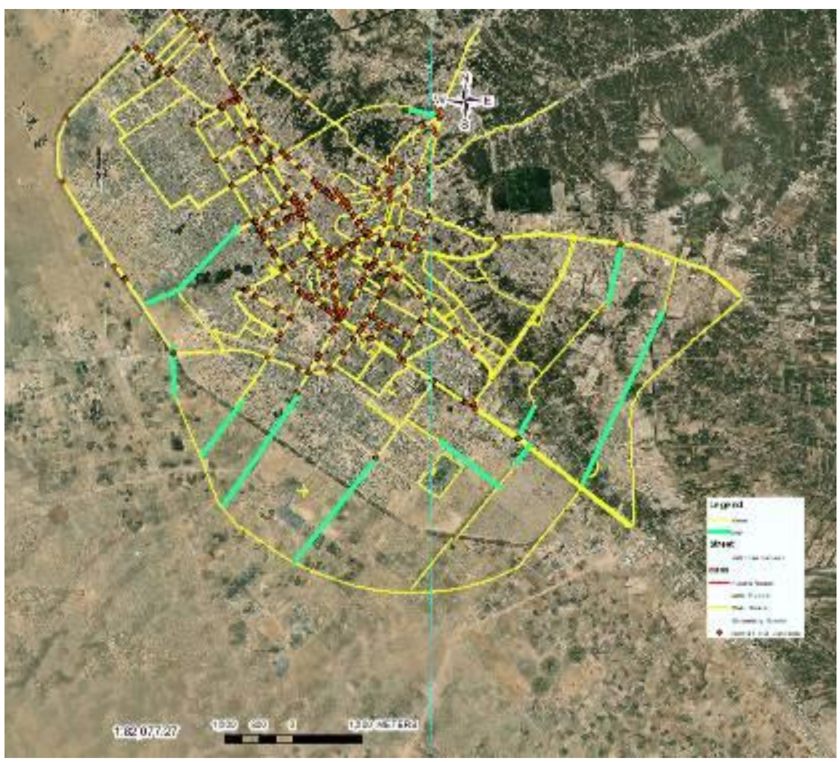


Figure 6.3: Closing Network Gaps

Table 6-1: Connectivity Strength Calculations for the Proposed Improvements

Parameter	Network Of Karbala	Improv 1 (create a ring road outside of the city)	Improv 2 (add streets to improve the functionality of the street network)	Improv 3 (Closing Network Gaps)
No. of node (υ)	741	765	850	796
No. of. link (e)	1087	1111	1196	1142
No. of. (p)	0	0	0	0
Alpha	0.234	0.207346	0.198066	0.170225
Beta	0.682	0.696269	0.702044	0.719368
Gamma	0.228	0.231115	0.232692	0.237423
GTP	0.505	0.371769	0.335637	0.227242
∑ L(Km)	489.15	582.4135	618.294	725.9354
A (Km^2)	176.625	139.9112	152.3504	189.6681
Eta	0.66	0.640731	0.633967	0.613676
Network density (km per km2)	2.769	3.29695	3.500063	4.109405
I(No. of. intersection)	223	230	250	238
Intersection density(per km2)	1.263	1.302646	1.415919	1.347955
CF	0.802	0.649231	0.701088	0.856659

The table compares Karbala's current street network with three improvement scenarios, revealing clear differences in structure and performance. Improvement 1 (outer ring road) increases network length (582.41 km) and density (3.30 km/km^2) but reduces internal accessibility, as shown by the drop in CF (0.649) and GTP (0.372). Improvement 2 (adding internal streets) achieves the highest node count (850) and intersection density (1.416/km^2), moderately improving CF (0.701) but with only modest GTP (0.336). Improvement 3 (closing network gaps) records the highest network length (725.94 km), density (4.11 km/km^2), and CF (0.857), but suffers from the lowest GTP (0.227), indicating reduced movement efficiency despite strong connectivity. Based on these results, Improvement

2 offers the best balanced enhancement strengthening internal connections and network integration without sacrificing accessibility as much as the other scenarios making it the most practical option for functional and sustainable urban mobility in Karbala.

6.4 Improve emissions problems and public transport.

Reducing emissions and enhancing public transportation systems can lead to a more sustainable, efficient, and livable urban environment. Here are a few strategies that can help tackle these issues:

6.4.1 Emissions Reduction Strategies:

1. **Promote Electric and Hybrid Vehicles:**
    - Introduce incentives such as tax rebates, reduced registration fees, and charging infrastructure to encourage the adoption of electric and hybrid vehicles.
    - Develop a network of fast-charging stations to make electric vehicle (EV) ownership more convenient (Diamond, 2009).
2. **Enhance Fuel Efficiency Standards:**
    - Implement stricter fuel efficiency standards for all types of vehicles, including personal, commercial, and public transport vehicles.
    - Encourage regular maintenance and inspection to ensure vehicles are operating at peak efficiency (Atabani,2011).
3. **Encourage Carpooling and Ride-Sharing:**
    - Develop and support carpooling programs and ride-sharing platforms to reduce the number of single-occupancy vehicles on the road.

- Implement high-occupancy vehicle (HOV) lanes to incentivize carpooling (Morris, 2009).

4. **Promote Active Transportation:**
    - Invest in infrastructure for walking and cycling, such as dedicated bike lanes, pedestrian pathways, and bike-sharing programs.
    - Encourage businesses to provide facilities for cyclists, like bike racks and showers (Young,2011).

6.4.2 Public Transportation Improvements:

1. **Enhance Bus Services:**
    - Increase the Frequency and coverage of bus routes to make them more accessible and convenient for users.
    - Invest in bus rapid transit (BRT) systems with dedicated lanes to reduce travel time and improve reliability.
2. **Develop Rail Networks:**
    - Expand and modernize urban and suburban rail networks, including light rail, metro, and commuter trains.
    - Ensure seamless integration between different modes of public transport with well-designed transfer stations.
3. **Implement Smart Public Transport Systems:**
    - Use real-time data and advanced analytics to optimize routes, schedules, and overall efficiency of public transport services.
    - Introduce mobile apps that provide real-time information on schedules, delays, and available seats to make public transport more user-friendly.

4. **Subsidize Public Transport:**
    - Offer subsidies or discounts to make public transportation more affordable, especially for low-income residents.
    - Implement programs like monthly passes and pay-as-you-go systems to cater to different user needs.

6.4.3 Holistic Approaches:

1. **Integrated Urban Planning:**
    - Design cities with mixed-use development to reduce the need for long commutes and promote walkable neighborhoods.
    - Encourage transit-oriented development (TOD) where residential, commercial, and recreational spaces are centered around public transport hubs.
2. **Green Infrastructure:**
    - Incorporate green spaces, parks, and urban forests to absorb pollutants and improve air quality.
    - Implement green roofs and walls on buildings to reduce the urban heat island effect and improve energy efficiency.
3. **Public Awareness Campaigns:**
    - Conduct campaigns to educate the public about the benefits of reducing emissions and using public transport.
    - Partner with local organizations and businesses to promote sustainable transportation options.

6.5 Improve the noise problem.

A few improvements can be suggested to reduce the levels of noise: Green noise barriers are an effective way to reduce noise pollution from traffic in urban areas while providing additional benefits. Noise barriers are physical structures designed to mitigate the effects of noise pollution on communities and individuals, as shown in Figure 6.1. These barriers reduce the sound energy transmitted from the noise source to the receiver (Federal Highway Administration, 2019). Incorporating greenery into noise barriers can reduce noise levels, improve air quality, and create habitats for wildlife. In addition, green noise barriers offer numerous environmental benefits, such as carbon sequestration and air purification (Kim and Hong, 2016; Rauch et al., 2018; Van Renterghem and Botteldooren, 2016). However, the effectiveness of green noise barriers depends on several factors, such as: 1. The type and density of vegetation used, as well as. 2. The distance and height of the wall.

Figure 6.4:Green Noise barrier (Wegen,2023)

Green noise barriers planted with native plant species reduce noise levels by 2-8 dB(A) compared to ordinary concrete walls. Thus, green noise barriers must be researched and promoted as a sustainable and effective road noise pollution remedy. Therefore, this innovation initiative seeks:
I. Create an eco-friendly, noise-reducing prototype green noise barrier.
II. Test the prototype green noise barrier's sound absorption.

Utami and Wiguna (2021) reported a 13-decibel average decrease in the Green Noise Barrier prototype (Figure 6.8). The Green Noise Barrier is unique because it uses coconut coir and climbing plants to reduce noise. The transparent elements in its design allow residents and road users to see more clearly. Its cost, sustainability, and social effect make this product commercially valuable.

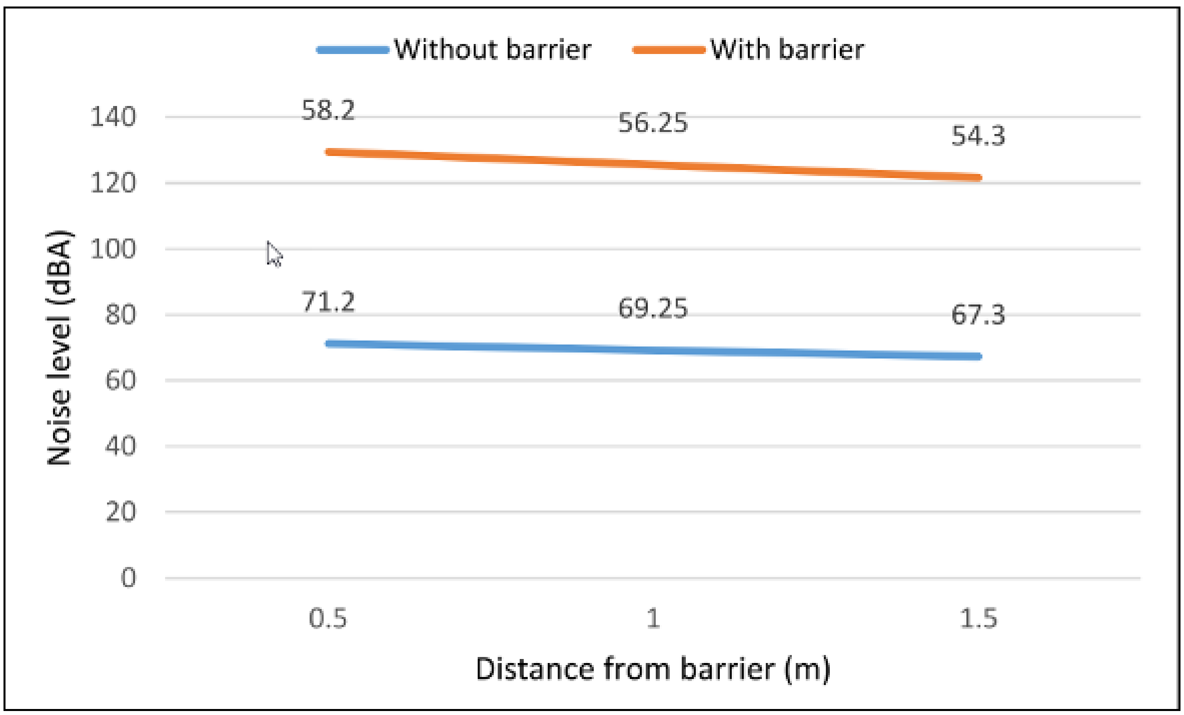


Figure 6.5: Relationship Between Noise Level and Distance from Barrier (Utami and Wiguna, 2021).

Chapter Seven: Conclusions and Recommendations

7.1 Conclusion

1- The urban road network in Karbala lies on a continuum between grid and tree patterns, as quantified by geometric indicators such as Alpha, Beta, and Gamma indices. Results show a dominance of fragmented tree-like configurations, particularly in the Central Business District (CBD), where these indices were significantly lower than standard urban values, indicating weak connectivity and limited redundancy.

2- Classification using X-type/T-type intersection ratios, cul-de-sac ratio (>0.45), and piercing street ratio categorized the network into four types: pure tree-like, cul-de-sac, T-shaped, and grid networks.

3- The Relative Neighborhood Graph (RNG) model identified low-connectivity zones suitable for reconfiguration to enhance flow performance and land-use integration.

4- Traffic volume data indicated that private vehicles dominate mobility, accounting for 73% of total trips during peak hours, causing recurring congestion at the 18 major intersections studied.

5- Public transport utilization was low, with buses comprising only 6% and minibuses 21% of peak-hour traffic, leading to an imbalanced modal share, higher operating costs, and increased emissions.

6- Noise levels reached 107 dBA in Al-Tarbiya, exceeding CPCB (75 dBA), EPA (70 dBA), and WHO (65 dBA) permissible limits.

7- Analytic Hierarchy Process (AHP) results assigned the highest weight to the environmental dimension (48.95%), followed by social (28.84%) and economic (22.22%), indicating ecological issues as the top priority.

8- Sustainability performance scores for the 18 sites ranged from 29% to 39%, with an average of 35%, reflecting low integration of sustainability principles in urban planning.

9- All sites failed to meet the baseline requirements of LEED, Green Star, CASBEE, and GSAS sustainability frameworks, revealing major compliance gaps.

10- Under BREEAM Communities, all sites achieved passing scores, suggesting the suitability of context-sensitive evaluation frameworks.

11- Variations in sustainability scores among sites were minimal, indicating that deficiencies are systemic rather than location-specific.

12- The findings call for the development of localized sustainability indicators, regional policy adjustments, and increased professional awareness of sustainable transportation planning.

13- Implementation challenges include land tenure conflicts, limited funding, and community opposition, despite the technical feasibility of proposed interventions.

14- The integrated models combining AHP, Fuzzy Logic, and GIS offer data-driven tools for transportation engineers to conduct context-specific evaluations and guide targeted design improvements.

15- Of the four tested improvement scenarios, adding radial roads (Improvement 4) achieved the highest performance: Connectivity Factor (CF) = 0.805, Network Density = 3.91 km/km^2, and Grid Topological Pattern (GTP) = 0.263.

16- The radial configuration proved most effective in enhancing internal-external accessibility, improving network resilience, and offering a replicable model for other urban contexts.

7.2 Recomondation

1- Classifying Road networks into tree-like or grid-like structures improves understanding of urban form and supports adaptable, data-driven planning tailored to each city's spatial context.

2- Identifying micro-patterns (e.g., T-shaped, cul-de-sac, grid) enables targeted, context-sensitive interventions appealing to stakeholders in customized urban design.

3- Transforming tree-like road structures into connected grids through traffic management reduces congestion, improves accessibility, and shortens travel times.

4- Expanding public transport, especially buses and minibuses, can address mobility challenges, reduce car dependency, and support environmental goals.

5- Redesigning noisy streets with speed reduction, buffer zones, and landscape barriers enhances livability and public health.

6- With the environmental dimension ranked highest (48.95%), projects should prioritize pollution reduction, green infrastructure, and climate resilience.

7- Passing BREEAM Communities criteria can be highlighted as proof of adaptability to sustainability standards.

8- GIS and spatial analysis tools should be promoted for their precision in identifying congestion hotspots and optimizing connectivity.

9- Planning should integrate technological solutions with economic and social realities to ensure feasibility and acceptance.

10- Proposed interventions should be framed as steps toward a smarter, sustainable Karbala, emphasizing data-driven planning, connectivity, and environmental stewardship.

References

Abhishek, K., Shrivastava, A., Vimal, V., Gupta, A. K., Bhuiyal, S. K., Biswas, J. K., Singh, L., Ghosh, P., Pandey, A., & Sharma, P. (2022). Biochar application for greenhouse gas mitigation, contaminants immobilization, and soil fertility enhancement: A state-of-the-art review. Science of The Total Environment, 853, 158562.

Al-Anbari, A., Abedali, D. A. H. A. H., & Alwash, A. A. A. (2020). Sustainable operation index of arterials in the CBD sector at Hilla City. International Journal of Civil Engineering and Technology, 10, 2019–2029.

Al-Bayati, M. M. A., Mohammed, H. R., & Fattah, M. Y. (2023). Minimizing the environmental impacts of traffic in Al-Mada'an city using the rerouting technique. IOP Conference Series: Earth and Environmental Science, 012039.

Al-Shebillawy, E., Korniyenko, S., & Al-Mossawy, B. (2024). Assessment of the green urban structure and its role in promoting sustainable environmental development in the city of Karbala, Republic of Iraq. In International Conference on Construction, Architecture and Technosphere Safety (pp. 426–437). Springer.

Al-Twaijry, A. A., Brierley, J. A., & Gwilliam, D. R. (2003). The development of internal audit in Saudi Arabia: An institutional theory perspective. Critical Perspectives on Accounting, 14(5), 507–531.

Aldous, D. (2006). Social, environmental, economic, and health benefits of green spaces. In XXVII International Horticultural Congress-IHC2006: International Symposium on Horticultural Plants in Urban and Peri-Urban (Vol. 762, pp. 171–186).

Allawi, A. H. (2022). Towards smart trends for tourism development and its role in place sustainability: A case study of the Karbala region. International Journal of Sustainable Development & Planning, 17(1), 97–107.

Alonso, A., Monzón, A., & Cascajo, R. (2015). Comparative analysis of passenger transport sustainability in European cities. Ecological Indicators, 48, 578–592.

Ameen, R. (2017). A framework for the sustainability assessment of urban design and development in Iraqi cities (Doctoral dissertation, Cardiff University).

Ameen, R. F. M. (2021). Evaluation of the sustainability of the urban development sector in Iraq. IOP Conference Series: Materials Science and Engineering, 012064.

Ameen, R. F. M., & Mourshed, M. (2019). Urban sustainability assessment framework development: The ranking and weighting of sustainability indicators using the analytic hierarchy process. Sustainable Cities and Society, 44, 356–366.

Anjomshoaa, E., Lamit, H. B., Shafaghat, A., Khan, T. H., & Mahdzar, S. S. B. S. (2017). Accessibility measurement techniques in urban studies: A comprehensive review. Journal of Biodiversity and Environmental Sciences (JBES), 10(1), 92–106.

Arvin, M. B., Pradhan, R. P., & Norman, N. R. (2015). Transportation intensity, urbanization, economic growth, and CO_2 emissions in the G-20 countries. Utilities Policy, 35, 50–66.

Awasthi, A., Omrani, H., & Gerber, P. (2018). Investigating ideal-solution-based multicriteria decision-making techniques for sustainability evaluation of urban mobility projects. Transportation Research Part A: Policy and Practice, 116, 247–259.

Bagler, G. (2008). Analysis of the airport network of India as a complex weighted network. Physica A: Statistical Mechanics and its Applications, 387(12), 2972–2980.

Bakosi, J., & Ristorcelli, J. (2010). Exploring the beta distribution in variable-density turbulent mixing. Journal of Turbulence, 11, N37.

Bandeira, R. A., D'Agosto, M. A., Ribeiro, S. K., Bandeira, A. P., & Goes, G. V. (2018). A fuzzy multi-criteria model for evaluating sustainable urban freight transportation operations. Journal of Cleaner Production, 184, 727–739.

Banister, D. (1999). Planning more to travel less: Land use and transport. The Town Planning Review, 70(3), 313–338.

Banister, D. (2008). The sustainable mobility paradigm. Transport Policy, 15(2), 73–80.

Basiago, A. D. (1995). Methods of defining 'sustainability'. Sustainable Development, 3(3), 109–119.

Baum, C., Malozemoff, A. J., Rosen, M. B., & Scholl, P. (2021). Mac'n'cheese: Zero-knowledge proofs for boolean and arithmetic circuits with nested disjunctions. In Advances in Cryptology – CRYPTO 2021: 41st Annual International Cryptology Conference (Vol. 12827, pp. 92–122). Springer.

Bian, Y., Hu, M., Wang, Y., & Xu, H. (2016). Energy efficiency analysis of the economic system in China during 1986–2012: A parallel slacks-based measure approach. Renewable and Sustainable Energy Reviews, 55, 990–998.

Bodor, J. N., Hutchinson, P. L., & Rose, D. (2013). Car ownership and the association between fruit and vegetable availability and diet. Preventive Medicine, 57(6), 903–905.

Boeing, G. (2021). Off the grid and back again? The recent evolution of American street network planning and design. Journal of the American Planning Association, 87(2), 123–137.

Boeing, G. (2022). Street network models and indicators for every urban area in the world. Geographical Analysis, 54(3), 519–535.

Boeing, G. D. (2017). Methods and measures for analyzing complex street networks and urban form (Doctoral dissertation, University of California, Berkeley).

Boeing, G., Higgs, C., Liu, S., Giles-Corti, B., Sallis, J. F., Cerin, E., Lowe, M., Adlakha, D., Hinckson, E., & Moudon, A. V. (2022). Using open data and open-source software to develop spatial indicators of urban design and transport features for achieving healthy and sustainable cities. The Lancet Global Health, 10(6), e907–e918.

Bogetoft, P., & Pruzan, P. M. (1991). Planning with multiple criteria: Investigation, communication, choice. North Holland.

Bojković, N., Anić, I., & Pejčić-Tarle, S. (2010). One solution for cross-country transport-sustainability evaluation using a modified ELECTRE method. Ecological Economics, 69(6), 1176–1186.

Brindle, R. E. (2005). Speed-based design of traffic calming schemes. In Proceedings of the ITE 2005 Annual Meeting and Exhibit Compendium of Technical Papers (pp. 7–10). Melbourne, Australia.

Bryce, J. M., Flintsch, G., & Hall, R. P. (2014). A multi-criteria decision analysis technique for including environmental impacts in sustainable infrastructure management business practices. Transportation Research Part D: Transport and Environment, 32, 435–445.

Brög, W., Erl, E., & Mense, N. (2002). Individualised marketing is changing travel behaviour for a better environment. In OECD Workshop: Environmentally Sustainable Transport (pp. 6–12). Berlin, Germany.

Camarero, L., & Oliva, J. (2024). Mobility and territorial cohesion: The shaping of the rural-urban mobility system. Revista Española de Investigaciones Sociológicas, 183, 3–22.

Camargo Pérez, J., Carrillo, M. H., & Montoya-Torres, J. R. (2015). Multi-criteria approaches for urban passenger transport systems: A literature review. Annals of Operations Research, 226(1), 69–87.

Castillo, H., & Pitfield, D. E. (2010). Elastic–a methodological framework for identifying and selecting sustainable transport indicators. Transportation Research Part D: Transport and Environment, 15(4), 179–188.

Cedillo-Campos, M. G., Flores-Franco, J. E., & Covarrubias, D. (2024). A physical internet-based analytic model for reducing the risk of cargo theft in road transportation. Computers & Industrial Engineering, 190, 110016.

Celikyilmaz, A., & Türksen, I. B. (2009). Modeling uncertainty with fuzzy logic. Springer.

Central Pollution Control Board. (2015). Ambient air quality and noise level: Deepawali festival monitoring report.

Chan, S. H., Donner, R. V., & Lämmer, S. (2011). Are urban road networks spatial networks with universal geometric features? A case study on Germany’s largest cities. The European Physical Journal B, 84(4), 563–577.

Chica-Olmo, J., Gachs-Sánchez, H., & Lizarraga, C. (2018). The route's effect on the perception of public transport services' quality. Transport Policy, 67, 40–48.

Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi-criteria decision analysis methods to conduct sustainability assessment. Ecological Indicators, 46, 138–148.

Cohen, M. (2017). A systematic review of urban sustainability assessment literature. Sustainability, 9(11), 2048.

Dalkmann, H., & Sakamoto, K. (2012). Urban transport: Policy recommendations for the development of eco-efficient infrastructure. Asian Development Bank.

De Almeida Guimarães, V., & Junior, I. C. L. (2017). Performance assessment and evaluation method for passenger transportation: A step toward sustainability. Journal of Cleaner Production, 142, 297–307.

De Campos, R. S., Simon, A. T., & De Campos Martins, F. (2019). Assessing the impacts of road freight transport on sustainability: A case study in the sugar-energy sector. Journal of Cleaner Production, 220, 995–1004.

De Freitas Miranda, H., & Da Silva, A. N. R. (2012). Benchmarking sustainable urban mobility: The case of Curitiba, Brazil. Transport Policy, 21, 141–151.

De Luca, A. I., Iofrida, N., Leskinen, P., Stillitano, T., Falcone, G., Strano, A., & Gulisano, G. (2017). Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: Insights from a systematic and critical review. Science of the Total Environment, 595, 352–370.

Derrible, S., & Kennedy, C. (2010). The complexity and robustness of metro networks. Physica A: Statistical Mechanics and its Applications, 389(17), 3678–3691.

Desing, H., Brunner, D., Takacs, F., Nahrath, S., Frankenberger, K., & Hischier, R. (2020). A circular economy within the planetary boundaries: Towards a resource-based, systemic approach. Resources, Conservation and Recycling, 155, 104673.

Ding, Y., Jin, M., Li, S., & Feng, D. (2021). Smart logistics based on the Internet of Things technology: An overview. International Journal of Logistics Research and Applications, 24(4), 323–345.

Dobranskyte-Niskota, A., Perujo, A., & Pregl, M. (2007). Indicators to assess the sustainability of transport activities. European Commission, Joint Research Centre.

Dobranskyte-Niskota, A., Perujo, M. D., Jesinghaus, J., & Jensen, P. (2009). Indicators to assess sustainability of transport activities Part 2: Measurement and evaluation of transport sustainability performance in the EU27. European Commission, Joint Research Centre.

Duleba, S., & Moslem, S. (2018). Sustainable urban transport development with stakeholder participation: An AHP–Kendall model. A case study for Mersin. Sustainability, 10(10), 3647.

Euler, L. (1741). Solutio problematis ad geometriam situs pertinentis. Commentarii Academiae Scientiarum Petropolitanae, 8, 128–140.

Fisichella, M., Pandolfi, A., & Targon, V. (2006). Risk management in transportation of dangerous goods. In the 5th AED Conference (pp. 12–14).

Fullerton, B. (1975). The development of British transport networks.

Ganin, A. A., Mersky, A. C., Jin, A. S., Kitsak, M., Keisler, J. M., & Linkov, I. (2019). Resilience in intelligent transportation systems (ITS). Transportation Research Part C: Emerging Technologies, 100, 318–329.

Garrison, W. L., & Levinson, D. M. (2014). The transportation experience: Policy, planning, and deployment. Oxford University Press.

Ghosh, S., Banerjee, A., Sharma, N., Agarwal, S., Ganguly, N., Bhattacharya, S., & Mukherjee, A. (2011). Statistical analysis of the Indian railway network: A complex network approach. Acta Physica Polonica B Proceedings Supplement, 4, 123–138.

Giduthuri, V. K. (2015). Sustainable urban mobility: Challenges, initiatives and planning. Current Urban Studies, 3(3), 261–274.

Gillis, D., Semanjski, I., & Lauwers, D. (2015). How to monitor sustainable mobility in cities? Literature review in the frame of creating a set of sustainable mobility indicators. Sustainability, 8(1), 29.

Golbabaei, F., Paz, A., Yigitcanlar, T., & Bunker, J. (2024). Navigating autonomous demand-responsive transport: Stakeholder perspectives on deployment and adoption challenges. International Journal of Digital Earth, 17, 2297848.

Goulder, L. H., & Parry, I. W. (2008). Instrument choice in environmental policy. Review of Environmental Economics and Policy, 2(2), 152–174.

Graham, D. J., & Glaister, S. (2003). Spatial variation in road pedestrian casualties: The role of urban scale, density, and land-use mix. Urban Studies, 40(8), 1591–1607.

Green, M. C., & Brock, T. C. (2000). The role of transportation in the persuasiveness of public narratives. Journal of Personality and Social Psychology, 79(5), 701–721.

Gugushvili, D. (2021). Public attitudes toward economic growth versus environmental sustainability dilemma: Evidence from Europe. International Journal of Comparative Sociology, 62(4), 224–240.

Guo, M., Han, C., Guan, Q., Huang, Y., & Xie, Z. (2020). A universal parallel scheduling approach to polyline and polygon vector data buffer analysis on conventional GIS platforms. Transactions in GIS, 24(6), 1630–1654.

Gössling, S., Choi, A., Dekker, K., & Metzler, D. (2019). The social cost of automobility, cycling, and walking in the European Union. Ecological Economics, 158, 65–74.

Günay, E. E., Kremer, G. E. O., & Zarindast, A. (2021). A multi-objective robust possibilistic programming approach to sustainable public transportation network design. Fuzzy Sets and Systems, 422, 106–129.

Han, B., Sun, D., Yu, X., Song, W., & Ding, L. (2020). Classification of urban street networks based on tree-like network features. Sustainability, 12(2), 628.

Harding, M. (2023). How the Central Mortgage and Housing Corporation influenced suburban community planning and design in post-World War II Canada (Doctoral dissertation). Queen’s University, Canada.

Hasan, A., Hasan, U., Whyte, A., & Al Jassmi, H. (2022). Lifecycle analysis of recycled asphalt pavements: Case study scenario analyses of an urban highway section. CivilEng, 3(1), 242–262.

Hassan, A. M., & Lee, H. (2015). Toward the sustainable development of urban areas: An overview of global trends in trials and policies. Land Use Policy, 48, 199–212.

He, H. A., & Greenberg, S. (2009). Motivating sustainable energy consumption in the home. In Defining the Role of HCI in the Challenges of Sustainability Workshop.

Hensher, D. A. (2008). Climate change, enhanced greenhouse gas emissions, and passenger transport: What can we do to make a difference? Transportation Research Part D: Transport and Environment, 13(2), 95–111.

Huang, J., Cui, Y., Chang, H., Obracht-Prondzyńska, H., Kamrowska-Zaluska, D., & Li, L. (2022). A city is not a tree: A multi-city study on street network and urban life: landscape and Urban Planning, 226, 104469.

Humphreys, P., Wong, Y., & Chan, F. (2003). Integrating environmental criteria into the supplier selection process. Journal of Materials Processing Technology, 138(1–3), 349–356.

Jarimopas, B., Singh, S. P., & Saengnil, W. (2005). Measurement and analysis of truck transport vibration levels and damage to packaged tangerines during transit. Packaging Technology and Science: An International Journal, 18(3), 179–188. [https://doi.org/10.1002/pts.680]

Jeong, J., Ji, C., Hong, T., & Park, H. S. (2016). Model for evaluating the financial viability of the BOT project for highway service areas in South Korea. Journal of Management in Engineering, 32(3), 04015036. [https://doi.org/10.1061/(ASCE)ME.1943-5479.0000403]

Jiang, F., Ma, L., Broyd, T., Chen, W., & Luo, H. (2022). Digital twin enabled sustainable urban road planning. Sustainable Cities and Society, 78, 103645. [https://doi.org/10.1016/j.scs.2021.103645]

Kansky, K., & Danscoine, P. (1989). Measures of network structure. FLUX Cahiers scientifiques internationaux Réseaux et Territoires, 5, 89–121.

Keeney, R. L. (1996). Value-focused thinking: A path to creative decisionmaking. Harvard University Press.

Kleine, A., & Von Hauff, M. (2009). Sustainability-driven implementation of corporate social responsibility: Application of the integrative sustainability triangle. Journal of Business Ethics, 85(3), 517–533. [https://doi.org/10.1007/s10551-009-0212-z]

Knowles, R. D. (2012). Transit-oriented development in Copenhagen, Denmark: From the Finger Plan to Ørestad. Journal of Transport Geography, 22, 251–261. [https://doi.org/10.1016/j.jtrangeo.2012.01.009]

Kraus, L., & Proff, H. (2021). Sustainable urban transportation criteria and measurement: A systematic literature review. Sustainability, 13(13), 7113.

Kreutzberger, E., Macharis, C., Vereecken, L., & Woxenius, J. (2003). Is intermodal freight transport more environmentally friendly than all-road freight transport? A review. In NECTAR Conference Proceedings (pp. 13–15).

Kumar, A., & Anbanandam, R. (2019). Development of a social sustainability index for the freight transportation system. Journal of Cleaner Production, 210, 77–92.

Lerner-Lam, E., Celniker, S. P., Halbert, G. W., Chellman, C., & Ryan, S. (1992). Neo-traditional neighborhood design and its implications for traffic engineering. ITE Journal, 62(1), 17–25.

Li, X., Qian, Y., Zeng, J., Wei, X., & Guang, X. (2022). Measurement of street network structure in strip cities: A case study of Lanzhou, China. Sustainability, 14(5), 2839.

Li, Z.-C., Lam, W. H., Wong, S., & Sumalee, A. (2012). Design of a rail transit line for profit maximization in a linear transportation corridor. Transportation Research Part E: Logistics and Transportation Review, 48(1), 50–70. [https://doi.org/10.1016/j.tre.2011.07.001]

Liang, H., Ren, J., Lin, R., & Liu, Y. (2019). Alternative-fuel-based vehicles for sustainable transportation: A fuzzy group decision supporting framework for sustainability prioritization. Technological Forecasting and Social Change, 140, 33–43.

Liang, H., Ren, J., Lin, R., & Liu, Y. (2019). Alternative-fuel-based vehicles for sustainable transportation: A fuzzy group decision supporting framework for sustainability prioritization. Technological Forecasting and Social Change, 140, 33–43.

Litman, T. (2013). Planning principles and practices. Victoria Transport Policy Institute, 1–35.

Litman, T. (2013). Planning principles and practices. Victoria Transport Policy Institute, 1–35. Retrieved from

Litman, T. (2021). Well-developed indicators for sustainable and livable transport planning. Victoria Transport Policy Institute.

Litman, T. (2021). Well-developed indicators for sustainable and livable transport planning. Victoria Transport Policy Institute. Retrieved from

Liu, X., Ma, S., Tian, J., Jia, N., & Li, G. (2015). A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO2 emissions: A case study of Beijing. Energy Policy, 85, 253–270.

Liu, X., Ma, S., Tian, J., Jia, N., & Li, G. (2015). A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO_2 emissions: A case study of Beijing. Energy Policy, 85, 253–270.

Liu, Z., Chen, H., Liu, E., & Hu, W. (2022). Exploring the resilience assessment framework of urban road networks for sustainable cities. Physica A: Statistical Mechanics and its Applications, 586, 126465.

Liu, Z., Chen, H., Liu, E., & Hu, W. (2022). Exploring the resilience assessment framework of urban road networks for sustainable cities. Physica A: Statistical Mechanics and its Applications, 586, 126465.

Lokhande, S. K., Jain, M. C., Dhawale, S. A., Gautam, R., & Bodhe, G. L. (2018). Realizing modeling and mapping tools to study the upsurge of noise pollution as a result of open-cast mining and transportation activities. Noise & Health, 20(93), 60–67.

Lokhande, S. K., Jain, M. C., Dhawale, S. A., Gautam, R., & Bodhe, G. L. (2018). Realizing modeling and mapping tools to study the upsurge of noise pollution as a result of open-cast mining and transportation activities. Noise and Health, 20(93), 60–67.

Loo, B. P., Chen, C., & Chan, E. T. (2010). Rail-based transit-oriented development: Lessons from New York City and Hong Kong. Landscape and Urban Planning, 97(3), 202–212.

Loo, B. P., Chen, C., & Chan, E. T. (2010). Rail-based transit-oriented development: Lessons from New York City and Hong Kong. Landscape and Urban Planning, 97(3), 202–212.

Lozano, D. L. A., Márquez, S. E. D., & Puentes, M. E. M. (2021). Sustainable and smart mobility evaluation in responsive cities through citizen participation. Transportation Research Procedia, 58, 519–526.

Lozano, D. L. A., Márquez, S. E. D., & Puentes, M. E. M. (2021). Sustainable and smart mobility evaluation in responsive cities through citizen participation. Transportation Research Procedia, 58, 519–526.

Léonardi, J., & Baumgartner, M. (2004). CO_2 efficiency in road freight transportation: Status quo, measures and potential. Transportation Research Part D: Transport and Environment, 9(6), 451–464. [https://doi.org/10.1016/j.trd.2004.08.004]

Mahdzar, S. S. B. S. (2008). Sociability vs accessibility in urban street life (Doctoral dissertation). University of London, University College London (United Kingdom).

Mahdzar, S. S. B. S. (2008). Sociability vs accessibility in urban street life (Doctoral dissertation). University of London, University College London (United Kingdom).

Malvestio, A. C., Fischer, T. B., & Montaño, M. (2018). The consideration of environmental and social issues in transport policy, plan, and programme making in Brazil: A systems analysis. Journal of Cleaner Production, 179, 674–689.

Malvestio, A. C., Fischer, T. B., & Montaño, M. (2018). The consideration of environmental and social issues in transport policy, plan, and programme making in Brazil: A systems analysis. Journal of Cleaner Production, 179, 674–689.

Manaugh, K. (2013). Incorporating issues of social justice and equity into transportation planning and policy. McGill University.

Manaugh, K. (2013). Incorporating issues of social justice and equity into transportation planning and policy. Transport Reviews, 33(6), 659–674.

Marcaida, A. K., Nguyen, T. H., & Ahn, J. (2018). Investigation of particle-related clogging of sustainable concrete pavements. Sustainability, 10(12), 4845.

Marcaida, A. K., Nguyen, T. H., & Ahn, J. (2018). Investigation of particle-related clogging of sustainable concrete pavements. Sustainability, 10(12), 4845.

Marletto, G., & Mameli, F. (2012). A participative procedure to select indicators of policies for sustainable urban mobility: Outcomes of a national test. European Transport Research Review, 4, 79–89.

Marletto, G., & Mameli, F. (2012). A participative procedure to select indicators of policies for sustainable urban mobility: Outcomes of a national test. European Transport Research Review, 4, 79–89.

Marshall, S., Gil, J., Kropf, K., Tomko, M., & Figueiredo, L. (2018). Street network studies: From networks to models and their representations. Networks and Spatial Economics, 18(3), 735–749.

Marshall, S., Gil, J., Kropf, K., Tomko, M., & Figueiredo, L. (2018). Street network studies: From networks to models and their representations. Networks and Spatial Economics, 18, 735–749.

McLeod, S., & Curtis, C. (2022). Integrating urban road safety and sustainable transportation policy through the hierarchy of hazard controls. International Journal of Sustainable Transportation, 16(2), 166–180.

Meier, K., & Brudney, J. (2002). Applied statistics for public administration (5th ed.). Wadsworth Publishing.

Mihyeon Jeon, C., & Amekudzi, A. (2005). Addressing sustainability in transportation systems: Definitions, indicators, and metrics. Journal of Infrastructure Systems, 11(1), 31–50.

Miller, P., De Barros, A. G., Kattan, L., & Wirasinghe, S. (2016). Analyzing the sustainability performance of public transit. Transportation Research Part D: Transport and Environment, 44, 177–198.

Mitra, S. K., & Saphores, J.-D. M. (2016). The value of transportation accessibility in a least developed country city: The case of Rajshahi City, Bangladesh. Transportation Research Part A: Policy and Practice, 89, 184–200.

Mocnik, F.-B. (2021). Benford's law and geographical information: The example of OpenStreetMap. International Journal of Geographical Information Science, 35(9), 1746–1772.

Mohring, H. (1972). Optimization and scale economies in urban bus transportation. The American Economic Review, 62(4), 591–604.

Mohsin, M. M., Beach, T., & Kwan, A. (2020). Consensus-based urban sustainability framework for Iraqi cities: A case study in Baghdad. Heliyon, 6(9), e04922.

Monzon, A., Fernandez, A., & Jorda, P. (2009). Environmental costs account: A base for measuring sustainability in transport plans. In Highway and Urban Environment (pp. 21–32). Springer.

Mosaberpanah, M., & Khales, S. D. (2013). The role of transportation in sustainable development. In ICsdec 2012: Developing the frontier of sustainable design, engineering, and construction (pp. 411–417).

Mouratidis, K., Peters, S., & Van Wee, B. (2021). Transportation technologies, sharing economy, and teleactivities: Implications for the built environment and travel. Transportation Research Part D: Transport and Environment, 92, 102716.

Mueller, N., Rojas-Rueda, D., Cole-Hunter, T., De Nazelle, A., Dons, E., Gerike, R., Götschi, T., Panis, L. I., Kahlmeier, S., & Nieuwenhuijsen, M.

(2015). Health impact assessment of active transportation: A systematic review. Preventive Medicine, 76, 103–114.

Nag, D., Paul, S. K., Saha, S., & Goswami, A. K. (2018). Sustainability assessment for the transportation environment of Darjeeling, India. Journal of Environmental Management, 213, 489–502.

Nathaniel, S. P., Yalçiner, K., & Bekun, F. V. (2021). Assessing the environmental sustainability corridor: Linking natural resources, renewable energy, human capital, and ecological footprint in BRICS. Resources Policy, 70, 101924. [https://doi.org/10.1016/j.resourpol.2020.101924]

Nationerna, F. (2015). Transforming our world: The 2030 agenda for sustainable development. United Nations.

Neumayer, E. (2003). Weak versus strong sustainability: Exploring the limits of two opposing paradigms. Edward Elgar Publishing.

Nicolas, J.-P., Pochet, P., & Poimboeuf, H. (2003). Towards sustainable mobility indicators: Application to the Lyons conurbation. Transport Policy, 10(3), 197–208.

Obaid, H. A. (2015). Modelling sewer overflow of Karbala city with a large floating population (Master's thesis). Universiti Teknologi Malaysia.

Ogata, R., Schmöcker, J.-D., Nakamura, T., & Kuwahara, M. (2022). On the potential of carsharing to attract regular trips of private car and public transport users in metropolitan areas. Transportation Research Part A: Policy and Practice, 163, 386–404. [https://doi.org/10.1016/j.tra.2022.07.004]

Oppio, A., Bottero, M., & Arcidiacono, A. (2022). Assessing urban quality: A proposal for a multi-criteria decision analysis evaluation framework. Annals of Operations Research, 1–18. [https://doi.org/10.1007/s10479-021-04284-7]

Pathak, D. K., Thakur, L. S., & Rahman, S. (2019). Performance evaluation framework for sustainable freight transportation systems. International Journal of Production Research, 57(19), 6202–6222.

Petrova, S., Nikolov, B., Velcheva, I., Angelov, N., Valcheva, E., Katova, A., Golubinova, I., & Marinov-Serafimov, P. (2022). Buffer green patches around the urban road network as a tool for sustainable soil management. Land, 11(3), 343.

Pojani, D., & Stead, D. (2015). Sustainable urban transport in the developing world: Beyond megacities. Sustainability, 7(6), 7784–7805.

Porta, S., Crucitti, P., & Latora, V. (2006). The network analysis of urban streets: A primal approach. Environment and Planning B: Planning and Design, 33(5), 705–725.

Postorino, M. N., & Mantecchini, L. (2014). A transport carbon footprint methodology to assess airport carbon emissions. Journal of Air Transport Management, 37, 76–86.

Potravny, I., Novoselov, A., Novoselova, I., Chávez Ferreyra, K. Y., & Gassiy, V. (2022). Route selection for minerals' transportation to ensure the sustainability of the Arctic. Sustainability, 14(24), 16039.

Psaraftis, H. N., & Kontovas, C. A. (2013). Speed models for energy-efficient maritime transportation: A taxonomy and survey. Transportation Research Part C: Emerging Technologies, 26, 331–351.

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: In search of conceptual origins. Sustainability Science, 14(3), 681–695.

Pérez-Martínez, P. J., & Sorba, I. A. (2010). Energy consumption of passenger land transport modes. Energy & Environment, 21(6), 577–600.

Reimers, P. (2021). The subsidized green revolution: The impact of public incentives on the automotive industry to promote alternative fuel vehicles (AFVs) in the period from 2010 to 2018. Energies, 14(18), 5765.

Roberts, M. J. (1970). Transport pricing and distribution efficiency. Land Economics, 46(2), 181–190.

Rodrigue, J.-P. (2020). The geography of transport systems (5th ed.). Routledge.

Sahebgharani, A., Wiśniewski, S., Borowska-Stefańska, M., Kowalski, M., & Mokoei, K. (2024). Analyzing the effect of depopulation on the spatial structure of the city of Łódź, Poland: Development and application of an integrated land use and transportation model. Habitat International, 143, 102992.

Santos, A. S., & Ribeiro, S. K. (2013). The use of sustainability indicators in urban passenger transport during the decision-making process: The case of Rio de Janeiro, Brazil. Current Opinion in Environmental Sustainability, 5(2), 251–260.

Saray, M., Saray, M., Kazan, C., & Guner, S. (2024). Optimization of renewable energy usage in public transportation: Mathematical model for energy management of plug-in PV-based electric metrobuses. Journal of Energy Storage, 78, 109946.

Sato, Y., & Tan, K. H. (2023). Inconsistency indices in pairwise comparisons: An improvement of the consistency index. Annals of Operations Research, 326(1), 809–830.

Sdoukopoulos, A., Pitsiava-Latinopoulou, M., Basbas, S., & Papaioannou, P. (2019). Measuring progress towards transport sustainability through indicators: Analysis and metrics of the main indicator initiatives. Transportation Research Part D: Transport and Environment, 67, 316–333.

Serageldin, I. (1996). Sustainability as opportunity and the problem of social capital. The Brown Journal of World Affairs, 3(2), 187–203.

Shang, W.-L., Gao, Z., Daina, N., Zhang, H., Long, Y., Guo, Z., & Ochieng, W. Y. (2022). Benchmark analysis for robustness of multi-scale urban road networks under global disruptions. IEEE Transactions on Intelligent Transportation Systems, 23(7), 6330–6344.

Shankar, R., Choudhary, D., & Jharkharia, S. (2018). An integrated risk assessment model: A case of sustainable freight transportation systems. Transportation Research Part D: Transport and Environment, 63, 662–676.

Shiau, T.-A. (2012). Evaluating sustainable transport strategies with incomplete information for Taipei City. Transportation Research Part D: Transport and Environment, 17(5), 427–432.

Shiau, T.-A., & Liu, J.-S. (2013). Developing an indicator system for local governments to evaluate transport sustainability strategies. Ecological Indicators, 34, 361–371.

Shlayan, N., Kachroo, P., & Wadoo, S. (2011). Transportation reliability based on information theory. 2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC), 1415–1420. IEEE.

Sienkiewicz, J., & Hołyst, J. A. (2005). Statistical analysis of 22 public transport networks in Poland. Physical Review E, 72(4), 046127.

Sierra-Vargas, M. P., & Teran, L. M. (2012). Air pollution: Impact and prevention. Respirology, 17(7), 1031–1038.

Small, K. A. (1999). Valuation of travel-time savings and predictability in congested conditions for highway user-cost estimation. Transportation Research Board.

Southworth, M., & Ben-Joseph, E. (1997). Streets and the shaping of cities and towns. McGraw-Hill.

Sperandelli, D. I., Dupas, F. A., & Dias Pons, N. A. (2013). Dynamics of urban sprawl, vacant land, and green spaces on the metropolitan fringe of São Paulo, Brazil. Journal of Urban Planning and Development, 139(4), 274–279. [https://doi.org/10.1061/(ASCE)UP.1943-5444.0000158]

Sreelekha, M., Krishnamurthy, K., & Anjaneyulu, M. (2020). Urban road network and its topology: A case study of Calicut, India. European Transport / Trasporti Europei, 77, 1–17.

Stach, W., Kurgan, L. A., & Pedrycz, W. (2008). Numerical and linguistic prediction of time series with the use of fuzzy cognitive maps. IEEE Transactions on Fuzzy Systems, 16(1), 61–72.

Statista. (2023). Number of cars sold worldwide from 2010 to 2023, with a 2024 forecast (in million units).

Stefaniec, A., Hosseini, K., Xie, J., & Li, Y. (2020). Sustainability assessment of inland transportation in China: A triple bottom line-based network DEA approach. Transportation Research Part D: Transport and Environment, 80, 102258.

Taaffe, E., Gauthier, H., & O’Kelly, M. (1996). Geography of transportation (1st ed.). Prentice Hall.

Tahmasbi, B., Mansourianfar, M. H., Haghshenas, H., & Kim, I. (2019). Multimodal accessibility-based equity assessment of urban public facilities distribution. Sustainable Cities and Society, 49, 101633.

Team, M. (2020). COVID-19 and the pre-existing trends in aerospace – part 1. Palomar Technologies. Retrieved from

Tiwari, G. (2003). Social dimension of transport planning. Transportation Research and Injury Prevention Programme, Indian Institute of Technology, Delhi.

Toth-Szabo, Z., & Várhelyi, A. (2012). Indicator framework for measuring the sustainability of transport in the city. Procedia – Social and Behavioral Sciences, 48, 2035–2047.

Transportation Research Board, National Academies of Sciences, Engineering, and Medicine. (2022). Highway capacity manual, 7th edition: A guide for multimodal mobility analysis. The National Academies Press.

Tsai, J., Wu, Y., & Shen, J. (2011). Maximizing port and transportation system productivity by exploring alternative port operation strategies. Georgia Transportation Institute University Transportation Center.

Tunnard, C., & Pushkarev, B. (1963). Manufactured America: Chaos or control? Yale University Press.

Twigg, M. V. (2007). Progress and Future Challenges in Controlling Automotive Exhaust Gas Emissions. Applied Catalysis B: Environmental, 70(1–4), 2–15.

Török, Á. (2014). Environmental comparison of road and railway transport: A case study in Hungary. International Journal for Traffic and Transport Engineering, 4(2), 210–219.

U.S. Environmental Protection Agency. (2009). Integrated science assessment (ISA) for particulate matter (Final report, Dec 2009, EPA/600/R-08/139F). Washington, DC.

Venkatanagaraju, E., Bharathi, N., Sindhuja, R. H., Chowdhury, R. R., & Sreelekha, Y. (2020). Extraction and purification of pectin from agro-industrial wastes. In Pectins – Extraction, purification, characterization and applications (pp. 1–15). IntechOpen.

Wang, J., & Huang, H. (2016). Road network safety evaluation using a Bayesian hierarchical joint model. Accident Analysis & Prevention, 90, 152–158.

Wang, Y., Ying, Q., Hu, J., & Zhang, H. (2014). Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in China during 2013–2014. Environment International, 73, 413–422.

Wei, S., Shen, X., Shao, M., & Sun, L. (2021). Applying data mining approaches for analyzing hazardous materials transportation accidents on different types of roads: sustainability, 13(23), 12773.

World Bank. (2019). Transport is fundamental to supporting economic growth. [Online]. Available at:

World Economic Forum. (2016). The number of cars worldwide is set to double by 2040. Retrieved from.

World Health Organization. (2020). WHO vaccine-preventable diseases: Monitoring system: 2009 global summary. World Health Organization. Retrieved from.

Wu, W. (2009). Optimization models for selecting bus stops for accessibility improvements for people with disabilities. Florida International University.

Xing, G., Mathews, N., Sun, S., Lim, S. S., Lam, Y. M., Grätzel, M., Mhaisalkar, S., & Sum, T. C. (2013). Long-range balanced electron- and holetransport lengths in organic–inorganic CH3NH3PbI3. Science, 342(6156), 344–347.

Yadav, P., Hasan, S., Ojo, A., & Curry, E. (2017). The role of open data in driving sustainable mobility in nine smart cities. Environment and Planning B: Urban Analytics and City Science, 44(2), 283–306.

Zhou, M. (2015). Infinite edge partition models for overlapping community detection and link prediction. In Artificial Intelligence and Statistics (pp. 1135–1143). PMLR. Retrieved from

Zhou, X., Guo, Y., Zhao, F., Shi, W., & Yu, G. (2020). Topology-controlled hydration of polymer network in hydrogels for solar-driven wastewater treatment. Advanced Materials, 32(43), 2007012.

Zito, P., & Salvo, G. (2011). Toward an urban transport sustainability index: A European comparison. European Transport Research Review, 3(4), 179–195.

Zou, X., Hu, P., Zhang, J., Wu, Q., & Zhou, X. (2024). Unraveling urban network dynamics with complex network modeling: A case study of Chengdu, China. Journal of the Knowledge Economy, 1–23.

Appendix A

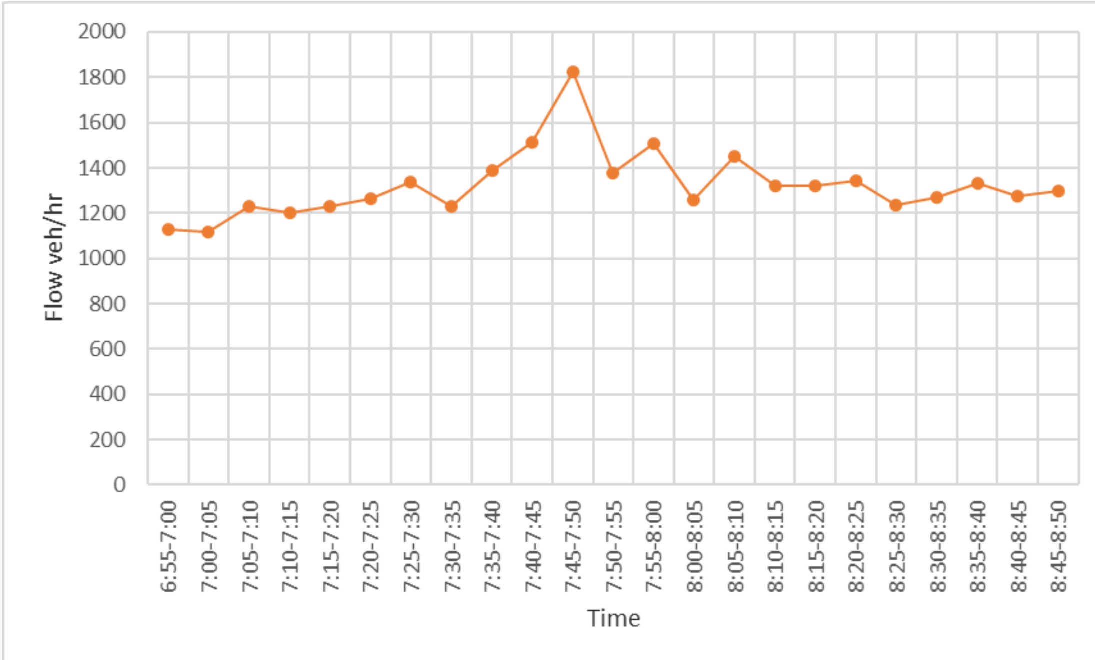


Figure A.1:Fluctuation of flow with time for Street 1 in 9/10/2023 Roundabout Al-Safina

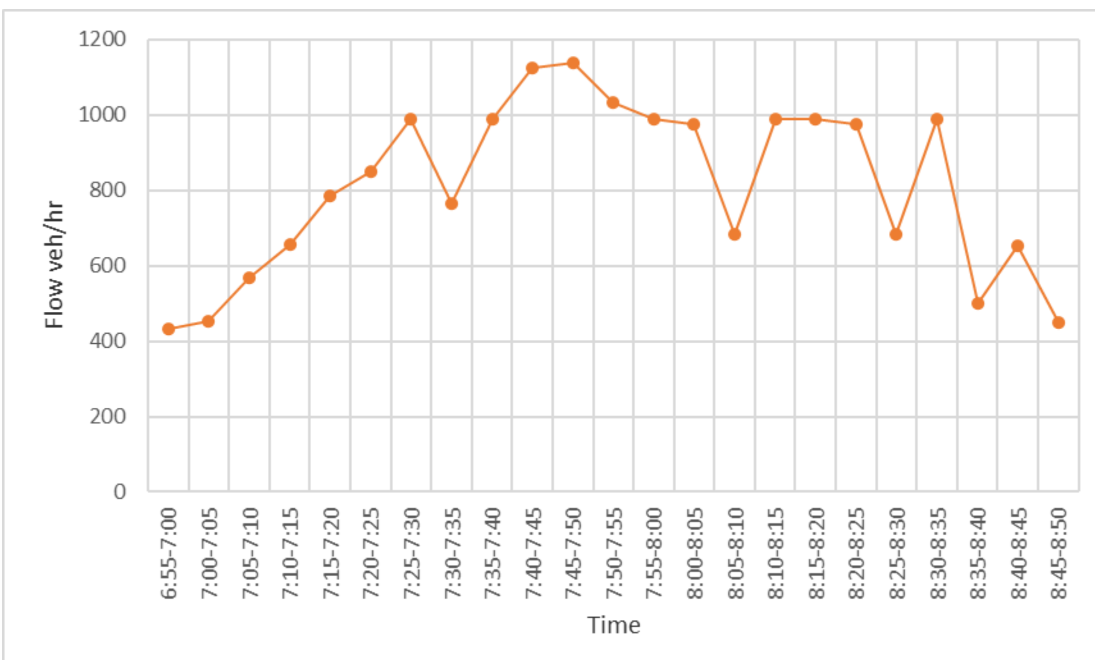


Figure A.2:Fluctuation of flow with time for Street 2 in 9/10/2023 Roundabout Al-Safina

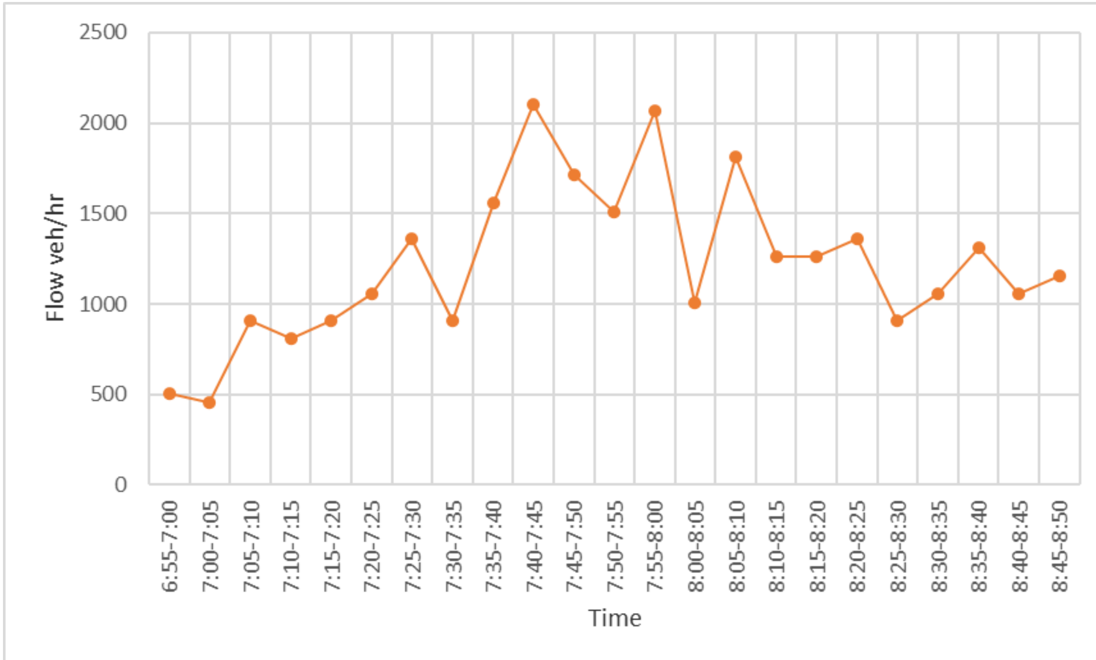


Figure A.3:Fluctuation of flow with time for Street 3 in 9/10/2023 Roundabout Al-Safina

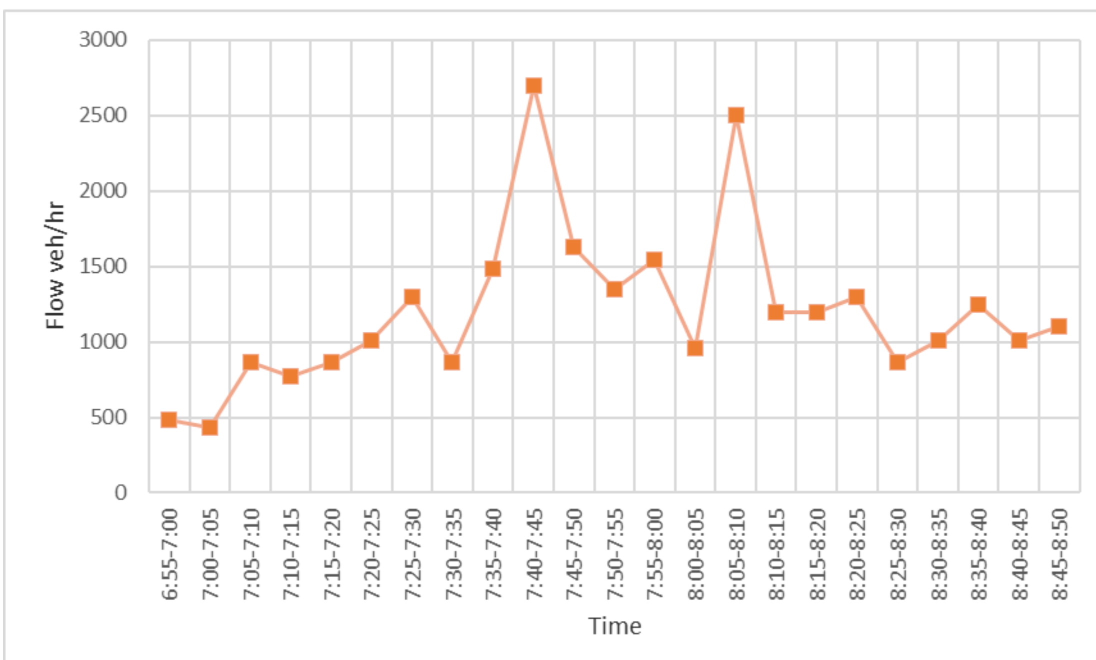


Figure A.41:Fluctuation of flow with time for Street 4 in 9/10/2023 Roundabout Al-Safina

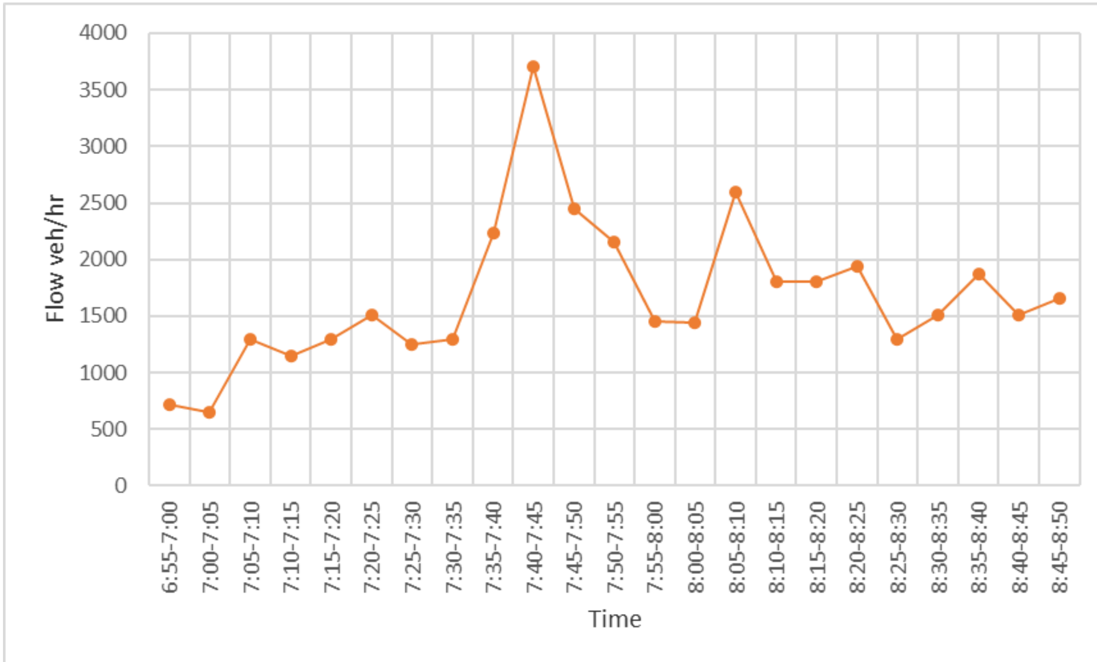


Figure A.5:Fluctuation of flow with time for Street 5 in 9/10/2023 Roundabout Al-Safina

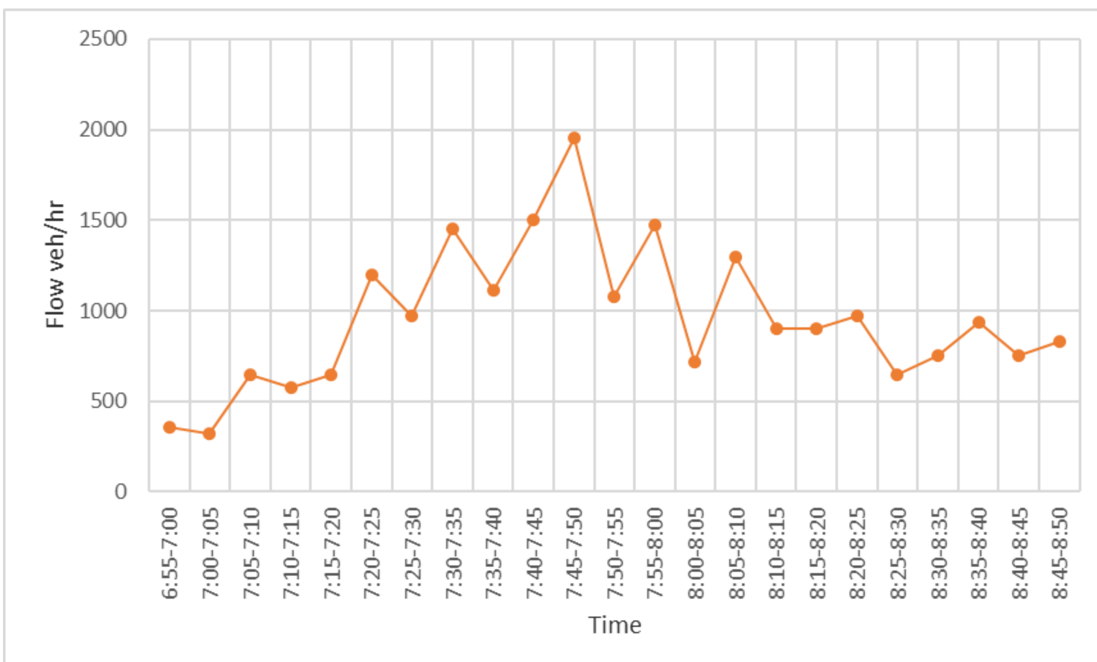


Figure A.6:Fluctuation of flow with time for Street 6 in 9/10/2023 Roundabout Al-Safina

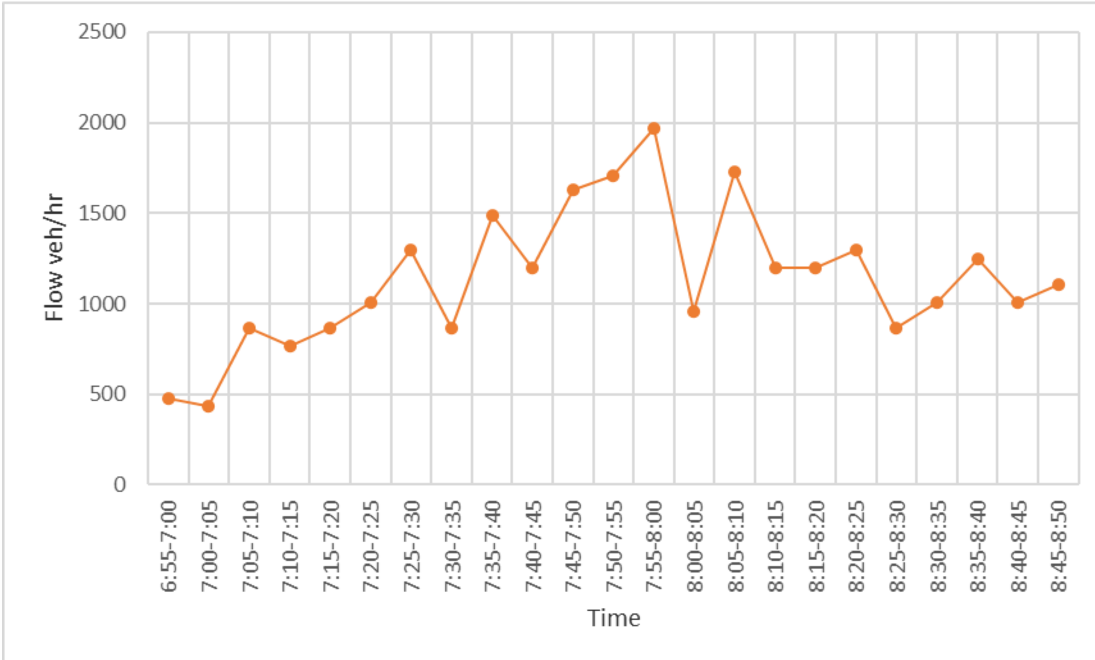


Figure A.7:Fluctuation of flow with time for Street 7 in 9/10/2023 Roundabout Al-Safina

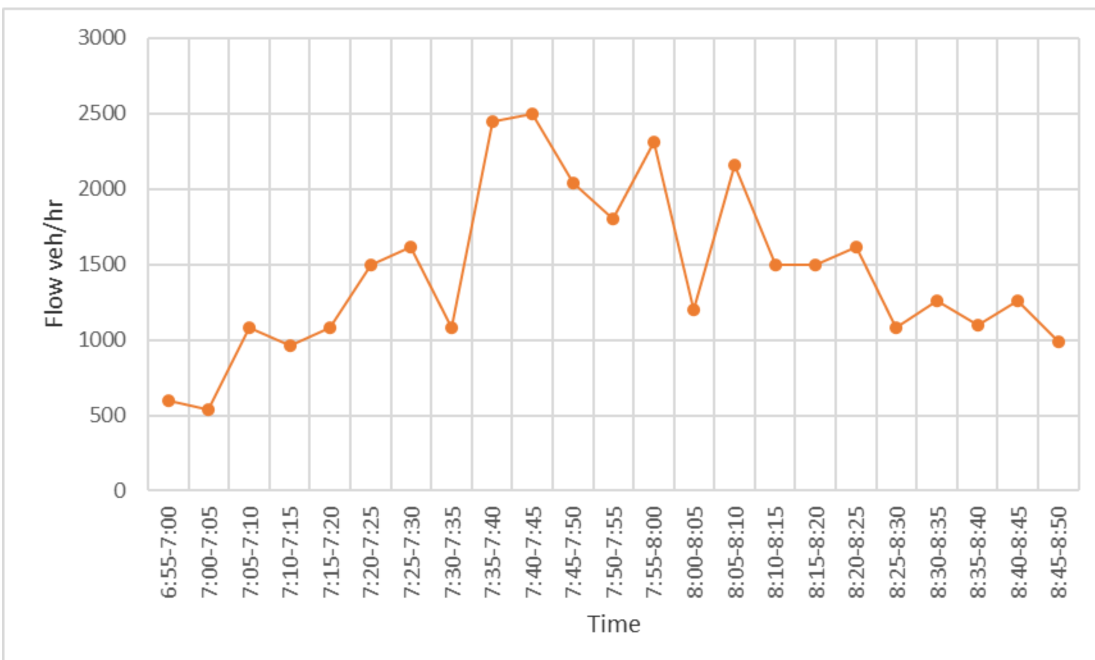


Figure A.8:Fluctuation of flow with time for Street 8 in 9/10/2023 Roundabout Al-Safina

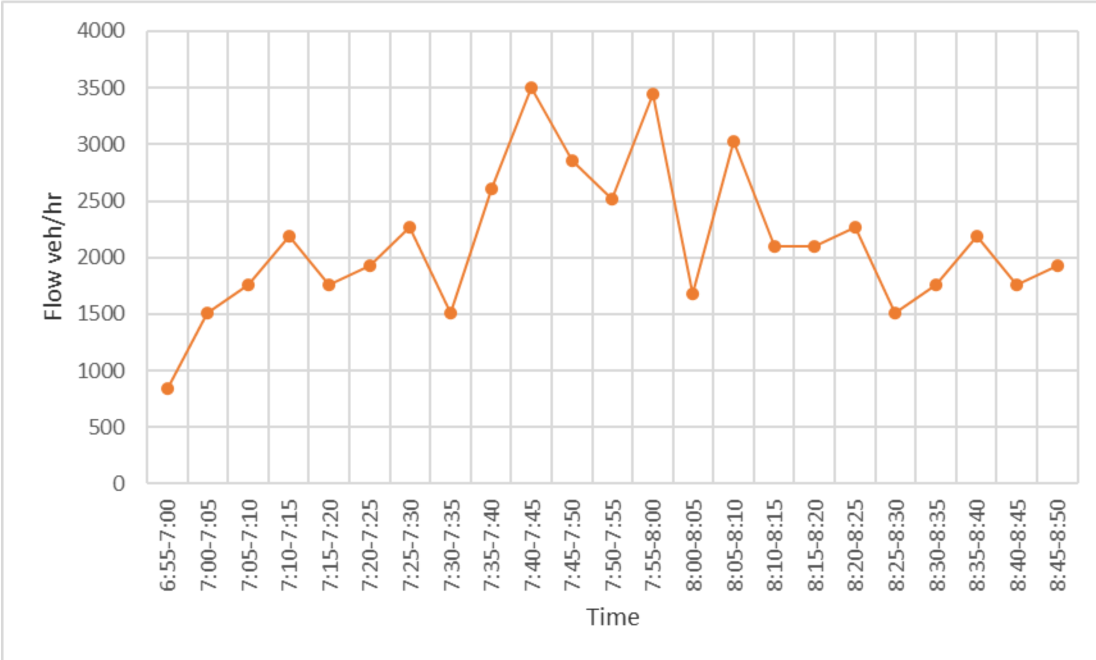


Figure A.9:Fluctuation of flow with time for Street 1 in 9/10/2023 Roundabout Sayid Al-Asaar Al-Jameia

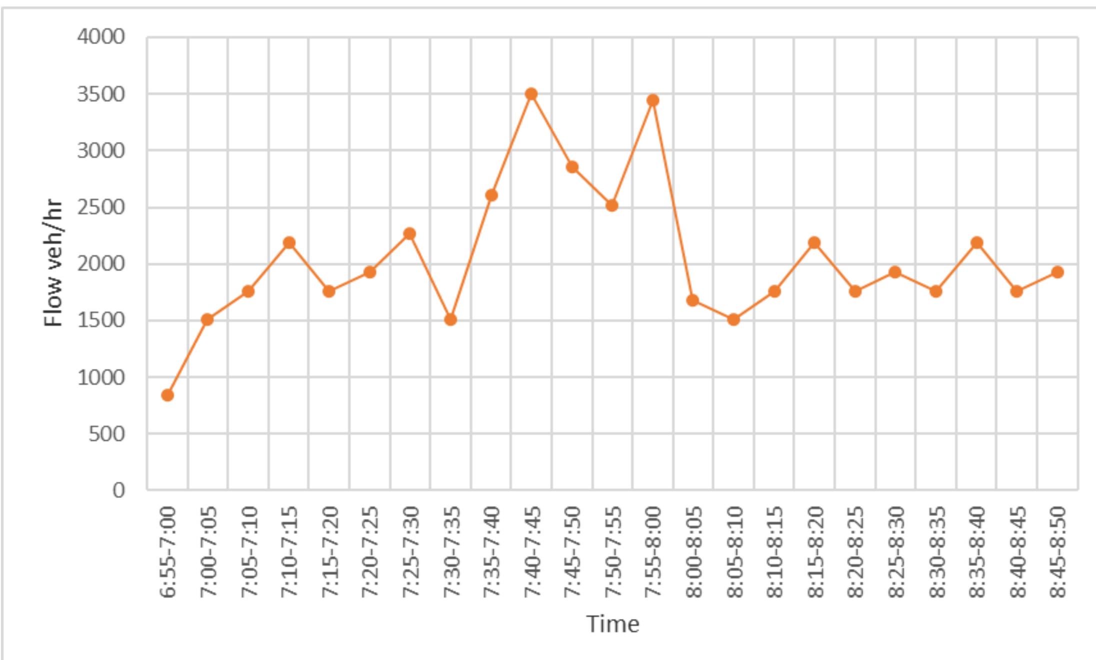


Figure A.10:Fluctuation of flow with time for Street 2 in 9/10/2023 Roundabout Sayid Al-Asaar Al-Jameia

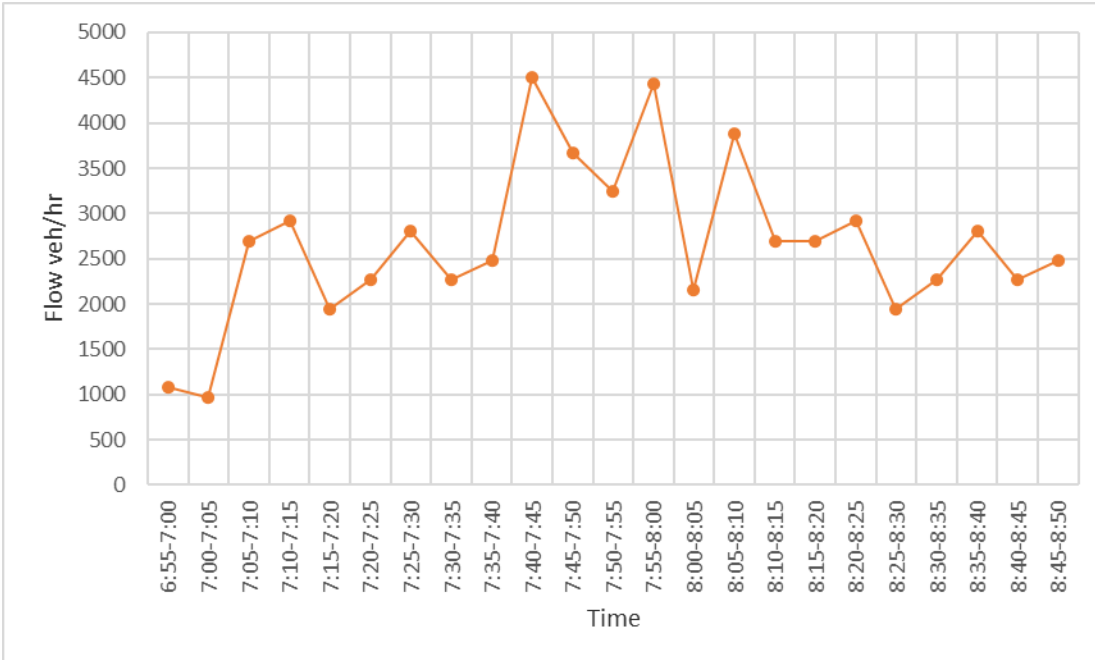


Figure A.11:Fluctuation of flow with time for Street 3 in 9/10/2023 Roundabout Sayid Al-Asaar Al-Jameia

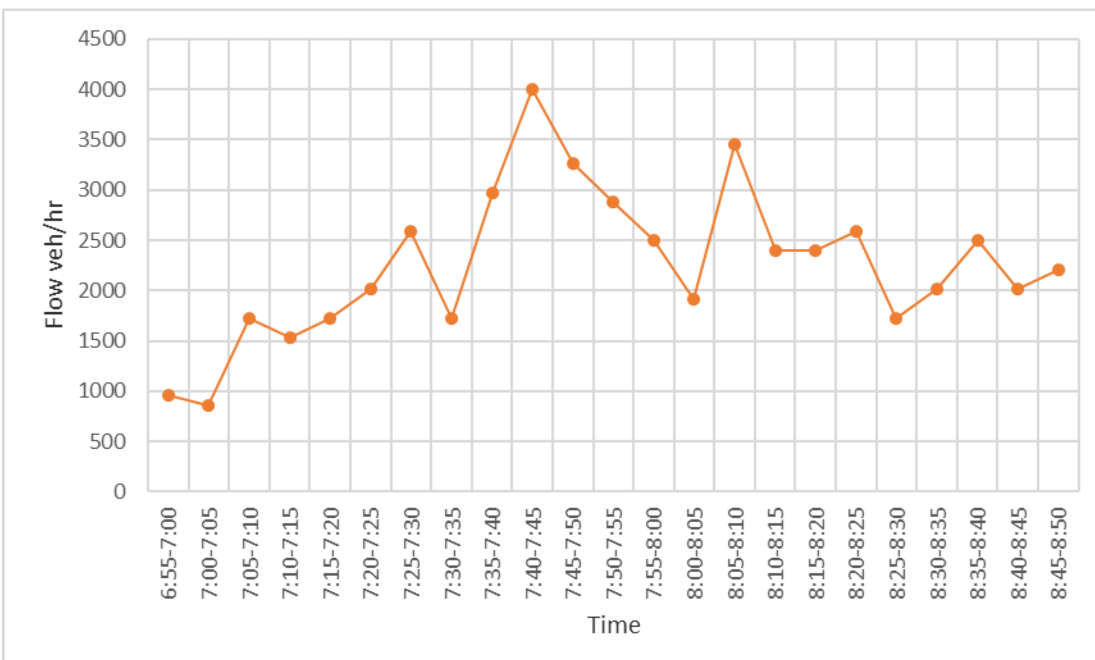


Figure A.12:Fluctuation of flow with time for Street 4 in 9/10/2023 Roundabout Sayid Al-Asaar Al-Jameia

Appendix B

Figure B-1: Collected gases Roundabout Al-Thawra

Time / variables	8:00 AM	8:05 AM	8:10 AM	8:15 AM	8:20 AM	8:25 AM	8:30 AM	8:35 AM	8:40 AM	8:45 AM	8:50 AM	8:55 AM	9:00 AM	units
CO2	526.94	527.86	528.77	530.61	513.19	508.61	504.03	490.17	485.59	484.68	471.08	467.42	466.51	ppm
CO	14.24	13.33	12.41	11.49	10.67	9.75	8.84	6.21	7.13	8.04	8.49	8.70	8.24	ppm
N2O	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.26	0.26	0.26	0.27	0.27	0.27	ppm
CH4	2.23	2.23	2.22	2.20	2.14	2.13	2.12	1.92	1.91	1.91	1.95	1.96	1.97	ppm
Propane	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Butane	0.87	0.87	0.87	0.87	0.71	0.71	0.71	0.60	0.60	0.60	0.64	0.64	0.64	ppm
Benzene	0.21	0.21	0.21	0.21	0.13	0.13	0.13	0.12	0.12	0.12	0.05	0.05	0.05	ppm
Toluene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Ethyl Benzene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Xylene	0	0	0	0	0	0	0	0	0	0	0.091587	0.091587	0.091587	ppm
Acetic Acid	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Formaldehyde	0.15	0.15	0.15	0.15	0.21	0.21	0.21	0.22	0.22	0.22	0.29	0.29	0.29	ppm
Acetaldehyde	0	0	0	0	0	0	0	0.03	0.03	0.03	0	0	0	ppm
Methanol	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Furan	0.02	0.02	0.02	0.02	0	0	0	0	0	0	0	0	0	ppm
Hydrogen cyanide	0	0	0	0	0.07	0.07	0.07	0.14	0.14	0.14	0.13	0.13	0.13	ppm
Chlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Phosgene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Ammonia	0.12	0.12	0.12	0.12	0.07	0.07	0.07	0.10	0.10	0.10	0.05	0.05	0.05	ppm
HCl	0.16	0.16	0.16	0.16	0.10	0.10	0.10	0.10	0.10	0.10	0.07	0.07	0.07	ppm
HF	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm

NO2	0.73	0.74	0.75	0.76	0.59	0.55	0.54	0.49	0.46	0.38	0.31	0.27	0.21	ppm
NO	3.24	3.13	3.12	3.02	2.79	2.76	2.74	2.73	2.64	2.53	2.40	2.39	2.38	ppm
SO2	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.73	0.73	0.73	0.57	0.57	0.57	ppm
Temperature	7.33	7.33	7.33	7.33	7.33	7.33	7.33	7.33	7.33	7.33	8.24	8.24	8.24	C
Wind direction	72.12	72.12	72.12	72.12	61.82	61.82	61.82	41.21	41.21	41.21	30.91	30.91	30.91	Degree
Wind speed	3	3	3	3	3	3	3	3	3	3	3	3	3	Km/hr
RH%	0.55	0.55	0.56	0.56	0.57	0.57	0.57	0.58	0.58	0.58	0.59	0.59	0.59	
Pressure	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	mbar
Noise	73.82	75.56	85.36	72.90	76.02	84.63	74.37	82.61	81.70	98.09	8 0.5	74.19	69.79	dBA
Speed	20-30	20-30	20-30	20-30	24-35	24-35	24-35	30-40	30-40	30-40	40-50	40-50	40-50	Km/h

Figure B-2: Collected gases Roundabout Al-Safina

Time / variables	8:00 AM	8:05 AM	8:10 AM	8:15 AM	8:20 AM	8:25 AM	8:30 AM	8:35 AM	8:40 AM	8:45 AM	8:50 AM	8:55 AM	9:00 AM	units
CO2	427.36	428.10	428.85	430.33	416.20	412.49	408.78	397.54	393.82	393.08	382.06	379.09	378.34	ppm
CO	11.55	10.81	10.06	9.32	8.65	7.91	7.17	5.04	5.78	6.52	6.89	7.06	6.69	ppm
N2O	0.23	0.23	0.23	0.23	0.22	0.22	0.22	0.21	0.21	0.21	0.22	0.22	0.22	ppm
CH4	1.81	1.80	1.80	1.78	1.74	1.73	1.72	1.56	1.55	1.54	1.58	1.59	1.60	ppm
Propane	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Butane	0.71	0.71	0.71	0.71	0.58	0.58	0.58	0.49	0.49	0.49	0.52	0.52	0.52	ppm
Benzene	0.17	0.17	0.17	0.17	0.10	0.10	0.10	0.10	0.10	0.10	0.04	0.04	0.04	ppm
Toluene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Ethyl Benzene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Xylene	0	0	0	0	0	0	0	0	0	0	0.07	0.07	0.07	ppm
Acetic Acid	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Formaldeh	0.12	0.12	0.12	0.12	0.17	0.17	0.17	0.18	0.18	0.18	0.24	0.24	0.24	ppm

yde														
Acetaldehyde	0	0	0	0	0	0	0	0.02	0.02	0.02	0	0	0	ppm
Methanol	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Furan	0.01	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0	ppm
Hydrogen cyanide	0	0	0	0	0.06	0.06	0.06	0.11	0.11	0.11	0.10	0.10	0.10	ppm
Chlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Phosgene	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
Ammonia	0.10	0.10	0.10	0.10	0.06	0.06	0.06	0.08	0.08	0.08	0.04	0.04	0.04	ppm
HCl	0.13	0.13	0.13	0.13	0.08	0.08	0.08	0.08	0.08	0.08	0.06	0.06	0.06	ppm
HF	0	0	0	0	0	0	0	0	0	0	0	0	0	ppm
NO2	0.59	0.60	0.61	0.62	0.48	0.45	0.44	0.40	0.37	0.31	0.25	0.22	0.17	ppm
NO	2.63	2.54	2.53	2.45	2.27	2.24	2.22	2.21	2.14	2.05	1.95	1.94	1.93	ppm
SO2	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.59	0.59	0.59	0.46	0.46	0.46	ppm
Temperature	5.94	5.94	5.94	5.94	5.94	5.94	5.94	5.94	5.94	5.94	6.69	6.69	6.69	C
Wind direction	58.49	58.49	58.49	58.49	50.14	50.14	50.14	33.43	33.43	33.43	25.07	25.07	25.07	Degree
Wind speed	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	Km/hr
RH%	0.45	0.45	0.45	0.45	0.46	0.46	0.46	0.47	0.47	0.47	0.48	0.48	0.48	
Pressure	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	1019	mbar
Noise	59.87	61.28	69.23	59.13	61.65	68.63	60.31	67	66.26	79.55	65.29	60.17	56.60	dBA
Speed	20-30	20-30	20-30	20-30	24-35	24-35	24-35	30-40	30-40	30-40	40-50	40-50	40-50	Km/h

Appendix C

Table C-1: Percentage of each sustainability criterion in the Al-Safina Roundabout

Dimension	Percentage of dimension %(A1)	Criterion	Fuzzy number(A2)	Percentage of criterion%(A3)	Weight of criterion(A1XA2XA3)
Environmental	48.95%	Air pollution	0.2	11.00%	0.0108
		Energy consumption	0.45	7.14%	0.0157
		Noise	0.15	8.93%	0.0066
		GHG emissions	0.6	16.07%	0.0472
		Renewable energy	0.09	12.50%	0.0055
		CO2 emissions	0.25	14.29%	0.0175
		Natural resource consumption	0.1	12.50%	0.0061
		Non-motorized modes	0.4	10.71%	0.0210
		Vibration	0.02	7.14%	0.0007
Social	28.84%	Safety	0.6	10.47%	0.0181
		Health	0.4	9.30%	0.0107
		Travel time	0.5	5.81%	0.0084
		Accessibility	0.15	8.14%	0.0035
		Congestion	0.4	4.65%	0.0054
		Affordability	0.59	5.81%	0.0099
		Accidents	0.05	10.47%	0.0015
		Security	0.47	6.98%	0.0095
		Reachability	0.71	6.98%	0.0143
		Participation	0.59	6.98%	0.0119
		Equality	0.54	8.14%	0.0127
		Fewer private cars	0.04	6.98%	0.0008
		Risk and danger	0.5	9.30%	0.0134
Economic	22.22%	Operation cost	0.65	12.81%	0.0185
		Occupancy	0.59	11.82%	0.0155

		Revenues	0.7	11.82%	0.0184
		Quality	0.55	10.34%	0.0126
		Investment cost	0.6	10.34%	0.0138
		Demand	0.75	8.87%	0.0148
		Subsidy	0.54	8.87%	0.0106
		Reliability	0.1	7.39%	0.0016
		Technical feasibility	0.74	7.39%	0.0122
		Productivity	0.75	5.91%	0.0098
		Cost of delay	0.7	4.43%	0.0069
The total percentage of sustainability					39%

Table C-2: Percentage of each sustainability criterion in the Al-Thawra Roundabout

Dimension	Percentage of dimension %(A1)	Criterion	Fuzzy number(A2)	Percentage of criterion%(A3)	Weight of criterion(A1XA2XA3)
Environmental	48.95%	Air pollution	0.2	11.00%	0.0108
		Energy consumption	0.45	7.14%	0.0157
		Noise	0.15	8.93%	0.0066
		GHG emissions	0.6	16.07%	0.0472
		Renewable energy	0.09	12.50%	0.0055
		CO2 emissions	0.25	14.29%	0.0175
		Natural resource consumption	0.1	12.50%	0.0061
		Non-motorized modes	0.4	10.71%	0.0210
		Vibration	0.02	7.14%	0.0007
Social	28.84%	Safety	0.6	10.47%	0.0181
		Health	0.4	9.30%	0.0107
		Travel time	0.5	5.81%	0.0084
		Accessibility	0.15	8.14%	0.0035
		Congestion	0.4	4.65%	0.0054
		Affordability	0.3	5.81%	0.0050

		Accidents	0.05	10.47%	0.0015
		Security	0.47	6.98%	0.0095
		Reachability	0.71	6.98%	0.0143
		Participation	0.59	6.98%	0.0119
		Equality	0.54	8.14%	0.0127
		Fewer private cars	0.04	6.98%	0.0008
		Risk and danger	0.5	9.30%	0.0134
Economic	22.22%	Operation cost	0.3	12.81%	0.0085
		Occupancy	0.59	11.82%	0.0155
		Revenues	0.02	11.82%	0.0005
		Quality	0.32	10.34%	0.0074
		Investment cost	0.2	10.34%	0.0046
		Demand	0.5	8.87%	0.0099
		Subsidy	0.54	8.87%	0.0106
		Reliability	0.1	7.39%	0.0016
		Technical feasibility	0.5	7.39%	0.0082
		Productivity	0.5	5.91%	0.0066
		Cost of delay	0.5	4.43%	0.0049
The total percentage of sustainability					32%

Appendix D

Table D-1: Recommended CO2 for indoor air quality and outdoor

Source/Agency	Limit (ppm)	Averaging Time	Notes
ASHRAE	1000	General indoor comfort	Recommended for indoor air quality
OSHA	5000	8-hour workday	Occupational exposure limit
NIOSH (TWA)	5000	10-hour workday	Time-weighted average limit
NIOSH (STEL)	30000	15 minutes	Short-term exposure limit
Typical Outdoor Level	400	Ambient air	The normal outdoor background level

Table D-2: Recommended CO2 for indoor air quality and outdoor

CO2 Level (ppm)	Air Quality	Health/Environmental Effects	
350 - 400	Fresh outdoor air	Normal atmospheric level	EPA (https://www.epa.gov/indoor-air-quality-iaq)
400 - 1,000	Good (indoor)	Typical indoor level with adequate ventilation	ASHRAE (https://www.ashrae.org/.../indoor-air-quality.pdf)
1,000 - 2,000	Moderate to stuffy	Drowsiness, lack of fresh air	EPA (https://www.epa.gov/indoor-air-quality-iaq)
2,000 - 5,000	Poor	Headaches, sleepiness, stale air, reduced concentration	OSHA (https://www.osha.gov/chemicaldata/183)
> 5,000	Unsafe	OSHA exposure limit; potential health risk if exposed long-term	OSHA (https://www.osha.gov/chemicaldata/183)
> 10,000	Dangerous	Risk of unconsciousness, asphyxiation, or serious health effects	OSHA (https://www.osha.gov/chemicaldata/183)

Table D-3: Limited of Energy Consumption

Transport Mode	Energy Consumption (kWh/passenger-km)	Source
Electric Car	0.167	IEA, EEA, DOE
Gasoline Car	0.639	IEA, DOE
Diesel Car	0.5	IEA, DOE
Hybrid Car	0.417	DOE
Bus (Diesel)	0.278	IEA, EEA
Bus (Electric)	0.167	IEA
Train (Electric)	0.111	EEA
Train (Diesel)	0.222	EEA
Airplane (Domestic)	0.694	IEA, EEA
Airplane (International)	0.528	IEA, EEA

Table D-4: Limited of Noise

Country/Standard	Noise Limit (dB)	Description
WHO Guidelines	53 dB (Lden)	Recommended limit to prevent health effects
European Union (EU)	55 dB (Lden)	Environmental noise directive for urban areas
United States (EPA)	70 dB (Leq)	Protective level for average outdoor exposure
Germany (TA Lärm)	59 dB (day) / 49 dB (night)	For residential areas near roads
UK (DEFRA)	63 dB (L10)	Urban road traffic daytime limit
Japan	65 dB (day) / 60 dB (night)	For residential zones
Australia (NSW EPA)	60 dB (day) / 55 dB (night)	Road traffic criteria

Table D-5: Limited of Emission intensity

Mode of Transport	Emission Intensity [gCO_2e/pkm]	Note / Source		
Walking / Cycling	0	No emissions		
Electric Train (High-speed, full)	~10–20	Very low when electricity is clean		
Metro / Light Rail	~20–50	Efficient public transport		
Electric Bus (full)	~30–60	Depends on the energy mix		
Diesel Bus (full)	~80–120	Varies by load factor and route		
Car (efficient, 1.5 pax)	~100–150	Shared trips reduce the intensity		
Domestic Flights	~250–350	One of the highest emissions		

*Unfortunately, specific data on the Emission Intensity of Greenhouse Gases [CO2 eq/pkm] isn't available in Karbala. This metric requires detailed studies on local transportation.

At the national level, Iraq was responsible for emitting approximately 252 million metric tons of CO2 equivalent in 2021, ranking 31st globally in total emissions (source: emission-index.com).

Table D-6: Emission intensity in many countries

Country / Block	Minimum Emissions (MtCO2e)	Notes
United States	5000	2030 Target: 50-52% reduction from 2005
European Union	2670	2030 Target: 55% reduction from 1990
China	10000	Peak before 2030, then reduce
India	2500	Future estimates depending on renewables
Russia	1500	Low target, limited commitment
Iraq	190	Lowest recorded in 2022

Table D-7: GHG Emissions in Iraq

Year	GHG Emissions (MtCO2e)	Source
2019	285.96	MacroTrends - https://www.macrotrends.net/global-metrics/countries/IRQ/iraq/ghg-

		greenhouse-gas-emissions
2020	261.29	TheGlobalEconomy.com - https://www.theglobaleconomy.com/Iraq/greenhouse_gas_emissions/
2021	252	Emission Index - https://www.emission-index.com/countries/iraq
2022	190	CountryEconomy.com - https://countryeconomy.com/energy-and-environment/co2-emissions/iraq
2023	192.91	CountryEconomy.com - https://countryeconomy.com/energy-and-environment/co2-emissions/iraq

Table D-8: Limit Renewable Energy

Country / Region	Minimum Share [%]	Maximum Share [%]	Notes	Source
European Union	8	42	8% in 2004, Target: 45% by 2030	IRENA - https://www.irena.org/
United States	6	13	6% in 2005, 13% in 2021 (mainly wind and solar)	IEA - https://www.iea.org/
China	7	26.4	7% in 2005, 26.4% in 2022	World Bank - https://databank.worldbank.org/source/sustainable-energy-for-all
India	5	24.3	5% in 2000, 24.3% in 2022	World Bank - https://databank.worldbank.org/source/sustainable-energy-for-all
Iraq	0.5	1.5	Estimated <1%, around 1.5% in 2022	IRENA / National estimates
Norway	60	90	>90% for decades, mostly hydropower	IEA / Norwegian statistics

Table D-9: Renewable energy in Iraq

Aspect	Current Status	Notes / Comparisons
Renewable Energy in Iraq	Does not exceed 1.5%	Global average exceeded 29% in 2022 (Source: IRENA, *Renewable Capacity Statistics 2023*)
Infrastructure	Solar and wind projects are still in pilot or planned stages	No comprehensive infrastructure yet
Dependence on Fossil Fuels	Almost complete reliance on oil and gas-fired power plants	A major barrier to the clean energy transition
Political and Security Stability	Political and security instability hinders sustainable investment	Negatively impacts long-term project implementation
Future Projects	Agreements with international companies like Total Energies and Masdar to build solar plants	A positive indicator of intention to shift
National Renewable Energy Plan	Aims to increase the renewable energy share to 20–30% by 2030	If properly implemented, it can lead to significant improvement
Conclusion	**Currently: Unsuccessful**	**Future: Potential to improve if plans are implemented**

Table D-10: Carbon footprint

Aspect	Details	Sources / Notes
Carbon Emissions Limits	No single fixed upper limit; varies by country, sector, and international agreements.	Based on global climate policies and frameworks
Key Factors	- Country status (developed vs. developing) - Sector (transport, industry, energy, etc.) - Climate agreements (e.g., Paris Agreement)	The Paris Agreement aims to limit global warming to below 2°C compared to pre-industrial levels.
Global Carbon Budget	To stay below 1.5°C warming, global CO_2 emissions should not exceed **400–500 gigatonnes.**	Source: Global Carbon Budget principles
Per Capita Acceptable Emissions	Average climate-safe emissions: **~2 tons CO_2 per person per year** Some studies suggest a tighter limit of **1.5 tons** per person per year	Widely used benchmark in climate studies
Conversion to Gg CO_2	1 gigaton = 1,000,000 gigagrams Therefore, 2 tons CO_2 per capita = **0.002 Gg CO_2** per capita per year	Standard unit conversion
Iraq's Current Emissions	**4 tons CO_2 per person per year.** Refer to: Worldometer – Iraq CO_2 Emissions	Data includes historical emissions and per capita values

Table D-11: Natural resource

Indicator	Description	Critical Threshold	Source
Use of natural resources (min)	Natural resource consumption / Degree of depletion of natural resources [%]	Approaching or >100% indicates unsustainable resource use	General sustainability literature
Ecological Footprint	Measures how much nature we use compared to how much it can regenerate	~170% (Global average, 2023)	https://www.footprintnetwork.org/
Overshoot Day	The date when humanity's demand exceeds what Earth can regenerate in a year	August 2nd, 2023	https://www.overshootday.org/
Country Examples	Some countries consume >500%-1000% of what their ecosystems can renew annually	Qatar, Luxembourg, UAE are among the highest	https://data.footprintnetwork.org/

Table D-12: Natural Resource Use in Iraq

Aspect	Details	Sources
Ecological Deficit	Iraq has an ecological deficit of approximately **-470%**, meaning it consumes about **4.7 times** more resources than its ecosystems can regenerate.	Global Footprint Network – Iraq Data

Ecological Footprint per Capita	**~1.8 global hectares** per person	World Population Review – Ecological Footprint by Country
Biocapacity per Capita	Only around **0.3 global hectares** per person	Global Footprint Network – Iraq Data
Natural Resource Dependency	Iraq heavily relies on **natural resource extraction**, mainly oil.	
Natural Resource Rents	A **significant portion of GDP** comes from natural resource rents.	World Bank – Natural Resource Rents (% of GDP)

Table D-13: Use of environmentally friendly modes

Sustainability Rating	Recommended Share of Non-Motorized Trips (%)	Source
Excellent	>= 50%	Victoria Transport Policy Institute (https://vtpi.org/tdm/tdm25.htm)
Good	35% - 49%	UN-Habitat – Sustainable Urban Mobility (https://unhabitat.org)
Moderate	20% - 34%	World Bank Urban Mobility Guidelines (https://www.worldbank.org/en/topic/transport)
Poor	< 20%	Victoria Transport Policy Institute (https://vtpi.org/tdm/tdm25.htm)

Table D-14: environmentally friendly modes in Karbala

Indicator	City	Estimated Share (%)	Source
Use of public transport during peak hours	Karbala	< 20%	https://www.e3s-conferences.org/articles/e3sconf/pdf/2023/64/e3sconf_icgee2023_04009.pdf
Share of non-motorized trips (e.g., walking, cycling)	Karbala	Data not available	Not reported in official studies
Non-motorized trips during the Arbaeen pilgrimage	Karbala	Very high (millions walking)	https://shafaq.com/en/Iraq/More-than-3-4-foreign-pilgrims-entered-Iraq-for-the-Arbaeen-official

Table D-15: Acceptable Vibration Frequency

Application Area	Acceptable Vibration Frequency [Hz]	Notes	Source
Human comfort (general)	4 – 8 Hz	Most disturbing frequencies for humans fall in this range.	ISO 2631-1 & ISO 2631-2 (https://www.iso.org)
Residential buildings	< 80 Hz	According to ISO 2631-2, vibrations should stay within this range for comfort.	British Standard BS 6472
Sensitive equipment	< 1 – 5 Hz	Highly sensitive to vibration; used in labs and precision facilities.	FTA Vibration Manual (https://www.transit.dot.gov)

(labs, etc.)			
Bridges, structures	< 20 Hz	To prevent resonance and ensure structural stability.	ISO 2631-2 (https://www.iso.org)

In Iraq, the vibration was recorded at about 94 decibels, approximately 100 to 200 hertz, higher than the permissible limits.

Table D-16: Noise Pollution

Category	Standard / Study	Description	Source
International Standards	**ISO 2631-1 & ISO 2631-2**	Evaluation of human exposure to whole-body vibration	ISO
	Federal Transit Administration (FTA)	Transit Noise and Vibration Impact Assessment Manual	FTA
	British Standard BS 6472	Evaluation of human exposure to vibration in buildings	Not publicly available online (N/A)
Local Iraqi Research	**Noise Pollution in Baghdad City**	Research article on urban noise levels in Baghdad	University of Karbala Journal
	Noise Mapping in Baghdad Using GIS	Study applying GIS tools to map noise levels across Baghdad	Iraqi Journal of Science
	Noise Pollution in Karbala City	Study on environmental noise levels in Karbala	College of Engineering, University of Karbala (access via university archives)

Table D-17: Limit of different indicators

Indicator	Global Threshold (Max/Min)	Reference/Source
Carbon footprint (CO_2 from fossil fuels) [Gg CO_2]	As low as possible – ideally below 1,000,000 Gg CO_2	IEA & UNFCCC Reports
Use of natural resources (Degree of depletion) [%]	Below 20% (sustainable use level)	UN Environment Programme (UNEP) Reports
Use of environmentally friendly modes (Share of non-motorized trips) [%]	Over 50% for sustainable urban mobility	European Commission & Sustainable Urban Mobility Plans
Vibration level [Hz]	Less than 80 Hz (for comfort in urban areas)	ISO 2631 & Building Research Establishment Guidelines
Protection against accidents (Injuries per Km traveled per mode per day)	Over 50,000 km per injury (higher is better)	PPIAF Urban Bus Toolkit, Vision Zero Initiatives

Table D-18: Global Benchmark (Injuries per Billion Km Traveled)

Mode of Transport	Global Benchmark (Injuries per Billion Km Traveled)	Reference/Source
Walking	40	OECD/ITF Road Safety Annual Report
Bicycling	25	European Transport Safety

		Council (ETSC)
Motorcycling	250	WHO Global Status Report on Road Safety
Car (Private)	3	UK Department for Transport Statistics
Bus (Public Transport)	0.5	
Train	0.1	International Union of Railways (UIC)

Table D-19: Injury Type in Karbala

Injury Type	Percentage (%)	Source
Head Injuries (General)	35.1	Risk Factors and the Pattern of Injuries of Road Traffic Accidents in the Holy City of Karbala, Iraq (2022)
Lower Limb Injuries (General)	32.3	Risk Factors and the Pattern of Injuries of Road Traffic Accidents in the Holy City of Karbala, Iraq (2022)
Upper Limb Injuries (General)	10.5	Risk Factors and the Pattern of Injuries of Road Traffic Accidents in the Holy City of Karbala, Iraq (2022)
Head and Face Injuries (Motorcycle-specific)	41.8	Risk Factors and Pattern of Injuries in Motorcycle Accidents in Holy Karbala (2018)
Lower Limb Injuries (Motorcycle-specific)	51.3	Risk Factors and Pattern of Injuries in Motorcycle Accidents in Holy Karbala (2018)
Upper Limb Injuries (Motorcycle-specific)	21.3	Risk Factors and Pattern of Injuries in Motorcycle Accidents in Holy Karbala (2018)

Table D-20: Injuries per Million Km

Safety Level	Injuries per Million Km (per mode per day)	Source
Excellent	< 0.05	WHO, OECD Transport Safety Data
Very Good	0.05 - 0.1	WHO, OECD Transport Safety Data
Good	0.1 - 0.5	WHO, OECD Transport Safety Data
Average	0.5 - 1.0	WHO, OECD Transport Safety Data
Poor	> 1.0	WHO, OECD Transport Safety Data

Table D-21: Traffic accident in Karbala

Category	Details	Source
Overview	Karbala is witnessing a worrying increase in road traffic accidents, leading to human and material losses.	
Traffic Accident Statistics	Over **618 injuries and fatalities** were reported in the **first half of 2023** More than **two accidents per day on average**	alsumaria.tv
Main Causes of Accidents	**Driver behavior** accounts for **79.2%** (speeding, phone use, etc.) Poor infrastructure and unsafe vehicles	to naseemkarbala.net

	also contribute heavily	
Infrastructure Issues	Bad road conditions and a lack of proper signage increase accident risks	Included in various local reports
Vehicle Safety	Many imported vehicles lack essential safety features.	
Measures Taken	- **Road expansion** (e.g., Karbala–Najaf road) improved safety in sections - **Awareness campaigns** - **Increased surveillance**	rudawarabia.net, karbala.gov.iq
Spatial Distribution	High accident concentration at intersections lacking signals and on major roads leading into the city	library.uoKarbala.edu.iq
Recommendations	- Upgrade infrastructure - Promote traffic safety education - Enforce stricter penalties for violations	Summarized from official insights and research

.Table D-22: Traffic accident in Karbala2023

Category	Details	Sources
1. Global Safety Standards	- Acceptable injury rate for transit systems: **< 0.05 injuries** per million kilometers - Road vehicles: **0.5–1 injury** per million km	WHO Road Safety Report OECD Report
2. Karbala Traffic Data	- **Over two accidents per day** (~60 monthly) - **More than 618 injuries and fatalities** in the first half of 2023	**Ministry of Planning – Republic of Iraq** https://mop.gov.iq
3. Comparative Analysis	- **Estimated vehicles**: 50,000 - **Avg. distance**: 30 km/day - **Total travel**: 1,500,000 km/day $\text{Accident Rate} = \left(\frac{\text{Number of Accidents}}{\text{Total Distance Traveled}}\right) \times 1,000,000$ - $\text{Accident Rate} = \left(\frac{2}{1,500,000}\right) \times 1,000,000 = \mathbf{1.33}\ \text{accidents per million km}$	Calculated from available data
4. Conclusion	Karbala's accident rate: The actual accident rate is approximately **1.33 accidents per million kilometers, which exceeds global safety thresholds**, indicating an **urgent traffic safety concern**	Based on WHO and OECD benchmarks

Table D-23: Limit Injury Severity

Scale Name	Definition	Range	Severity Classification	Source
Injury Severity Score (ISS)	A medical score to assess trauma severity in patients with multiple injuries.	1 - 75 (higher is more severe)	1-8: Minor, 9-15: Moderate, 16-24: Severe, >25: Critical	https://pubmed.ncbi.nlm.nih.gov/8680606/
Glasgow Outcome Scale (GOS)	Used to categorize outcomes after traumatic brain injury.	1 - 5 (1=Death, 5=Good Recovery)	1: Death, 2: Persistent vegetative state, 3: Severe disability, 4: Moderate disability, 5: Good recovery	https://en.wikipedia.org/wiki/Glasgow_Outcome_Scale

APACHE II	Scoring system to measure disease severity for adult ICU patients.	0 - 71 (higher indicates more severe illness)	No strict classification, but higher scores = higher mortality risk	https://en.wikipedia.org/wiki/APACHE_II
Abbreviated Injury Scale (AIS)	Used to assess the severity of individual injuries in different body regions.	1 - 6 (1=Minor, 6=Unsurvivable)	1: Minor, 2: Moderate, 3: Serious, 4: Severe, 5: Critical, 6: Unsurvivable	https://road-safety.transport.ec.europa.eu/european-road-safety-observatory/statistics-and-analysis-archive/post-impact-care/impairment-disability-and-loss-function-scales-and-scores_en

Table D-24: Injury Severity

Injury Severity Category	**Estimated % of Cases**	**Estimated Number of Cases**	**Injury Severity Score (ISS) Range**	
Minor	50%	2000	1 – 8	Approximate Estimation of Injury Severity in Karbala - 2023 Based on data from Imam Hussein Medical City, around 4000 traffic-related injury/death cases were reported during the first half of 2023 in Karbala. This estimation applies the Injury Severity Score (ISS) system to categorize injury levels: - Minor Injuries: ISS 1–8 - Moderate Injuries: ISS 9–15 - Severe Injuries: ISS 16–24 - Critical Injuries or Deaths: ISS >25 These categories are based on international ISS classifications (Source: https://pubmed.ncbi.nlm.nih.gov/8680606/). Note: These are approximate values and should be validated using official health datasets or trauma registries for accuracy.
Moderate	30%	1200	9 – 15	
Severe	15%	600	16 – 24	
Critical/Death	5%	200	>25	

Table D-25: Injury Severity from Hospital

Category	**Details**	**Source**
Total Number of Cases	Approximately **618accident-related cases** occurred during the first 6 months of 2023.	Statistics from **Imam Hussein Hospital, Karbala**
Injury Severity (ISS)	**- Head injuries** **- Fractures of the extremities** (especially lower limbs) **- Abdominal and chest injuries**	Based on **local studies**

	- Polytrauma	
Health Impact Severity (HIS)	The approximate **average ISS score** for all cases is **10-12**.	Indicates **moderate to critical injury severity** (most cases had moderate severity, with critical cases too)
Impact Summary	A significant proportion of cases involved **serious injuries and deaths**, with many cases requiring urgent medical care.	Based on local health impact assessments and hospital data

Table D-26: Speed and travel time limits

To determine the speed and travel time limits for transportation services in a city, these limits typically depend on several factors related to infrastructure, transportation type, and traffic density.
Possible limits for city transportation speed limits:
Maximum Speed:
In major cities, the maximum speed typically ranges between 50-80 km/h on major roads.
In urban areas, the maximum speed is typically 50-60 km/h, but it may drop to 30-40 km/h in densely populated areas or narrow streets.
Average Speed:
In cities with high traffic density, the average speed may range between 20-40 km/h in urban areas with heavy traffic.
In cities with a developed infrastructure, the average speed may reach 50-60 km/h.
Travel Time:
Typical travel time within a city depends on distance, traffic density, and available means of transportation. For example:
A distance of 5 to 10 km may take approximately 10-30 minutes.
A distance of 10 to 20 km may take approximately 30-60 minutes in heavy traffic conditions.
Other influences:
Public transportation system: In cities that rely on public transportation, such as buses and trains, average speeds may be slower than those used by private cars.
Infrastructure: The presence of a network of highways, tunnels, and bridges may increase average speeds.
Areas with high traffic density, such as city centers or commercial areas, may experience a significant reduction in average speeds.
References and sources: Report from the International Transport Organization (ITO): (e.g., World Bank - Transport Sector (https://www.worldbank.org/en/topic/transport)). Local studies of major cities: Transportation speeds can vary from city to city based on specific factors.

Table D-27: Speed Classification and range

Speed Classification	Speed Range	Description	Example Locations
1. Low Speed	Less than **20 km/h**	Found in areas with heavy traffic, residential areas, or narrow streets requiring increased safety.	Residential areas with heavy congestion
2. Moderate Speed	**20–50 km/h**	Common in cities with moderate traffic, such as Karbala, during normal times.	Karbala (30-40 km/h)
3. High Speed	**50–80**	Achieved in cities with good infrastructure or	Highways or well-

	km/h	on major roads with less dense traffic.	developed urban areas
4. Very High Speed	Over **80 km/h**	Found on highways, expressways, or rapid transport systems like trains and express trains.	High-speed rail systems, expressways

Table D-28: Limit equity and social inclusion standard

Standard	Description	Global Accessibility Standards	References/Sources
1. Accessibility	The ability to access places and services easily without barriers. Includes infrastructure such as roads, transportation, and public facilities.	- **Minimum**: 90% of public buildings and facilities in major or developed cities should be accessible to people with disabilities, including wheelchair ramps.	United Nations CRPD: Convention on the Rights of Persons with Disabilities
2. Mental Accessibility	Refers to the ability of people with intellectual or psychosocial disabilities to access information and services easily. Includes designs that accommodate people with cognitive impairments or mental disabilities.	- **Minimum**: Information must be understandable for people with intellectual or psychosocial disabilities, using simple language, visual symbols, or assistive technology.	United Nations CRPD
Direction & Guidance	Public systems should provide clear and easy-to-understand directions for people with intellectual disabilities.	- Direction systems should be simple and understandable for people with intellectual disabilities.	United Nations CRPD

Table D-29: Equity and social in Karbala

Category	Sub-Category	Global Standard	Karbala Classification	Description	Sources
1. Physical Accessibility	Accessibility of buildings and streets	80–90% of public facilities must be accessible to people with disabilities.	60–70% accessible → **Moderate Accessibility**	Karbala has seen improvements, but still lacks widespread accessibility across all areas.	WHO, ADA, CRPD
Low Accessibility	< 50% accessible	Not applicable to Karbala	Reflects severe barriers and a lack of accessibility infrastructure.		
High Accessibility	> 80% accessible	Goal for future improvements	Indicates strong infrastructure adaptation for people with disabilities.		

2. Mental Accessibility	Access to understandable information & services	Minimum 60% for high accessibility; use of clear language, symbols, or assistive tech.	< 50% accessible → **Moderate Mental Accessibility**	Karbala is in the early stages of mental accessibility efforts. Limited systems for cognitive impairments; improvement needed.	WHO, CRPD
Low Mental Accessibility	< 30%	Not applicable to Karbala	Indicates major gaps in accessible information or support for mental disabilities.		
High Mental Accessibility	> 60%	Target for future development	Use of assistive tech and simplified communication formats.		
Sustainability Standards	Sustainable Street Design (LEED-ND, Complete Streets)	At least 70–80% of sustainability elements must be met.	Karbala: Improving, but not meeting full criteria yet	Requires streets to meet environmental, social, and safety design principles.	World Bank, UN SDG 10, Amnesty
Key Notes	-	-	-	Karbala, like many developing cities, is progressing but needs stronger implementation of inclusive design and mental accessibility features.	PubMed, Google Scholar

Table D-30: Time spent traveling under congested conditions [minutes]

Indicator	Definition	Global Benchmark / Example	Karbala Value	Interpretation	Sources
Travel Time Index (TTI)	Ratio of travel time during peak hours to free-flow conditions.	TTI = 1.3 means trips take 30% longer in peak times. In congested cities, TTI can	Estimated TTI not provided	Used to measure peak-hour traffic inefficiency. Higher values reflect more congestion.	Urban Mobility Report – Texas A&M

		exceed **1.35.**			
Planning Time Index (PTI)	Ratio of 95th percentile travel time to free-flow time.	PTI = 2.5 means plan 75 minutes for a trip that takes 30 minutes under ideal conditions.	Estimated PTI not provided	Indicates trip reliability. Higher PTI values require more buffer time to arrive on time.	FHWA Reliability Metrics
Road Accident Mortality Rate	Deaths per 100,000 population annually.	Global average: **15 deaths / 100,000 people (2021)** according to WHO.	Not specified for Karbala	It could be calculated with local fatality data.	WHO Road Safety Report 2023
Road Accidents per 100,000	Number of traffic accidents reported annually per 100,000 people.	Varies by country and city.	**44 accidents / 100,000 people (2023)**	Indicates a moderate to high incident rate compared to cities with stricter road safety enforcement.	[Iraq Transport & Communication Stats 2023]
Total Road Accidents	Total number of reported accidents annually.	-	**540 accidents (Karbala, 2023)**	Reflects the burden on health, police, and infrastructure services.	[Directorate of Transport & Communications – Iraq 2023]
Population	Number of residents in the city.	-	**1,204,505.2 (Karbala, 2023)**	Used for calculating per capita accident rates.	[Iraq Central Statistical Organization]

Table D-31: Risk Management in Karbala

#	Type of Risk	Activity / Initiative	Responsible Entity	Details / Outcome	Source
1	**Financial / Strategic Risk**	Study on **Credit Risk Management** and its role in **preventing organizational collapse** in Iraqi banks.	University of Karbala – College of Administration	Assessed credit, financial, operational, and strategic risks in Iraqi banking institutions.	University of Karbala – Study
2	**Traffic Safety Risk**	**Scientific seminar** on traffic system issues in Karbala and traffic safety awareness.	University of Karbala – College of Medicine	Aimed to spread a traffic safety culture among students and the wider community.	Seminar Reel – Instagram
3	**Health / Environmental Risk**	**Awareness campaign** in schools on transmissible diseases, water	Karbala Environment Directorate	Promoted public health practices and hygiene education, especially for	Environment Directorate – Facebook

		usage, and hygiene.		children.	
4	**Fire Risk**	**Fire risk reduction measures** and activation of **emergency teams** during the summer.	Karbala Governorate	Coordinated emergency response between departments to mitigate fire risks during high-temperature seasons.	Governorate Website
5	**Disaster / Emergency Risk**	Radio program on the **role of civil defense** in protecting people and property.	Al-Hussain Holy Shrine Radio	Highlighted fast response, risk preparedness, and community safety.	Al-Hussain Holy Shrine Radio Broadcast

Table D-32: System Reliability and Availability of Transportation Mode (On-time)

Category	Definition	Global Standards / Best Practices	Karbala Situation	Sources
System Reliability	Ability of transport to operate consistently without failures or disruptions.	**ISO 17020** – Ensures system reliability through assessment and performance consistency.	Reliability is challenged during peak events (e.g., Arbaeen), resulting in system strain and vehicle breakdowns.	ISO.org
On-Time Performance	Percentage of services (buses, taxis) arriving/departing as scheduled.	Target: **95–98%** on-time performance (e.g., APTA, UITP benchmarks).	Performance drops significantly during religious events due to congestion and delays.	APTA, UITP
Service Availability	The percentage of time public transport is available for users.	Target: **99–100%** availability in developed cities.	Availability is limited during non-peak hours and becomes overwhelmed during high-demand periods.	World Bank Transport
Public Transport Fleet	The variety and Frequency of public transport services.	Developed cities operate buses, metros, and trains with fixed schedules and large fleets.	Karbala depends mostly on **taxis and private buses**; it lacks a large-scale, frequent public transit network.	Local observations
Mean Time Between Failures (MTBF)	Time between equipment failures (reliability measure).	High MTBF indicates strong reliability – used in rail/bus systems globally.	MTBF data unavailable, but anecdotal reports indicate frequent vehicle issues during peak usage.	ISO 9001
Mean Time To Repair (MTTR)	Average time to repair a system after a breakdown.	Lower MTTR means faster service	Delays in vehicle repairs can further strain service during	ISO/IEC Reliability Metrics

		restoration.	pilgrimage season.	
Infrastructure Support	Physical and organizational structures that enable transport systems.	Requires well-maintained roads, stations, and support systems.	Infrastructure in Karbala is **underdeveloped**, especially compared to major global cities.	Local government reports
Special Events Response	The system's ability to scale for large crowds during special occasions.	Global cities implement flexible transport plans (e.g., event buses, reroutes, crowd control systems).	Karbala experiences a surge in bus usage during Arbaeen, but often lacks the full infrastructure or coordinated planning to support it.	[Iraq Ministry of Transport]

Table D-33: Sustainability Assessment Systems – Certification Levels and Percentages

Certification Level	Required Points	Required %
Chapter One: LEED-ND Certification Levels		
Certification Level	Required Points	Required %
Certified	40 - 49 points	40% - 49%
Silver	50 - 59 points	50% - 59%
Gold	60 - 79 points	60% - 79%
Platinum	80+ points	80% or more
Chapter Two: BREEAM Communities Certification Levels		
Certification Level	Required Points	Required %
Pass	≥ 30% of total points	≥ 30%
Good	≥ 50% of total points	≥ 50%
Very Good	≥ 60% of total points	≥ 60%
Excellent	≥ 70% of total points	≥ 70%
Chapter Three: Green Star – Communities Certification Levels		
Certification Level	Required Points	Required %
Certified	≥ 40 points	≥ 40%
Silver	≥ 50 points	≥ 50%
Gold	≥ 60 points	≥ 60%
Platinum	≥ 70 points	≥ 70%
Chapter Four: CASBEE for Urban Development		
Certification Level	Required Points	Required %
Class B	60 - 69 points	60% - 69%
Class B+	70 - 79 points	70% - 79%
Class A	80+ points	80% or more
Chapter Five: GSAS – Urbanism		
Certification Level	Required Points	Required %
Certified	≥ 50 points	≥ 50%
Silver	≥ 60 points	≥ 60%
Gold	≥ 70 points	≥ 70%
Platinum	≥ 80 points	≥ 80%

الخلاصة

تُقدِّم هذه الدراسة تقييماً شاملاً ومتعدد التخصصات وحسّاساً للسياق لمدى استدامة النقل الحضري في مدينة كربلاء، العراق. وتهدف إلى معالجة التحديات المعقدة التي تواجه التنقل الحضري في المدن سريعة النمو، من خلال صياغة إطار تحليلي متين ومرن يدمج الأبعاد البيئية والاجتماعية والاقتصادية للاستدامة. وبهذا، تسد الفجوات الحرجة في نماذج التقييم القائمة التي غالباً ما تفشل في مراعاة التعقيدات الاجتماعية-المكانية والبنيوية في مدن الجنوب العالمي.

لتحقيق هذه الأهداف، تم اعتماد منهجية متعددة تجمع بين عملية التحليل الهرمي (AHP) والمنطق الضبابي (Fuzzy Logic) ونظم المعلومات الجغرافية .(GIS) وقد مكّن هذا النهج من تطوير نموذج مرن لاتخاذ القرار متعدّد المعايير (MCDM) قادر على قياس أداء استدامة شبكة الطرق الحضرية في كربلاء من الناحيتين المكانية والمفهومية. بدأت الدراسة بمراجعة أدبية موسعة شملت 197 مصدراً علمياً، استُخلصت منها 33 مؤشراً للاستدامة صُنّفت بشكل منهجي ضمن الأبعاد البيئية والاجتماعية والاقتصادية.

ارتكزت الدراسة التطبيقية على 18 تقاطعاً رئيسياً وممرات حضرية في مركز كربلاء، خصوصاً المناطق التي تربط المركز التجاري المركزي (CBD) بالمناطق السكنية والتجارية والمؤسسية عالية الكثافة. جُمعت البيانات الأساسية خلال ساعات الذروة لثلاثة أيام متتالية في أكتوبر 2023، وشملت عدّ المركبات، أزمنة الرحلات، هندسة الطرق، معدلات الحوادث، والقياسات البيئية مثل مستويات الضوضاء وتركيز الملوثات الهوائية. استُخدمت أجهزة متقدمة مثل جهاز GASMET DX4040 FTIR لرصد ملوثات تشمل ثاني أكسيد الكربون(CO_2) ، ثاني أكسيد النيتروجين(NO_2) ، ثاني أكسيد الكبريت(SO_2) ، الميثان(CH_4) ، الأمونيا (NH_3) والبنزين، مما وفّر تقييمات بيئية دقيقة وفورية.

أظهر التحليل الطوبولوجي والهندسي أن شبكة الطرق، خصوصاً في منطقة المركز التجاري، تتخذ شكلاً متشعباً يشبه الأشجار، مع مؤشرات ألفا وبيتا وغاما منخفضة وضعف في ترابط الرسم البياني النسبي .(RNG)هذه العيوب البنيوية تؤدي إلى ضعف إمكانية الوصول، ضعف الترابط الداخلي، وانعدام البدائل الطرقية، مما يقوض مرونة وكفاءة النظام المروري.

أما تحليل أنماط التنقل فقد كشف عن اعتماد كبير على السيارات الخاصة التي شكّلت 73% من حركة المرور في ساعات الذروة، بينما شكّلت الحافلات 6% والميني باص 21% فقط. هذا الخلل يؤدي إلى تفاقم الازدحام وزيادة التأخيرات وتكاليف التشغيل والأثر البيئي. وسُجلت مستويات ضوضاء تتجاوز 107 ديسيبل في ممرات حرجة مثل شارع التربية، متخطية بكثير الحدود الدولية التي وضعتها منظمة الصحة العالمية (WHO) والهيئة المركزية لمكافحة التلوث (CPCB) ووكالة حماية البيئة الأمريكية .(EPA)

وبالتوازي، أظهرت تحاليل جودة الهواء مستويات مرتفعة من الملوثات، ما يشكل خطراً صحياً جسيماً على السكان خاصة في المناطق عالية الكثافة والضعيفة التهوية.

أظهر التقييم باستخدام AHP أن المؤشرات البيئية كانت الأكثر أهمية بوزن نسبي بلغ 48.95%، تلتها المؤشرات الاجتماعية (28.84%) ثم الاقتصادية (22.22%). وتراوحت درجات الاستدامة الكلية بين 29% و39%، ما يعكس أداءً ضعيفاً يستدعي تدخلات عاجلة. وعند مقارنة أداء كربلاء مع أطر الاستدامة العالمية مثلLEED و Green Star و CASBEE و GSAS و BREEAM Communities ، تبين أن المدينة فشلت في تلبية الحدود الدنيا لجميع الأنظمة عداBREEAM ، مما يؤكد الحاجة إلى أدوات تقييم مرنة وحساسة للسياق المحلي.

لعبت النمذجة المكانية باستخدام GIS دوراً محورياً في عرض وتحليل ديناميكيات المرور، بؤر الازدحام، ومناطق الضغط البيئي، كما ساعدت في تحديد الممرات ذات الإمكانات العالية للتنمية والاستثمار في البنية التحتية المستدامة. ومع ذلك، لوحظت عوائق عملية مثل نزاعات الملكية، نقص التمويل البلدي، الجمود المؤسسي، ومقاومة بعض المجتمعات المحلية.

تدعو الدراسة إلى تحول جذري في تخطيط النقل الحضري، بالانتقال من السياسات المجزأة والتفاعلية إلى استراتيجيات متكاملة واستباقية قائمة على الاستدامة. وتشدد على أهمية صُنع السياسات الشاملة، وأنظمة دعم القرار القائمة على البيانات، والأطر التخطيطية طويلة الأمد التي تتماشى مع الاحتياجات المحلية والأجندات العالمية للتنمية. وقد تم تصميم الإطار المقترح خصيصاً ليناسب النسيج الحضري لمدينة كربلاء، مع قابليته للتوسع والتطبيق في مدن أخرى من الجنوب العالمي تواجه تحديات مماثلة.

وباختصار، تساهم هذه الأطروحة في تطوير نموذج جديد وشامل لتقييم الاستدامة يجمع بين الصرامة العلمية والملاءمة العملية، ويزوّد المخططين الحضريين والمهندسين وصناع القرار بأدوات لتقييم وتصميم وتنفيذ حلول تنقل مستدامة تعزز من المرونة والعدالة وجودة الحياة في البيئات الحضرية المعقدة.

جمهورية العراق

وزارة التعليم العالي و البحث العلمي

جامعة كربلاء

كلية الهندسة

قسم الهندسة المدنية

تقييم ونمذجة مؤشرات الاستدامة لشبكة الطرق الحضرية في مدينة كربلاء (كدراسة حالة)

اطروحة مقدمة الى مجلس كلية الهندسة / جامعة كربلاء وهي جزء من متطلبات نيل درجة الدكتوراة في علوم الهندسة المدنية/بنى تحتية

المؤلف:

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رجب - 1443 شباط – 2025