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Sustainable Public Transportation for Karbala City: TRAM As a Case Study

A Thesis Submitted to the Department of Civil Engineering, University of Kerbala in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy of Science in Civil Engineering (Infrastructure Engineering)

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DEDICATION

To my family

ABSTRACT

Rapid urbanization, population growth, and the increasing number of vehicles have significantly worsened congestion, air pollution, and noise in Karbala City. This problem leads to increase the travel time, air pollution, traffic accidents and adverse effects on the comfort of passengers. In order to solve this problem, a strategic policy was developed including the establishment of a tramway networks in Karbala City to meet the increasing of transport needs, as well as alleviate the problem of traffic congestion.

The tram system was selected over other public transport modes such as buses or metro due to its balanced advantages. Unlike buses, they offer higher capacity, lower emissions, and reliable fixed routes, while being more cost-effective and feasible for mid-sized cities than metro systems.

The research began with an assessment of current transport conditions including traffic flow, speed, delays, air pollutants (CO, CO_2, NO_2, PM2.5, PM10), Air Quality Index (AQI), and noise. The assessment results showed that over 70% of road segments operated at critical LOS (D–F), more than half of the corridors recorded unhealthy AQI levels, and noise levels exceeded WHO thresholds.

To identify optimal tram routes, the main criteria were selected: LOS, land use, delay time, air quality, and traffic noise. Station location criteria included land use, population, and accessibility, with a preferred walking distance of 300–500 meters from vital places.

Analytical Hierarchical Process (AHP) was used for weighing the main criteria based on Saaty's nine-point comparison scale. The AHP weighting process revealed that the LOS had the highest weight (37.8%), followed by

land use (29.4%), delay (19.1%), AQI (8%), and noise (5.6%). For station selection, walking distance was the greatest importance (56%).

A GIS-based Multi-Criteria Decision-Making (MCDM) framework was applied, producing four tram route alternatives with total length of 61.23 km and 106 stations. Routes were evaluated for accessibility, service area, residential coverage, and construction costs using CRITIC and EDAS methods. Route 1 ranked highest, followed by Routes 2 and 4, while Route 3 was least suitable.

Microsimulation modeling using PTV VISSIM was conducted to simulate two traffic scenarios, the existing conditions and post-tram implementation. The results showed substantial improvements: LOS F and E segments dropped from 70% to zero, average traffic speed rose by 131%, delays decreased by over 60%, and emissions were reduced by 13–60%. Public transport coverage and efficiency also improved significantly.

The study concludes that implementing a tram system in Karbala would offer a sustainable solution to traffic congestion, environmental pollution, and mobility inequality. The proposed framework can also be adapted for transit planning in other mid-sized cities of developing countries.

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ABBREVIATIONS/ACRONYMS	
AHP	Analytic Hierarchy Process
AQI	Air Quality Index
BRT	Bus Rapid Transit
CO	Carbon monoxide
CO_2	Carbon dioxide
CBD	Central Business District
CFCs	Chlorine Fluorocarbons
CPCB	Central Pollution Control Board
CRITIC	Criteria Importance Through Intercriteria Correlation
DEM	Digital Elevation Model
EDAS	The Evaluation based on Distance from Average Solution
ES	Expert Systems
FIS	Fuzzy Inference System
GIS	Geographic Information System
HCM	Highway Capacity Manual
HCs	Hydrocarbons
LCP	Least Cost Path
LOS	Level of service
LRT	Light Rail Transit
MCDM	Multi Criteria Decision Making Methods
MRT	Metro Rail Transit
NO_2	Nitrogen dioxide
PMX	Particulate matter
PM	Particle matter
PT	Public Transport
RRT	Rapid Rail Transit
ROW	Right Of Way

SMCA	Spatial Multi Criteria Analysis
SAW	Simple Additive Weighting
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TOD	Transit-Oriented Development
v/c	Volume to Capacity ratio
VOC	Volatility Organic Pollutants
WHO	World Health Organization

Chapter One
Introduction

1.1 Background

With the continuous growth of population and vehicle ownership accompanying urban development, transportation networks are increasingly contributing to major urban challenges, particularly traffic congestion, pollution, accidents, and other issues related to municipal transportation (Yang et al., 2018).

Traffic congestion remains a significant problem in many large cities worldwide, especially in urban streets. The severity of congestion in these zones continues to rise due to increasing population, economic growth, car ownership, urbanization, and the suburbanization of housing, employment, and services (TRC, 2007).

Therefore, urban planning and development must give careful consideration to a range of transport-related challenges, particularly traffic congestion resulting from high automobile dependency and the mismatch between residents' travel demands and insufficient or inefficient transportation services, especially public transit (Bajaj et al., 2017; Zhang et al., 2019).

To establish a sustainable urban transportation system that meets residents' mobility needs while promoting a more efficient and environmentally friendly transport fleet, many cities are investing in alternatives to private motor vehicles such as tramways, light rail systems, and buses that can help to reduce traffic-related pollutant emissions (Fernandez-Sanchez & Fernandez-Heredia, 2018; Kuang et al., 2019).

Public transport is the key to sustainable mobility. It is considered an essential factor in any social and economic development of a city because it is fundamental in the life of societies where there is continuous movement. It allows the mobility of individuals in their social activities and brings together a plurality of different activities and services. When the means of transport do not exist or are minimized, as they are in many developing countries, economic activity remains in the substance and self-consumption stage (Harkat *et al.*, 2022).

Rail-based public transport can be divided into heavy rail and light rail systems. Light rail (tramway) is defined as a passenger-carrying system that runs on parallel steel rails, supports and guides vehicles on flanged wheels, and is often designed to run on urban streets where vehicles are manually operated based on what the driver sees ahead, similar to buses or cars rather than through fully automated systems.

Trams operate on dedicated rail lanes along urban streets and offer greater passenger capacity and higher speeds, less noise and air pollution compared to buses (Ji et al., 2019). They typically serve relatively small urban regions and help alleviate traffic congestion within these areas. In comparison to metro systems, trams are less costly to construct and maintain, and their routes can be modified more flexibly, making them a more adaptable option for evolving urban environments. Moreover, implementing tram systems in newly developed cities can significantly enhance public transportation services and promote environmentally friendly travel habits among residents (Ji et al., 2019).

Therefore, many cities around the world have built several tram lines for purposes like meeting the small or medium scale of daily travel demands of residents, enhancing the convenience of travelling within the city and connecting some famous scenic spots for sightseeing (Xu and He, 2020).

Any project of transportation development should start with scouting the existing projects needed. This development must meet the current and future demands. This problem stimulates the sequences of the process beginning with searching out geographic areas and specific sites (Zak and Kurek, 2020).

The locations that satisfy the main objectives and criteria are submitted to an elaborate evaluation. The main objectives involve engineering, institutional, economic purpose, environmental, and social objectives (Farkas, 2009).

1.2 Problem Statement

The main problem related to Karbala city network is congestion, the main cause of congestion include:

1- Insufficient public transport: according to Al-Khzali et al. (2022) and Theyab et al. (2021), the percentage of minibuses is less than 10% of the vehicle fleet, and that of buses is less than 1%.

2- Increase of vehicles: Based on Karbala Statistical Directorate, between 2010 and 2023, the number of registered vehicles in the city rose by approximately 122%, equivalent to a compound annual growth rate of about 6.33% which classified as high in a global context (Dargay et al., 2006; Wu et al., 2014).

3- High population growth: Karbala city one of the most populated areas in Iraq which grows rapidly which yearly growth rate about 4.1%. The rates exceeding 3% generally considered very high (Bloom, 2020; United Nations, 2024; Vollset et al., 2021).

4- Most main streets and intersections in Karbala operated at poor levels of service (LOS E–F), leading to delays, low speeds, and environmental impacts (Fadhlallah Hussein et al., 2024; Fahad et al., 2023; AL-Khzali et al., 2022; Theyab et al., 2021; Al-Murshidy et al., 2019).

1.3 The Aim and Objectives of the Study

This study aims to propose the best location for tram networks as a solution to the congestion problem challenges, enhancing environmental quality, and improving urban mobility in Karbala City. To achieve this aim, the study is guided by the following specific objectives:

1- Evaluating the existing road network and traffic performance in Karbala based on operational indicators such as flow, speed, delay, and LOS.

2- Assessing traffic environmental impacts, including traffic noise, air pollution, and Air Quality Index (AQI) under current traffic conditions.

3- Identifying the most important criteria and limitations that agree with the case study, for selecting the best tram routes/stations in urban areas.

4- Identifying the best locations for tram routes and stations using Geographic Information System (GIS) based spatial analysis and Multi-Criteria Decision-Making techniques (MCDM) and Analytic Hierarchy Process (AHP) method.

5- Developing a ranked set of tram route alternatives that maximize accessibility, minimize construction costs, and align with sustainable urban transport principles using Criteria Importance Through Intercriteria Correlation (CRITIC), and Evaluation based on Distance from Average Solution model (EDAS).

6- Simulations of the tram networks using VISSIM software and the comparisons of traffic performance scenarios with and without tram integration were carried out in terms of speed, noise, emissions, LOS, and delay.

1.4 Scope of the Study

This thesis consists of seven chapters as follows:

Chapter One: Includes a general background, problem statement, aim, objectives, and finally, thesis layout.

Chapter Two: Is devoted to reviewing the congestion problems, public transportation systems, tramway system definition and its characteristics and benefits, GIS program definition, the objectives and related criteria for the best tramway route and stations selection definition, and previous studies related to networks evaluation and public networks site selection were conducted.

Chapter Three: Contains an explanation for the methodology of tramway components site selection, definition of study area, data collection, and data representation.

Chapter Four: Involves data analysis, graphical and statistical relationships, and current public transport analysis.

Chapter Five: Consists of the achievements and triumphs of the tramway component site selection system. This methodology was applied to identify the most suitable locations that satisfy the objectives and specific criteria.

Chapter Six: Simulating the integration of a tram system within key streets of Karbala using VISSIM software and making comparisons of traffic performance indicators before and after tram implementation.

Chapter Seven: Presents the main conclusions and recommendations for tramway components site selection.

Chapter Two

Literature Review

2.1 Introduction

This chapter provides an overview of traffic congestion problems, their causes, impacts, and measurement methods in urban traffic. One of the policies proposed to control traffic congestion is providing public transportation systems. These systems can carry a large number of passengers, which leads to reduced urban traffic congestion. One of the most important public transportation systems is the tramway network which has the highest passengers' capacity in comparison with other public systems. Optimal planning requires optimal locations for tramway systems to meet current and future demands. This chapter reviews studies and research that concentrated on the public transportation system site selection strategies, especially tramways, by using geographical information.

2.2 Traffic Congestion

The phenomenon of traffic congestion started in the second half of the twentieth century (Pan. et al., 2020). This arose because of our society's constant increase in demand for mobility (Pan. et al., 2020). The excessive traffic of vehicles attempting to use the same infrastructure at the same time is what causes congestion. The consequences are well-known: delays, air pollution, reduced speed, and dissatisfaction (which may lead to risky maneuvers, reducing pedestrian and other driver safety) (Jawad and Nitulescu, 2024). There are multiple definitions of congestion, including: reduced speed below the design or speed limit is one of these, and it has to do with traffic engineering and urban planning that prioritizes environmental concerns and air pollution (Wang. et al., 2014; 11 Pan. et al., 2020).

Falcocchio et al. (2015) defined congestion as a physical phenomenon, and it is characterized as a scenario in which demand for road space exceeds supply, resulting in slower speeds, longer journey durations, and greater motor vehicle queuing (Falcocchio et al., 2015). It is a relative occurrence where there is a disparity between road performance and road user expectations (Elmansouri et al., 2020). Congestion may be seen as an unavoidable result of insufficient transportation amenities such as road space, parking areas, road signals, and good traffic management (Jawad and Nitulescu, 2024). Thus, traffic congestion on road networks develops because of excessive usage of road infrastructure beyond capacity, and slower speeds, longer journey times, and greater vehicle queuing characterize it. Any economically busy and thriving city will rarely be free of traffic congestion (Jawad and Nitulescu, 2024). According to Raheem et al. (2015), there are two major competing opinions on traffic congestion. The first point of view is that it may be seen as a sign of economic progress as well as an urban way of life. The second point of view is that it is regarded as a sign of the decline of urban life.

2.2.1 Types of Traffic Congestion

Retallack, and Ostendorf (2019), defined three forms of congestion: recurrent congestion, non-recurring congestion, and pre-congestion condition. These classifications are based on the frequency and predictability of traffic congestion, both of which affect driving behavior. Congestion expenses are expected to vary depending on the type of congestion. Non-recurrent congestion costs may be more challenging to measure because of the scarcity of relevant data. It may be claimed that the costs are higher since drivers have not been able to factor in the likelihood of congestion when planning their travel, or the costs might be lower. Some routes are increasingly subject to non-recurrent congestion, just like accident black spots. In these cases, drivers may learn an expected cost in terms of delays and successful contingency routes. Pre-congestion will bear some costs equivalent to congestion, including loss of driver environmental control, environmental degradation, and other consequences. For freight transport companies, the increase in road congestion is more than just a time-consuming annoyance. High levels of traffic congestion have been recognized as reducing the number of trips a truck driver can make in a day, increasing the cost of transportation.

2.2.2 Congestion Causes

According to Engström (2016), poor road infrastructure, rapid urbanization, and an inadequate public transportation system are primary factors contributing to traffic congestion. The situation is further worsened by the expansion of informal public transport and behavioral issues such as driver indiscipline, which are compounded by inadequate enforcement of traffic laws. Karimi (2021) stated two main reasons for congestion, which were:

1. Too much traffic for the available physical capacity to handle. Just like a pipe carrying water supply or the electrical grid, there are only so many vehicles that can be moved on a roadway for a given time or so many transit patrons that can be accommodated in a given number of buses or trains. Transportation engineers refer to this as the physical capacity of the highway system. Physical bottlenecks are locations where the physical capacity is restricted, with flows from upstream sections (with higher capacities) being funneled into smaller downstream segments.

2. Traffic flow is not only affected by physical capacity, but also by external events and other traffic-influencing factors. These include traffic incidents such as crashes and vehicle breakdowns, work zones, bad weather, special events, and poorly timed traffic signals. When these events occur, their main impact is to reduce the roadway's physical capacity. Events may also cause changes in traffic demand by prompting travelers to rethink their trips (e.g., snow and other types of severe weather). Nationally, a composite estimate of how much each of these sources contribute to total congestion is depicted in Figure (2.1).

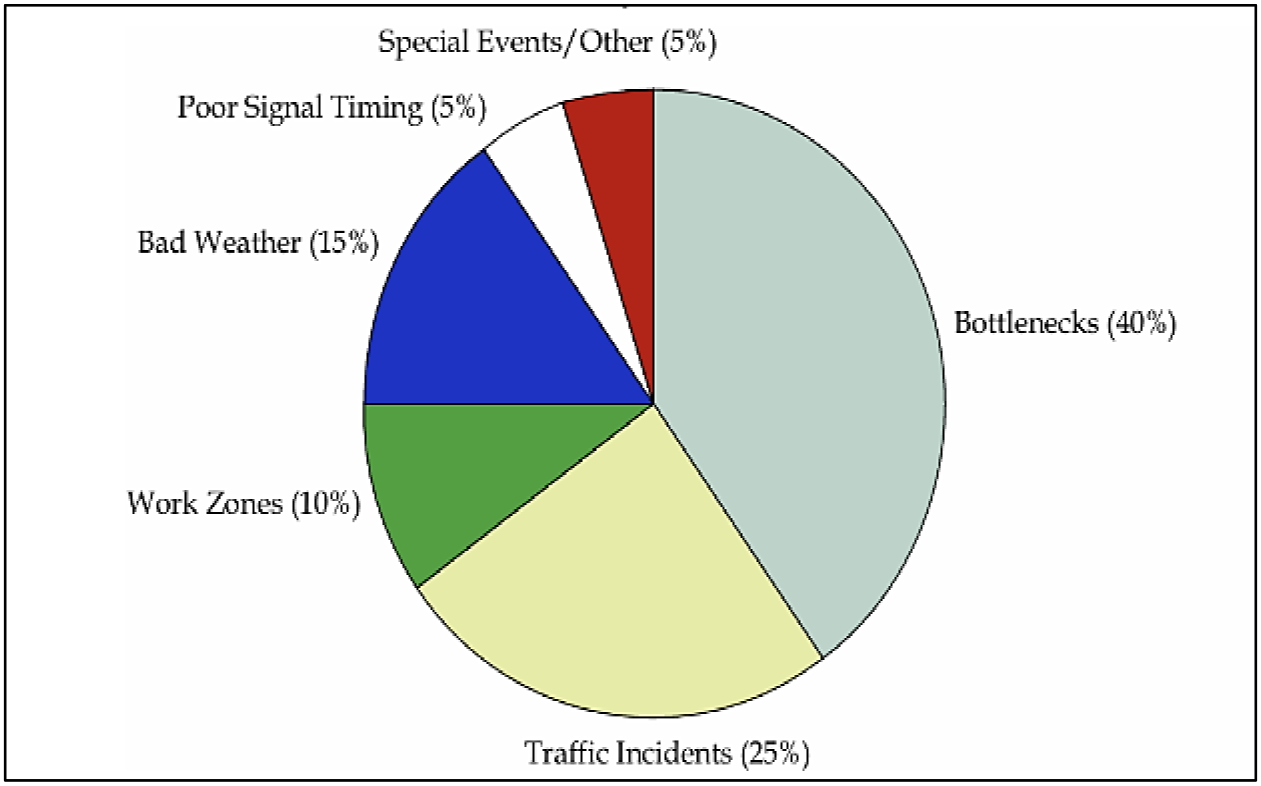

Figure (2.1): The sources of congestion (Karimi 2021).

According to Muñoz (2024), Karimi (2021), and Committee (2014), the main causes of traffic congestion are as follows:

1. **Extra Number of Vehicles**

   The limited public road network and transport infrastructure have resulted in insufficient capacity for the increasing number of cars.

2. **Insufficient Absence of Public Transport.**
3. **Inadequate and Limited Road Space and Infrastructure Transport**

There is a difficulty and a limit for future expansion of the public road network or the construction of streets, especially in areas with high population density, because these roads have been expanded in the past decades.

4. **Overpopulation**

   The increase in the population leads to a rise in the demand for trips and consequent traffic congestion.

5. **Activates on Roads**

   Sometimes, activities on the road may lead to obstructed traffic and reduced mobility, particularly at busy roads and intersections.

   a) Loading and unloading goods from vehicles.

   b) Picking up and dropping off passengers from the buses and taxis.

   c) Vehicles rotating looking for parking places on the street.

6. **The Existence of Important Institutions**

   These institutions, including schools, universities, and public establishments, are an essential source for attracting trips.

2.2.3 Problems Related to Congestion

Raheem *et al.*, (2015) and Luu and Marek (2025) demonstrated the congestion effects as follows:

1. Delay: It refers to the amount of time lost due to blocked traffic.
2. Inaccurate travel time forecasting causes drivers to devote more time to traveling and less time to productive pursuits.
3. Fuel consumption levels will also increase, resulting in high levels of vehicular emissions such as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HCs), and nitrogen oxide (NO_2), increasing concern about the environment. Motor vehicle emissions represent 90%

of air pollution, and the adverse effects of these emissions hurt not only people but also animals and plants.

4. Vehicles wear and tear from frequent breaking and acceleration as well as idling in traffic, which results in more frequent repairs and replacements.
5. Traffic jams are a stressful, aggravating experience, with stop-and-go traffic causing discomfort and fatigue to passengers and drivers alike. It makes the chances of collision high, leading to multiple cases of injury and even death.
6. Many agricultural products are rotting, some experiences can be broken down into three overall groups: environmental, health, and economic.
7. Environmental impacts:

   According to Kumar et al. (2015), Traffic congestion is one of the biggest causes of environmental degradation in cities, especially in terms of spatial pollution and noise pollution. Because vehicles are repeatedly accelerated and decelerated, and have to spend more time idling, this pattern creates substantial increases in fuel consumption and exhaust emissions during congested conditions, and increases traffic noise via engine vibrations, tire friction, and frequent breaking. These phenomena are more acute in the case of urban centers with greater density and where the traffic congestion is more frequent and prolonged impacting mobility but also environmental quality. According to the World Health Organization (WHO, 2021), ambient air pollution and transportation noise exposure for long periods of time are associated with a greater frequency of adverse health outcomes ranging from respiratory diseases to cardiovascular disease and mental stress.

2.2.3.1 Traffic Noise

Numerous factors contribute to higher levels of road traffic noise, especially on highways, including an automobile's engine, exhaust, tire engagement with the pavement, roadway condition, traffic control, passing air and moving cars, speed of vehicles, and traffic patterns. When the road's width decreases and building height increases, the highway noise level increases (Halim and Abdullah, 2014).

The effect of noise from roadways is assessed using standard external noise exposure indicators (WHO, 2021).

One of the most used noise indicators is the weighted equivalent continuous sound pressure level over a particular day or during a 24-hour period. The regulatory authorities use this signal in their regulations and evaluation standards (EPA, 2012).

However, typical traffic noise indicators are not sensitive to distinguishable traffic noise events or changes in the noise profile over time (Hurtley Ed., 2009). The World Health Organization and the Central Pollution Control Board (CPCB) have set international noise limitations of 70 dBA and 65 dBA, respectively (Cheba and Saniuk, 2016).

2.2.3.2. Traffic Pollution

About one-third of the chlorine fluorocarbons (CFCs), 20% of CO_2, and fifty percent of the No_2 emitted by burning fossil fuels are caused by the transportation sector (Xia and Shao, 2005).

Traffic-related air pollution is a serious issue for the general public. In Hong Kong and other urban areas, car exhaust of No_2, emissions like CO, volatility organic pollutants (VOC), $PM_{2.5}$ and PM_{10} are major contributors to air pollution. Transportation-related greenhouse gases, including CO_2, might be contributing to global warming, while air pollutants, like NO and PM_x, are harmful to human health. Since motor vehicles are the leading cause of air pollution in cities, management strategies that minimize environmental effects while optimizing motorized transportation efficiency must be developed (Tsakalidis and Exarchou, 2017).

According to the Environmental Protection Agency (EPA), the AQI serves as a measurement tool for emissions. CO, NO_2, sulfur dioxide (SO_2), ozone (O_3), PM_{10} and $PM_{2.5}$ are the five primary pollutants that the US EPA uses to define AQI. According to Shaharil et al., (2015) and Pande, et al. (2025), the index of each pollutant separately has been determined using regard concentration data and concentrations gathered using the linear interpolation formula, as indicated in the following equation.

$$IP = \frac{I\,HI - ILO}{BPHI - BPLO} (Cp - BP_{LO}) + I_{LO} \ldots\ldots (2.1).$$

Where:

IP =Index for any pollutant (P).

C_p = Concentration of pollutant P.

BP_{HI} = A breaking point that is equal to or greater than Cp.

BP_{LO} = A break point that is equal to or less than Cp.

I_{HI} = AQI value correlates with BPI.

I_{LO} = AQI value correlates with $BP_{LO.}$

The maximum quantity of pollution that can be present in outdoor air without endangering human health is defined by ambient air quality regulations. Following a thorough study of scientific literature, the California Air Resource Board (CARB) set a new annual average level for PM_x in 2002, while maintaining the current annual and 24-hour standard average limits for PM_{10}. The national annual average $PM_{2.5}$ limit was most recently amended in

2012, after an extensive examination of new research revealed evidence of an elevated risk of early death at lower $PM_{2.5}$ concentrations than the old level. Table (2.1) summarizes the international air quality standards for key environmental pollutants, including CO, CO_2, NO_2, and $PM_{2.5}$ and PM_{10}. These limits are defined by globally recognized organizations such as the WHO, and the U.S Environmental Protection Agency (US EPA).

Table (2.1): Recommended exposure limits for selected air pollutants (WHO, 2021; EPA, 2013).

World Health Organization		
Pollutants	Duration	Limits
CO	1 hour	26 ppm
CO_2	Ambient Air	400–420 ppm
NO_2	1 hour	200 µg/m³
	Annual	10 µg/m³
$PM_{2.5}$	Daily	15 µg/m³
	Annual	5 µg/m³
PM_{10}	Daily	45 µg/m³
	Annual	15 µg/m³
U.S. Environmental Protection Agency		
CO	1 hour	35 ppm
CO_2	—	—
NO_2	1 hour	188 µg/m³
	Annual	100 µg/m³
$PM_{2.5}$	Daily	35 µg/m³
	Annual	12 µg/m³
PM10	Daily	150 µg/m³
	Annual	—

2.2.4 Main Police for Reducing Traffic Congestion

Jonathan Olaniyi and Adeolu Emmanuel (2024), explained that there are some policies that the local government must follow to reduce the phenomenon of traffic:

1. **Infrastructure Improvement**: Prioritizing the repair and upgrading of existing road infrastructure and ensuring the construction of new roads to accommodate the growing urban population. This should include expanding key arteries and repairing roads that are in poor condition to improve traffic flow.
2. **Public Transport Development**: Offering viable alternatives to private car use. Enhancing the reliability, coverage, and convenience of public transport can encourage more commuters to switch from personal vehicles to public transit, easing road congestion.
3. **Urban Planning Integration**: Developing and implementing urban planning strategies that incorporate transportation needs. This could involve zoning laws that control urban sprawl and enhance the development of public transport networks to reduce reliance on personal vehicles.
4. **Traffic Management Enhancements**: Introducing advanced traffic management systems that optimize traffic flow during peak periods. Technologies such as synchronized traffic lights and real-time traffic monitoring systems can significantly reduce congestion times.
5. **Driver Education and Law Enforcement**: Strengthening the law enforcement on traffic regulations and increasing public awareness campaigns about safe driving practices. This approach should aim to alter driver behavior, which is a significant factor in congestion.

2.2.5 Measure of Congestion

Level of service is the most commonly used indicator of traffic congestion. LOS is the ratio of supply to demand for traffic and is categorized into six groups, ranging from A for optimal conditions to F for the worst (HCM, 2010). The buffer region of the street network's land use and environmental development affected traffic flow and created various speed characteristics. The surrounding development is linked to poor traffic flow or traffic congestion on urban streets. Urban planning and transit system optimization can help regulate and alleviate traffic congestion since future planning will address it by managing urban density and implementing sensible land use planning (Zhang K. et al., 2021).

2.3 Sustainable Transportation

Sustainability is commonly explored in terms of the theories of sustainable development. A widely used definition of sustainability comes from the Brundtland Commission’s report, our common future Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). Transportation and sustainable development go hand in hand. For instance, cities worldwide have clogged roads due to people's reliance on cars, leading to emissions and societal costs, including accidents (Elassy et al., 2024). Transportation networks thus play a contradictory role, stimulating urban growth while also posing several obstacles. The effects on the economy, society, and environment are among these challenges (Elassy, et al., 2024). These three categories' challenges collectively are referred to as "sustainability challenges." Investing in public transportation is frequently presented as a vital tool for decreasing reliance on personal vehicles, mitigating the negative effects of transportation networks on the environment and society, and preserving transportation's vital role in sustainable development.

A key concept in applying sustainability to transport is the triple bottom line. Kaneti et al. (2025), Faheem et al. (2024), Theis (2012), and Black (2010) consider sustainable development issues using three dimensions: environment, economy, and society. These three dimensions are commonly referred to as a 'triple bottom line' (Pei et al., 2010). They are defined as follows by (Stewart, 2024):

1. Environment: the ecological or environmental component considers how changes in local and global surroundings are impacted by human activity and developments.
2. Economy: the process of a community's growth or progress towards economic goals, such as increased wealth, employment, productivity, or ultimately welfare.
3. Social: the social dimension of sustainability is frequently defined as addressing issues of equity and inclusion.

Black (2010) suggests that a sustainable transportation system is one that applies the Brundtland definition or simply said "transportation that satisfies the current transportation and mobility needs without compromising the ability of future generations to meet those needs" (Black, 2010). This definition locks sustainable transport in line with broader research on sustainability.

Sustainability lists the following three crucial components of sustainable transportation:

1. provides for the safe and equitable fulfillment of the basic needs of individuals and communities in a way that respects the health of people and ecosystems, as well as equity within and between generations.
2. It is reasonably priced, runs smoothly, gives a variety of transportation options, and fosters a thriving economy.
3. Limits emissions and waste within the planet's capacity to absorb them, minimizes the use of nonrenewable resources, restricts the use of renewable resources to the level of sustainable yield, reuses and recycles its constituent parts, and reduces the amount of land and noise it produces (The Centre for Sustainable Transportation, 2005).

Faheem et al. (2024) outline a sustainable transportation paradigm composed of four aspects:

1. Actions to reduce the need to travel.
2. Encouragement of modal shift.
3. Short trip lengths.
4. Increased efficiency.

2.3.1 Transportation Sustainability Challenges

The environment and many facets of society are intersected by transportation, which has several positive effects on human wellbeing. It may link people with essential services and promote economic growth. It may, nonetheless, also provide some challenges. Table (2.2) represents the transportation impact on urban facilities, which was derived from Litman and Burwell (2006). As seen in it, an increasing amount of research indicates that the present trends in automobile-oriented transportation are unsustainable due to significant implications across environmental, economic, and social concerns. Adverse effects of transportation include those on the environment (increased pollution), the economy (loss of production), and society (effects on human health and equity). Other than energy production and industrial processing, transportation is the main source of pollution, particularly air pollution (Dobranskyte-Niskota et al., 2007). Litman and Burwell (2016) analyzed the economic effects of congestion and contend that a system is deemed unsustainable from a financial perspective if it is unable to offer sufficient levels of mobility for various reasons and modalities.

Table (2.2): Transportation impacts on urban facilities (Litman and Burwell, 2016).

Environmental	Economic	Social
Air pollution	Accessibility quality	Equity/fairness
Climate change	Traffic congestion	Impacts on mobility disadvantaged
Noise pollution	Infrastructure costs	Affordability
Water pollution	Consumer costs	Human health impacts
Hydrologic impacts	Mobility barriers	Community cohesion
Habitat and ecological degradation	Accident damages	Community livability
Depletion of non-renewable resources	Depletion of non-renewable resources	Aesthetics

2.4 Urban Public Transport Modes

According to the Un-Habitat (2013) report, mass rapid transit, also known as public transit, is a service that allows for the simultaneous transportation of a significant number of people. It is distinguished by its rapid speed and high passenger occupancy rate, as well as the fact that it charges fewer fees than other modes of transportation. With a specific stopping station, it typically operates on a limited route or a detached and particular usage of a potential general route. The essential need of Mass Rapid Transit (MRT) in a developing country is to carry high numbers of passengers, and the basic requirement of MRT in a developing city is that it carry large amounts of passengers, rapidly. According to Litman (2016), the Public transport benefits are:

1. Providing convenient and comfortable transportation.
2. Reducing traffic congestion.
3. Providing high traffic safety.
4. Reducing noise and air pollution.
5. Providing accessibility and mobility.
6. Supplying less passenger fees.

Table (2.3) summarizes public transit benefit and cost categories (Litman, 2016).

Table (2.3): Public transport benefits (Litman, 2016).

Category	Key indicators	Key benefits
1.Improved transit service	Quality of service (speed, comfort, safety, reliability)	• Better service for current users • More convenience, comfort, and safety • Benefits low-income users • Improved efficiency and lower travel time
2.Increased transit travel	Increase in the number of transit users (ridership)	• Encourages more people to use public transit • Increased revenue and enhanced safety at stations
3.Reduced automobile travel	Decrease in private vehicle use (mode shift)	• Reduced traffic congestion and travel delays • Less demand for parking and roads • Lower fuel use and emissions • Increased road safety

Litman (2021) recommended that planners optimize the following factors to improve transit services and attract new riders:

1. **Ease**: Is the system or product easy to use? What difficulties do new users face? Transit example: are your timetables legible and easily decipherable, even by inexperienced users? Are transfers convenient?
2. **Effectiveness**: How well does the system help users complete a task? Does the product serve its purpose well? transit example: Do routes

operate on time and predictable schedules? Can passengers make their desired trips in a reasonable time?

3. **Comfort**: Do users feel safe, secure, and relaxed when using a product? Does use ever cause discomfort? Transit example: Do stops, stations and vehicles and vehicles always feel safe and secure? Do seats accommodate passengers of different sizes and abilities?
4. **Aesthetics**: Simply, does the product appeal to users? Is it visually and tactilely appealing? How does using the system affect all five senses? Transit examples: Are vehicles clean, both inside and out? Do the vehicles' temperature, fabrics, and handholds feel good? Are there any unpleasant smells, glaring lights, or blaring audio systems?

2.4.1 Sustainable Public Transport Infrastructure

To provide services that support economic development, public transportation infrastructure is essential. To achieve the goal of lowering fuel consumption and capital costs. Yang et al., (2016) imply that improvements in transport infrastructure services are projected to minimize transport costs, with lower congestion, shorter distances, and higher speeds. The feasibility study of technical engineering for transport infrastructure ignores this issue when evaluating the economics and concurrently raising awareness of environmental sustainability and natural resource protection, even though congestion reduces the operational efficiency of the transportation system and increases air pollution (Yang et al., 2016). According to Yang et al. (2016), public transportation projects should strive to incorporate sustainability considerations by evaluating potential designs' transport performances as well as the design's effects on the environment, society, and economy throughout the infrastructure projects' lifetime.

2.4.2 Right of Way (ROW)

According to Vuchic (2002), the public transport runs on land, which has a right-of-way that is divided into three categories, A, B, and C, relying on their separation extent from other traffic, and the categories are explained as follows:

1. **Category A**

   This category is the situation in which the right-of-way is wholly controlled. The right way can be above ground, at-grade, or underground. Crossings exist below or above the right-of-way.

2. **Category B**

   This category is the situation where the right-of-way is longitudinally discrete by curbs, obstructions, space, and grade, so the crossings exist at-grade.

3. **Category C**

   This category refers to situations where right-of-way traffic is mixed on the roads. In general, they move with other traffic on the streets.

   Public transportation modes are divided into five groups, including: para transit, bus, Light Rail Transit (LRT), suburban rail, and Rapid Rail Transit (RRT) (Vuchic, 2002).

2.4.3 Public Transportation Modes

Public transportation modes are divided into five groups: para transit, bus, Light Rail Transit (LRT), Suburban Rail, and Rapid Rail Transit (RRT) (Ahmed and Asmael, 2015).

2.4.3.1 Para Transit

An illustration of this service is a taxi, which is seen as a vehicle that carries a limited number of passengers and has grown in popularity due to the dearth of alternative public transportation options. It satisfies the growing demand for transportation, unlike specific public transportation systems that are restricted to fixed routes and schedules; the user has complete control over their travel route, timetable, and working hours. Additionally, it offers home delivery, making it a more accessible service. The paratransit speed ranges from 12 to 20 km/hr.

2.4.3.2 Bus Transit

The bus system is the most common in both urban and rural areas. This service follows a set timetable and follows a unique track. Additionally, it offers the benefit of fixed passenger transit fees that apply to all distances within the area, with bus speeds ranging from 10 to 12 km/hr and up to 25 km/hr in low-density regions.

2.4.3.3 Light Rail Transit (LRT)

It is known as electric power rail systems, and it is characterized by the following:

1. Passengers are transported from the street surface or a low station.
2. They generally run either short trains (3 coaches) or single vehicles.
3. They run in the B or C rights-of-way category.

There are three categories of Light Rail Transit: tramways, Light Rapid Transit (LRT), and metro.

2.4.3.4 Tramway

The tramway consists of simple streetcars; it runs on rails within a fixed and single unit in mixed traffic on the street. The capacity range is from 100 to 200 passengers. The operating speed is around 12 km/hr.

2.4.3.5 Light Rapid Transit (LRT)

LRT is usually made from 2 or 3 coaches, which are linked together in one unit as a train. It runs on a separate right-of-way, and its route is limited. Train passenger capacity ranges between 700 and 900 passengers. The total capacity is around 20000 passengers/hr. The operating speed is 15 km/hr with a capacity of 36000 passengers/hr.

2.4.3.6 Suburban Rail

Suburban rail runs on the same routes as intercity passenger and truck trains. Trains consist of 10, 12, and 14 coaches. A 12-coach passenger capacity is 2750 passengers. Moreover, the capacity for lanes is 55000 passengers /hr, operating speeds are about 45 and 55 km/hr, and the range of distance between stations is from 2 to 3 km.

2.4.3.7 Rail Rapid Transit (RRT)

This system operates on the right-of-way in elevated tunnels or cuttings. These trains have a set and constrained route. Although the underground system is not affected by weather variations, this system offers a high degree of safety and dependability. The operating speed is about 100 km/hr; it is carrying 80000 passengers/hr at an operating speed of 30-35 km/hr. This system has a high capital cost of 40 - 120 million US$ per km of route. Due to the high cost of tunnel construction, this cost varies depending on whether it passes through a subterranean tunnel or an elevated one. Willer (2019) also summarized the most essential characteristics of different types of public transportation in Table (2.4).

2.5 Tram History

The tramway was the initial mass transit system (Savchuk and Nahornyi, 2020). The first horsecar tramway network was introduced in Swansea, Wales, in 1807.

With the development of electrical power in the German city of Berlin in 1880, tram transit became widely used in cities throughout Europe and North America. Cities with high terrain have specifically designed "cable cars," a kind of transportation (Savchuk and Nahornyi, 2020).

Table (2.4): Important characteristics of public transportation (Willer, 2019).

properties	Public transportation types				
	BRT	Bus transit	Tramway	Suburban rail	Metro
capacity (p/hr/dir)	4000-12000	1200	6000-15000	55000	80000
Operating speed (km/hr.)	20-40	15-20	15-45	45 -55	100
Stop space (m)	300-2000	200-500	200-600	2000-5000	400-3000
Headway (min)	13 s	5	6	2.5	1.5
Path away characteristic	It routes are not constrained and the passengers are free to select their own path.	Fixed and restricted path.	It runs on rail within a fixed and single unit in the mixed traffic on the street	Runs on the same routes of truck train	Runs on rights of way that is in cutting or elevated tunnel. These trains have a specific and constrained path.

Some cities in the US, Canada, and Europe have created modern tramway systems that are as effective as metro (subway) systems, even though they primarily utilize land-based rails and lighter rolling stock. The contemporary equivalent of the classic tramway is LRT. Therefore, new tramway tracks and equipment were being built globally as part of an activation and regeneration process. (Savchuk and Nahornyi, 2020). Figure (2.2) illustrates the tramway renaissance by showing the number of newly constructed tramway systems per global region between 1978 and 2019 (Savchuk and Nahornyi, 2020).

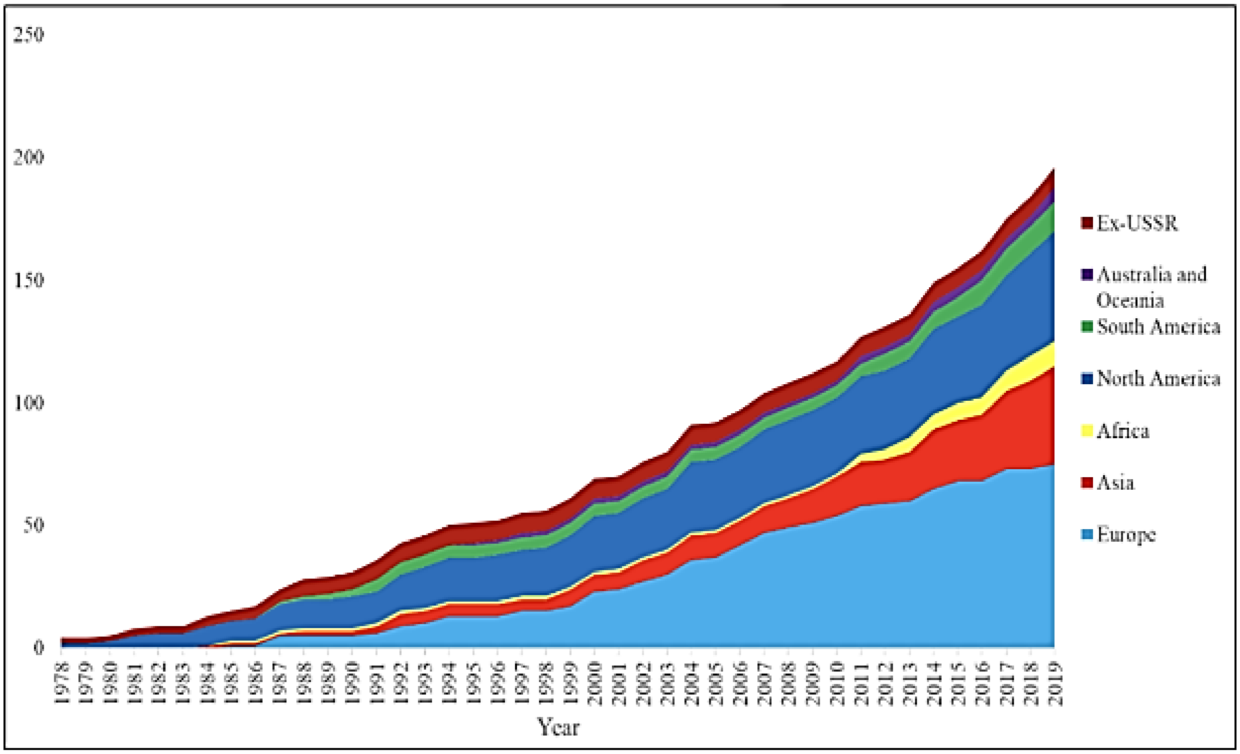

Figure (2.2): Tramway renaissance number of recently built tramway networks by global region between 1978 and 2019 (Savchuk and Nahornyi, 2020).

2.6 Tram Characteristics

Rail transportation (subways, trams, monorails, etc.) is more mass transit and punctual than other public transportation systems (Choi et al., 2022). Increased public transit accessibility, reduced automobile congestion, and shorter waiting times all increase the likelihood that a passenger car user may switch to public transportation (Redman et al., 2013). According to the American Public Transportation Association (APTA), a tramway is an electric railway system that can operate one or more cars.

It can be found along exclusive rights-of-way at ground level, on aerial structures, in streets or subways, and it can pick up and drop off passengers at station platforms, street, track, or car-floor level. Typically, it is powered by overhead electrical wires.

According to this description, a tramway is a system of electrically powered passenger cars with steel wheels that travel on a track made of steel rails. The cars, the tracks, and the streets themselves must be able to accommodate both people and vehicles with rubber tires. According to Brunckerhoff (2012) and Alkubaisi (2014), the track system may also be built inside exclusive rights-of-way.

Trams are another type of railway mode that has been shown by Kaewunruen et al. (2015) to have positive environmental effects, including lower carbon emissions and less traffic. Trams combine routes with existing roadways and have a lower construction cost per mile than light rail or subways, according to Zielinski et al. (2020) and Prud'-homme et al. (2011), contended that "road diets" can discourage the use of passenger automobiles by lowering carbon emissions by integrating existing roads and tram routes (Choi et al., 2022).

McGreevy (2021) stated that two-way laying of tram rails would reduce the number of traffic lanes available to cars and increase the inconvenience of vehicle drivers, which could stimulate the conversion of private cars to public transport. Buehler and Pucher (2011) noted that the transition from passenger cars to public transport can help alleviate environmental and social problems by reducing energy consumption and CO_2 emissions. Börjesson et al. (2014) noticed that, unlike subways, which require many structures for construction, trams are less expensive to build and operate because they can be used only by laying rails on existing roads. Tramway, as a commonly used public transport system in cities, consists of 1 to 4 wagons that move along a railway by electricity, which is why it is lighter, shorter, and more flexible. The width of each wagon is from 2.3 to 2.9 meters, while its length is from 14 to 40 meters. Its operation speed is 50 km/hr along the streets, while it can be up to 80 km/hr along dedicated lines out of residential districts. Its capacities range from 120 to 280 passengers on each trip, or 10,000 to 28,000 passengers per hour (Ventejal, 2001).

2.7 Track Alignment Design

Track Alignment is the position and direction given to the center line of the rail track on the ground. Tram tracks can be laid on various surfaces. For example, they may use standard rails on sleepers, similar to conventional railway tracks, or grooved rails embedded in concrete within street pavements. Historically, the first tramways, developed by Alphonse Loubat in 1852, featured rails that were projected above the road surface (Sumith, 2009). While in Liverpool in 1924, another environmentally friendly or ecologically friendly alternative is to lay tracks into grass turf surfaces; this is known as a grassed track (Topalovic and Lottimer, 2009). In addition, the track is laid on a bed of crushed stone or a concrete foundation. This configuration, along with the supporting roadway, is referred to as the rail right of way (Topalovic and Lottimer, 2009).

Several considerations should be taken into account when aligning tracks, including design speed, ease of curves, ease of gradients, and the need for good scenery along the route. In addition, the special features of the track, which also influence the alignment, are the gauge of the track, crossing railroad and other crossings, suitability of station site, the highest flood level in case of stream crossing, availability of funds, and obligatory or control points. The desirable operating speed of the tramway is usually 40 to 55 mph (Vazirani and Chandola, 2009). The alignment of the tramway should be carefully considered in terms of various roadways and urban factors. These include road geometry such as intersections and roundabouts; pedestrian footways and crossings; cyclist needs and cycle tracks; access requirements for fronting properties; public utilities; roadway clearance; minimum allowable curvature radii; engineering constraints of the tramway; the location and design of tram stops; and the positioning of overhead electric traction systems and other fixed infrastructure (Commission RSC, 2009).

Tramways have been classified into two main categories according to their tracks, which are: **off-street** and **on-street** tramways. In off-street tramways, the tram tracks are totally separated from any street, while on-street tramways are operated on the street. Tramways that operate on streets can be classified into three categories (Graebner et.al, 2007):

1. **Shared On-Street:** The tracks are embedded in the street surface and may be used by other vehicles or pedestrians.
2. **Segregated On-Street:** The tracks are laid within the street but elevated slightly above the regular street level, providing partial separation.
3. **Protected On-Street:** The tracks are placed in the street but are entirely separated from general traffic, typically using physical barriers or curbs.

The tram track consists of several key components, including the gauge, gradient, superelevation, horizontal alignment, and vertical alignment (Chandola, 2011). The following sections illustrate the tram track components.

2.7.1 Gauge

Rail tracks consist of two parallel steel rails, secured to crossbeams (or crossties), which maintain a constant distance between the two rails, referred to as the gauge. Therefore, the gauge is a measure of the distance between two parallel rails (Topalovic and Lottimer, 2009). According to Upadhyay (2011), there are three types of gauge: Broad Gauge (B.G) “when the clear distance between the inner faces of two rails is 1.787 m” also this gauge called Standard Gauge; Metre Gauge (M. G.) “when the clear distance between the inner faces of two rails is 1.7 m"; and Narrow Gauge (N. G.) "when the clear distance between the inner faces of two rails is 7.562 m" (Upadhyay, 2011). Several factors govern the adoption of a gauge. They are the availability of funds, volume and nature of traffic, future development of the area, physical features of the country, and speed of traffic. A wider gauge requires more land width, resulting in higher land acquisition costs. Additionally, the volume of earthwork is increased, leading to higher earthwork costs (Upadhyay, 2011).

2.7.2 Gradient

Gradient is the rate of rise or fall of the track. It is expressed as the ratio of vertical distance to horizontal distance. The purposes of providing gradients are to reduce the cost of earthwork, to provide a uniform rate of rise or fall as far as possible, to reach the station situation at different elevations, and to drain off rainwater (Gupta, 2009). Several factors affect the selection of gradients. They include the nature of the ground, safety requirements, drainage needs, and hauling capacity of railroad engines (Chandola, 2011).
While climbing a grade depends on several factors, including the type/model of vehicle, the length of the grade, and the weather conditions, it will be encountered throughout seasonal changes. For instance, as the weight of the vehicle increases, its ability to climb a grade decreases (Topalovic and Lottimer, 2009).

2.7.3 Vertical Alignment

The vertical alignment of tramway track is composed of constant grade tangent segments connected at their intersection by parabolic curves having a constant rate of change in grade (Brinckerhoff, 2012). A vertical curve provides a change of gradient of a track for providing a gradual change in grade, comfort to passengers, and adequate visibility and safety to traffic.

Vertical curves include two types of curves, which are: valley (or sag) and summit (or crest) (Chandola, 2011).

Yarra trams and Frank Engelen (2003) explained the specifications of vertical curves in Table (2.5).

Table (2.5): Track standard of vertical curves, (Yarra trams and Frank Engelen, 2003).

Vertical alignment	
Grade	
Maximum	6.67%
Minimum	0.25%
Radius	
Desirable minimum	760 m
Absolute minimum: - under curve	500 m
Absolute minimum: - over curve	500 m
Superelevation	
Tangent track, inner rail above outer rail	6 mm
Maximum	100 mm
Desirable development rate	1 in 600
Maximum development rate	1 in 300

2.7.4 Horizontal Alignment

The horizontal alignment of the track consists of a series of tangents joined to circular curves, preferably with spiral transition curves. The purpose of providing curves is to provide a gradual change in direction, a gradual change in gradient, easy to be turning of train (Brinckerhoff, 2012). A curve is defined either by its degree or radius. The degree of a curve is the angle subtended at the center by a chord of 30.5 m length. The degree of curvature can be calculated from the formula (Gupta, 2009):

$$\theta = \frac{1750}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}.$$

where: R is the radius of curve, and θ is the degree of curve. Thus, a curve has a radius of 1750 meters. There are two types of curves used in tramway track design - circular curves "constant radius" and transition curves "varying radius". Circular curves are subdivided into simple, compound, reverse, and deviation (Chandola, 2011).

The minimum circular curve length is stated by ride comfort, and it is not related to the vehicle's physical characteristics. The desired minimum circular curve length is generally determined by the Equation (2.3) (Tabrizi, 2009):

$$L_c = 0.57V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}.$$

Where: Lc is the curve's length; and V is the speed in km/hr. For most modern Tramway designs, whether high or low floor, the most common absolute minimum radius appears to be 25 meters (Tabrizi, 2009). Transition curve is a spiral changing radius from infinite in the tangent to the radius of the circular curve. The transition curve prevents sudden changes in lateral acceleration between the tangent and circular curves, providing a smoother path for transitioning from the tangent to the circular curve. It also ensures a gradual rate of change to achieve the actual superelevation in the circular curve (Chandola, 2011).

2.7.5 Superelevation

Superelevation is the height difference in inches (or mm) between the high (outside) and low (inside) rail. Superelevation is used to counteract or partially counteract the centrifugal force acting radially outward on a train when it is traveling along the curve (Caltrain, 2011). Raising the outer rail causes the perpendicular component of the gravitational force to the plane of the two rails to be equivalent to centrifugal force at a given speed. Therefore, passengers would feel no centrifugal force (Tabrizi, 2009). The amount of required superelevation to make equivalent centrifugal force and perpendicular component of gravity is called equivalent superelevation / can't be calculated by Equation (2.4) (Tabrizi, 2009).

$$Eq = Ea + Eu = 11.7\left(\frac{V^2}{R}\right) \quad (2.4).$$

Where Eq: equilibrium superelevation, in millimeters.

Ea: actual superelevation to be constructed, in millimeters.

Eu: unbalances superelevation, in millimeters.

V: design speed through the curve in km/h.

R: radius of curve in meters.

In practice, if complete equilibrium superelevation (Eq) is installed, then it would require an extremely spiral transition curve. It could also reveal that passengers feel discomfort on a tram that is moving much slower than the design speed or stops in the middle of a steeply superelevated curve. Consequently, only a part of the calculated equilibrium superelevation (Eq) is commonly allowed to be installed and called the actual superelevation (Ea) (Tabrizi, 2009).

2.8 Standard Geometric Dimensions for Tram Infrastructure

According to International Association of Public Transport (UITP, 2020), the recommended spatial requirements for tram tracks and platforms are:

- **Single track width**: 3.5–4.0 meters (includes clearance on both sides)
- **Double track width**: 7.0–8.5 meters (includes spacing between tracks and lateral clearance)

- **Platform width**: 2.5–3.0 meters (side platforms); 3.0–4.0 meters (central platforms)
- **Platform length**: Typically, 30–45 meters, depending on tram length and capacity.

2.9 Tram Benefits

1- Less-Pollution

Trams are considered environmentally friendly since they are powered mainly by electricity and significantly reduce urban pollution through lower carbon emissions (Yan, 2015). Their direct waste is limited to minor metal shavings from wheel rail friction, unlike trolleybuses that cause air and land impacts from rubber tire wear. Modern trams also utilize asynchronous motors with regenerative braking systems, allowing part of the consumed energy to be returned to the grid, while their metal wheels consume less electricity compared to rubber-tired vehicles. In terms of safety, trams are equipped with more advanced braking systems than buses and trolleybuses (Savchuk and Nahornyi, 2020). Furthermore, tramway lines often enhance urban aesthetics and environmental quality by incorporating grassy or lawn-covered tracks, which contribute to reducing urban heat-island effects through higher albedo values and mitigating rail heating problems (Zelezny, 2014; Savchuk and Nahornyi, 2020).

2- High Passenger Capacity

According to Abdi Kordani et al. (2020), one of the most significant aspects of tramways is their capability to move large numbers of passengers, which helps to relieve traffic congestion on city streets.

3- Economy and Saving

Public transportation that uses the least amount of energy is the tramway. The tram utilizes less power than the metro, in addition to the electric recuperation factor that was previously mentioned (because passenger and technical facilities do not need to be maintained at stations) and a trolleybus (because wheels slide on rails more easily) (Dronova and Brunn, 2018; Savchuk and Nahornyi, 2020).

4- Reduction of Noise Level

The tram is generally quieter than the bus. Because of rail-wheel contact, the tram is slightly noisier than the bus when traveling at high speeds, although the bus is noisier overall because of its peak engine noise. According to noise impact research conducted by Loughborough University, the maximum bus noise measured at 7.5 meters is 93 dB, while the maximum tram noise is 87 dB (Hensher, 2015).

5- More Comfortable

Tram offers more comfort to riders than underground metros or trains (Hensher, 2015). In addition, it is simpler for elderly or disabled individuals to utilize (low floor rolling stock, easy access to the platform from ground level) (Savchuk and Nahornyi, 2020).

6- Reliable Due to the Timetables

Timetabling is an essential stage of movement planning. The timetable itself is the primary document for every transport company because it declares the number of races to be paid from the city budget. Therefore, this document serves as the primary reference for both transport companies and passengers planning transfers between locations. This explains the relevance of the timetable (Gorbachev,2020).

7- Less Infrastructure Cost

The tramway network requires infrastructure (tracks, overhead lines, stops), but it is cheaper than the infrastructure for a railway or an underground metro (Alkubaisi, 2014).

8- Provide Business Opportunities

Because the tramway routes are easily accessible to many clients, the company tends to focus on them. Tramway corridors are distinguished by equitable business prospects at various levels, in contrast to the concentrated concentration of most major firms and network services surrounding metro stations (caused by the division of rental rates) (Savchuk and Nahornyi, 2020).

2.10 Tram Disadvantages

1- High Initial Cost

In contrast to a bus route, a tram or streetcar project is always substantially more expensive up front (Abdi Kordani, 2020). According to the American Public Transportation Association's 2016 fact book an average streetcar or light rail project costs $123.3 million, while a bus project typically costs $4 million. According to Savchuk and Nahornyi (2020), the newly built tramway lines cost between $5 million USD per kilometer in Daugavpils, Latvia, and $40 million in Utrecht, Netherlands.

2- Limited Adaptability of Its System

In addition, the transit agency can easily reroute buses if the serving area shows a decrease in ridership, where trams are rather permanent, which means the only options are to either keep the line running or shut down the station. Interestingly, the non-flexibility of trams can serve as both an advantage and a disadvantage (Savchuk and Nahornyi, 2020).

3- Limit Maneuverability

Reliance on railroads limits traffic maneuverability and raises the expense of rail and wagon infrastructure (Garrett, 2004). According to Wang, (2023), discussed the main characteristics of tram and the difference between tram, Bus Rapid Transit (BRT), and subway presented in Table (2.6). Compared to BRT systems, the tram can offer more capacity along with lower energy consumption, pollution, and emissions. The constructed cycle is only one-third that of subways, and the cost per kilometer of construction is a tenth of that of subways.

Table (2.6) Comparisons among BRT, tram, and subway, (Wang, 2023).

Item	BRT	Tram	Subway
Vehicle length (m)	18-25	15-40	90-140
Vehicle capacity (person)	80-120	120-300	800-1500
One-way capacity(person/hour)	4000-12000	5000-15000	30000-60000
Maximum speed (km/hr)	100	70-80	80-100
Average traveling speed (km/hr)	15-30	15-30	25-40
The minimum curve radius (m)	15	15-25	125
Construction cost (million / km)	20-50	40-90	300-800
Right of way	Partly or exclusive	Partly or exclusive	Exclusive

By using an indicator called passenger flow intensity, Xu and He (2020) examined the passenger flow impacts of 49 tram lines in China and other countries. Their findings indicate that, overall, the passenger flow effects of tram lines in different countries are far better than those in China. The effects of adjacent regions' land exploitative intensity, the average distance between stations, and the traffic conditions of the same corridor on the influence of passenger flow are evaluated based on circumstances to determine the major causes and countermeasures. These analyses demonstrate that effective ways to improve the passenger flow effect of tram lines include shortening the average station spacing, increasing the intensity of land development along the tram line, and placing the tram line in a corridor with high traffic volume and no other parallel rail transit lines. Choi et al. (2022) investigated the potential atmospheric effects of tram construction-induced mode conversion to public transportation as well as the extent to which increased physical activity brought on by public transportation contributes to illness prevention. The four-stage demand for transportation prediction model's modal split process was used to examine the impact of the transformation of types of transportation brought about by tram construction in Dongtan new town, Korea, the study region where trams are planned to be implemented. According to their analysis, trams will result in 54,700 trips per day that are converted to public transit in the impacted area. The benefit of reducing air pollution is 25.13×108 KRW/year. Finally, it is estimated that using public transportation will result in a 65.63.5 ×108 KRW/y reduction in diseases brought on by greater physical activity.

2.11 Routes and Stations Selection Criteria

Routes and station's location selection is the process of finding locations that satisfy the main criteria (Farkas, 2009). According to Sharifi et al., (2006), the aim of site selection process is to identify the best and suitable future rail corridors to serve the people and to meet the social, economy, institutional, environment, and engineering objectives, as well as to promote the use of public transportation systems. El-Yazory, (2013) defined the criteria as a set of guidelines or requirements that are used as the basis of decision making (a choice between alternatives). For more supporting the evaluation of public network can be achieved by breaking down the main objectives into specific objectives or criteria. These criteria are used to evaluate the performance of each alternative option on each main objective (Farkas, 2009). According to (Sharifi et al., 2006), Figure (2.3) represents the hierarchical structure of objectives and criteria.

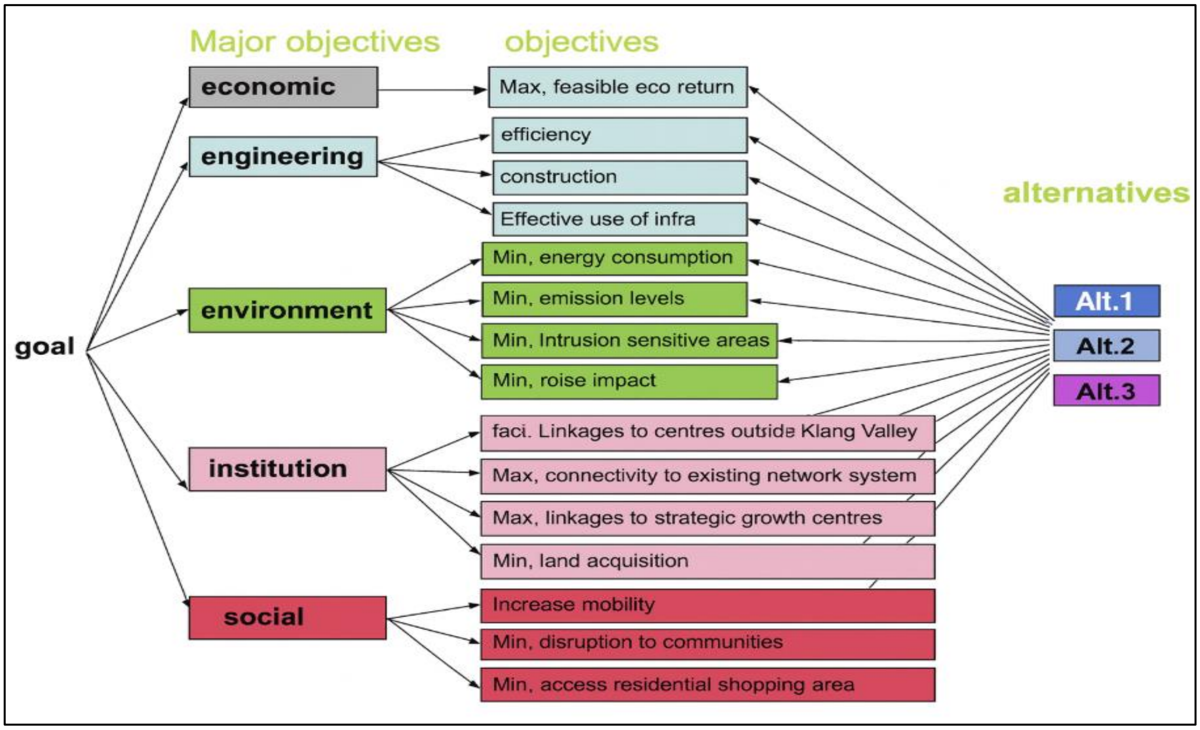

Figure (2.3): The hierarchical structure of objectives and criteria (Sharifi et al., 2006).

The main objectives and related criteria have been defined by (Farkas, 2009) and (Sharifi et al., 2006) as follows:

1. **Economic Objective**

   The purpose of economic objectives is to optimize the system's feasible financial return on investment. The effectiveness of an option is evaluated based on a number of factors, including the benefit/cost ratio, first-year return, the internal rate of exchange, the net present value, construction and operation costs, as well as the minimization of land acquisition (property expropriation), intensification of current land use, and location potential.

2. Engineering Objective

This goal examines three primary issues, including the system's efficiency:

a) A transit option is advantageous and will receive a high score if it reduces travel time relative to time spent on the roads, offers pedestrian access that is nearly optimal, connects to other local and commuter modes of transportation, and effectively connects housing, employment, retail establishments, and recreational areas.

b) From the perspective of construction, a high score for this criterion will be obtained by going through high-demand areas like commercial, industrial, institutional, and high-density built-up areas.

c) Engineering characteristics are evaluated by measuring the attributes related to geological-environment, hydro-geological-conditions, and geo technics.

3. Institutional Objective

This objective measures the match between the transit system and spatial policies of the government/urban municipality, e.g. to maximize interconnectivity to existing public transport systems; to maximize linkages to strategic growth centers (as designated/proposed in local plans), to provide good linkages among urban centers and suburban railway networks, airports, long-distance bus stations, park, and ride lots as well as to minimize land acquisition.

4. Social Objective

Establishment of a transit system should increase social mobility by way of easy access to existing and future settlements. This can be measured by forecasting the passenger/km reduction for residential to employment areas, and residential to educational institutions.

5. **Environmental Objective**

The proposed transit system should have minimum damage to the environment. This includes minimal energy consumption, minimal emissions of toxic gases, minimal sound, and noise impact to sensible land-use such as (residential places, universities, and hospitals).

6. **Accessibility**

Accessibility can be defined as the relative ease of reaching particulars locations or areas. It is selected to include two of important sub-criteria, which are: travel time and land use. Accessibility-oriented public transportation planning can improve the operational efficiency of public transportation, guide orderly urban development, and alleviate issues such as traffic congestion, environmental pollution, and resource consumption in large cities (Su et al., 2023).

7. **Safety and Reliability**

Since safety is a top concern for those who utilize public transportation, improvements in raising consumer satisfaction with public bus services are required. Negative events that damage public transportation's reputation include delayed service or inaccurate information about bus and rail routes and schedules (Bakar et al., 2022), (Zakaria et al., 2024). Ensuring the provision of safe and comfortable stop stations and pedestrian walkways is crucial for users. Additionally, factors such as public transportation clearance, safety, punctuality, and other amenities play a vital role in the overall service quality (Md Diah et al., 2022).

Moreover, improvements in the quality of public services, coupled with ongoing efforts to encourage their use, result in passengers feeling unthreatened but comfortable and confident in continuing to utilize the services provided. This positive shift is expected to lead to an increase in the number of passengers and a subsequent reduction in the number of cars on the road. Consequently, the reliability of public transportation will reduce traffic congestion where this concern affects elderly mobility as stated by (Jahangir et al., 2022).

Offering passengers with a sense of comfort and confidence to continue using the services without feeling threatened. This is anticipated to have a favorable impact by increasing passenger volume and subsequently decreasing the number of cars on the road. As a result, where traffic congestion impacts senior mobility, the dependability of public transit will lessen it, as noted by (Jahangir et al., 2022).

2.12 Geographic Information System (GIS) and Spatial Multi Criteria Decision Analysis (MCDA):

According to Ondieki and Murimi (2009), GIS is a computer-based system designed for the storage, management, analysis, and display of spatial information. It integrates geographic knowledge, such as natural resources, land use, and population distribution, by linking attributes to specific earth locations. GIS has become a powerful tool for spatial data handling, offering capabilities like data overlay, map-based analysis, and output generation (Yoo et al., 2006; Ondieki and Murimi, 2009). In transportation, GIS has been widely applied in planning, modeling, accident analysis, and transit service design due to its ability to manage and analyze large datasets efficiently (Wang et al., 2025; Akinboyewa et al., 2025). It not only improves impartiality and flexibility in site selection but also supports rapid processing of complex spatial information (Farkas, 2009).

The selection of locations for major transport facilities, such as metro systems, is a strategic and long-term investment that influences urban economies and social life, requiring careful decisions by planners (Farkas, 2009; Erdem, 2014).

Decision-making in site selection typically follows a structured process, from problem identification to recommendation, where the quality of each stage determines the reliability of the outcome (Sharifi et al., 2006). Given the complexity of this process, GIS combined with multi-criteria decision analysis (MCDA) helps planners achieve more accurate and suitable results (Ahmed and Asmael, 2015).

In particular, Spatial Multi-Criteria Decision Analysis (SMCA) involves collecting and transforming spatial data into judgments and suitability results through GIS modeling (Farkas, 2009; Ahmed and Asmael, 2015). The output is often a suitability map that highlights optimal locations based on defined criteria (Ondieki and Murimi, 2009). Criteria are represented as map layers with attributes measuring objective achievement, while undesirable areas are excluded (Kropp, 2010). Multi-Criteria Decision Making (MCDM) further supports evaluating alternatives by assigning criterion weights reflecting decision-maker priorities (Kropp, 2010). Through these approaches, GIS provides an effective framework for identifying the most viable sites for transport facilities (Akinboyewa et al., 2025).

2.13 PTV VISSIM Software

PTV VISSIM is an internationally established microscopic, multimodal traffic simulation software package produced by PTV Planning Transport Verkehr AG, initially released in 1992. Still, it is a reference model for microscopic modeling of urban transport (PTV Group, 2023). This program has the following key capabilities:

Microscopic Behavior Modeling: Uses the Wiedemann car-following model, which can realistically depict driver behavior and lane-change dynamics (PTV Group, 2023). As well as it able to simulate mixed traffic within the same simulation (PTV VISSIM Manual, 2023).

Traffic Control and Public Transport Integration supports fixed-time and traffic-actuated signals as well as advanced support for signal priority and public transport operations (PTV Group, 2023).

Network flexibility and 3D visualization allows complex road geometries to be modeled and detailed 2D/3D visualizations to be created in order to help with scenario planning and stakeholder engagement (PTV Group, 2023).

Environmental and Emissions Assessment: Interfaced with emissions modeling tools like module for pollutant emissions and traffic noise analysis (Bosch and PTV, 2022).

International Usage: used in more than 2500 global cities by over16,000 professionals with consistent updates and validation over 30 years (PTV Group, 2024).

Verified: Backed by academic and real-world assignments by means of calibration metrics including GEH stats (Al-Madinah Calibration Study, 2021). Advanced Research Applications: CAV systems, COM interface scripting, PTV VISUM connectivity for hybrid simulation (PTV Developer Resources, 2023). PTV VISSIM is a traffic simulation tool based on science, science, and versatility. Its application in this study verifies the dependability of simulation-oriented assessments in urban transport planning for cities such as Karbala City.

2.14 Studies of Sites Evaluation Criteria

Farak (2009) explained how GIS with the value-focused approach of MCDM processes to determine the suitable metro line locations in Cochabamba City. Region of Bolivia depending on engineering characteristics and geological soil structure, ecological suitability, population density, and projected construction costs criteria.

Jakimavičius and Burinskiene (2013) evaluated the technological advancement of an extra tram network for public transportation in Vilnius City in Lithuania. The optimal transport development alternative was found by comparing two methods: Simple Additive Weighting (SAW) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution).

Alkubaisi (2014) adopted a methodology of using MCDM with GIS to find the best route of tram in Al-Ramadi City in Iraq based on main criteria (accessibility, safety, environment, economic, and security). The study recommended that proposing tram routes based on traffic demand data: traffic flow, speed, and LOS are more efficient than using land use criteria only.

Ghani Ahmed and Moutaz Asmael (2015) selected metro route in Baghdad, Iraq using a multi-criteria evaluation based on three primary criteria: the environment, the economy, and engineering. Data preparation and analysis are done using a GIS in this process. AHP and TOPSIS techniques were employed in a two-stage MCDM model for data analysis. Additionally, several route options were investigated using GIS. Each option was assessed in relation to the chosen criteria in order to determine which was the best. In addition to expert judgments, the weighting system incorporates a set of measurements derived from actual data.

Shafik (2016) identified the optimal metro locations for stations and route in the Gaza Strip, Palestine based on MCDM, criteria that have been relied upon in choosing the best site included: population density, vital places, important intersections, suitable land, soil type, ground water, slope, and land use. for weighing criteria simple linear combination methods have been used.

El-Hallaq and Khalid (2017) involved the evaluation of a case study in Gaza City, Palestine to select the metro site route by using analysis. The criteria that are used are population density, vital places, available parking, the area of intersection, traffic important of intersection, and land use. Each of the previous criteria has a weight which is confirmed by experts.

Awasthi et al. (2018) explained the use of Fuzzy TOPSIS, three three-ideal-solution-based MCDM for the sustainability evaluation of three sustainable mobility projects, which were the installation of an electric vehicle car-sharing, the establishment of an additional tramway, and the reorganization of the city's bus lines to provide optimal service in Luxembourg's City center, Europe. The economic, environmental, social, and technical factors that the review process was reliant on. A new tramway in Luxembourg City's downtown was determined to be the best option for implementation based on the results of the assessment.

Al-Yasery H., et al (2018) selected the optimal locations for metro stations in Karbala City, Iraq, based on a variety of factors (population, land use, trip attraction zone, critical places distances), to serve the most significant number of passengers and connect important destinations with densely inhabited areas. GIS, a potent tool for spatial analysis, is used in this investigation. The criteria were assigned weights and a chosen scale for importance using the AHP. According to the findings, 31 station locations could be selected as the ideal locations for metro stations.

Farooq *et al.* (2018) concentrated on creating a transportation model that would improve connectivity, decrease travel time, and maximize transfer capacity between Beijing and Xiong in China. A network capable of meeting future demand has been suggested after an analysis of the current transportation system between the two cities. Employing a GIS, several options were investigated in the first step. A mass transportation system's planning and implementation needs making decisions between many possibilities, including a new high-speed rail line, an existing intercity railway line, and/or choices for motorways. Analyzing these possibilities, considering specific criteria, they used AHP in their second phase of study. The alternatives were assessed based on several factors that were used to determine which alternative would be best. It was discovered that the most critical factors were journey time, cost, safety, dependability, accessibility, and environment. The optimum option for action, according to the multicriteria analysis and GIS, was to construct a new high-speed train route.

Tubis et al., (2019) presented the findings of a study evaluating the stop zones' degree of safety for the chosen tram lines in Wroclaw, Poland. This evaluation will make it possible to put appropriate corrective measures in place. The safety assessment of the stop zones was based on an indicator that included three parameters: (the location and infrastructure of the stop, its accessibility, and the volume of traffic in the stop zone). These parameters have been identified as the most important from the point of view of the safety of stops.

Yildirim and Bediroglu (2019) utilized network analysis based on GIS and the AHP to determine the best routes for a high-speed railway project on the Erzincan–Trabzon leg of the Turkish railway network. Slope, geology, soil quality, rivers, protected areas, highways, land cover, and lakes were the eight elements that made up the route-generating study. Around 12% less money was spent on building the new hybrid route, and its environmental efficiency was verified by the least-cost path study.

Zak and Kurek (2020) used MCDM methodologies based on universal and standard sustainable parameter to evaluate and present the study of tram specifications in several countries, such as the Czech Republic, France, Germany, Hungary, Poland, and Turkey. The primary evaluative variables were (travel comfort, dependability, longevity, safety, traction-operational features, cost of operations, utility, environmental friendliness, and functionality).

Ghorbanzadeh *et al.* (2020) proposed five subway stations along the suggested subway line for a planned future mass transportation system in Rasht City, Iran, based on a range of parameters connected to the population, their socioeconomic features, and the larger surroundings. The Traffic and Transportation Agency of Rasht recommended a number of potential locations for subway stations, and this study aims to use geospatial analysis to find the best ones. A GIS-based multi-criteria decision approach along with an implementation of AHP to select the best subway station locations.

Görçün (2021) provided a MCDM approach that is used to assess the choice of urban rail cars that are used in Turkey's public transportation systems which were metro and tram, based on 22 factors (commercial speed, design speed, passenger capacity, length, width, height, max tractive force, emission (CO_2), noise (dB), seat number, purchase cost, maintenance cost, maintenance, vehicle weight, energy consumption, max braking force, max grade slope, accelerate, min. radius, wheelbase, life span, axle load). It can be determined that tram rail was the best and most suitable rail vehicle.

Czerepicki *et al.* (2021) provided a priority solution analysis for trams at a particular set of intersections in Warsaw, Poland. A coordinated series of intersections was modeled using computer simulation. The average speed, the amount of electricity used for propulsion, and the number of pollutants each vehicle emits were chosen as comparison points for the different solutions. The current control system, the newly planned coordinated fixed-time control system, and the adaptive control system with active priority were the three test scenarios that were created. For each of the three different scenarios, specific travel characteristics of the trams and other traffic participants in a chosen stretch were collected throughout the simulation procedure. The amount of electricity required for traction requirements and emissions of pollutants has been determined for every variation. According to the analysis, applying the adaptive priority will, for the configuration under consideration, minimize tram time losses by up to 25%, reduce energy consumption by up to 23%, and minimize individual vehicle pollution emissions by up to 3% when compared to the original version. The results of this study could serve as the basis for a thorough evaluation of how well adaptive priority is applied in the design of new tram lines and the renovation of existing ones.

Sawicki and Sawicka (2021) studied the location selection of a new tram among the already existing ones in Poznań, Poland. The evaluation of the alternatives precedes the selection. Economic, technological, environmental, and organizational considerations should all be considered while evaluating the new tram depot locations. The authors suggest a methodology that combines optimization and multiple evaluation techniques to address such a complicated decision problem. The established method is used experimentally to choose one of the five locations for tram depots in the Poznań, Poland, public transportation system. All the computational experiments are performed by means of optimization and MCDA methods and tools, i.e., a linear optimization engine Solver Premium Platform and the AHP method with its application AHORN simple. The calculations are the basis for recommending the location of a new depot in the central part of the transport network, which is a reasonable solution considering, e.g., the proximity of the main railway line, the possibility of triple distribution of the means of transport from the depot.

Balket and Asmael (2021) determined the routes of a new means of public transit in the city of Kut, Iraq, bus rapid transit, and the main purpose was to encourage citizens to leave the private car to alleviate traffic congestion by refining the LOS and performance for the public transport system in the city and the citizen's comfort as a final outcome by delivering citizens to their place of residence or their place of work as soon as possible and at the lowest cost. The application of the AHP program to compute criteria weights and the processing and analysis of data involved the adoption of the GIS. The main criteria that were used were (population, land use, government sites, health sites, education sites, and bus stops).

Harkat et al. (2022) used MCDM to investigate and evaluate the Constantine tramway line's effects in Algeria, North Africa. Its methodology involves conducting investigations, interviews, and on-site surveys with a population comprised of individuals who utilize a variety of transportation options. The results confirm that:

a) The tramway line has a strong effect on ridership by providing comfort for passengers, especially the elderly, students, and the disabled.
b) Achieving the highest reliability of buses to the timetable.
c) Reducing travel time by half the time spent on the bus.
d) Reducing the use of different travel modes.

The main parameters used were (Social, economic, reliability, comfort, and time saving).

Djouani et al. (2022) assessed the effectiveness of tram tracks in the Algerian city, North Africa, by integrating the GIS methodology with the AHP. To identify the primary weights for each predetermined criterion, which included (traffic safety, security, accessibility, economic, practicality, exploitation by citizens preservation, and the environment), several predetermined criteria were arranged and analyzed in the AHP. The results of the study demonstrated that the city's tramway track selection was unsuccessful in terms of the location selected, and that the efficiency and quality criteria relevant to urban transportation were not taken into consideration throughout the selection process.

Vilke, Petrović and Tadić (2022) evaluated and selected of an optimal railroad route between Rijeka and Zagreb as part of the Mediterranean Corridor. The large number of criteria used to analyze solutions makes this decision-making complex, encompassing economic, transport, Constructional-technical, urban planning, and Ecological-Sociological Aspects. The optimization method of multi-criteria analysis was used to analyze an alternative railroad route. A model comprising the defined criteria and sub-criteria, including their weighting coefficients, was set. To perform the analysis, the authors applied the defined model for evaluation and selection of a railway route between Rijeka and Zagreb using the PROMETHEE II method for multi-criteria ranking of alternatives and the computer software “Visual PROMETHEE”. The criteria employed were (trip distance, trip time, and travel speed).

De Ridder and Farah (2023) developed a multi-objective model for optimizing stop locations within an urban tram network while considering multiple transit objectives. Detailed socio-economic data of zones is used in the model, alongside current travel behavior, to estimate transit demand precisely. Additionally, the effects of stopping relocation on operations are assessed using running time data. As a result, optimal stop locations for an entire transit system can be determined. The results of a case study of the tram system of the Hague, Netherlands, indicate that in areas where trip distances are short and near the end of a tram line, stop spacing should be denser compared to other parts of the system. Moreover, it is concluded that stops are not always optimal where two transit lines intersect. Only in the event of a high share of transfer passengers should a stop be located irrespective of the other factors. Finally, it is concluded that the potential speed on a line section does not affect the optimal stop spacing significantly.

The literature consistently shows that environmental, social, and accessibility criteria are most aligned with sustainability goals and passenger needs, while engineering factors are less significant due to their variability across regions. Some studies also incorporated additional considerations such as reliability, safety, and security; however, these are more relevant when comparing different modes of transport, as tram systems inherently offer high levels of reliability and passenger safety.

However, a key research gap remains, as no previous study has explicitly integrated the Level of Service (LOS) as a primary evaluation criterion; instead, most focused only on traffic volumes. Moreover, air quality indices were not adequately considered in the assessment process. Another significant gap lies in the absence of simulation-based evaluations of proposed tram networks within cities. Previous studies did not utilize microsimulation tools to compare network performance with and without tram implementation, limiting the ability to capture the full operational and environmental impacts of such systems.

2.15 Summary

This chapter reviews the literature on integrating tram systems into urban transportation networks. It begins by addressing key urban challenges such as traffic congestion, air pollution, and the energy issues associated with increasing urbanization and reliance on motorized transport. The chapter then focuses on sustainable transportation, emphasizing the role of public transit networks in achieving environmental, social, and economic sustainability. Various public transport options are discussed, with particular emphasis on trams, highlighting their benefits, including high passenger capacity, energy efficiency, low emissions, and reliability compared to buses and subways. The chapter also outlines the criteria for selecting tram routes and station locations, emphasizing accessibility, safety, dependability, and economic, environmental, and social considerations. It notes that accessibility, social justice, and environmental factors are commonly prioritized in global sustainable mobility research, while economic and engineering criteria are more context specific. Finally, the chapter reviews global research methods like AHP, MCDM, and TOPSIS, showing how evaluation criteria align with urban transportation goals and sustainability, providing a foundation for future methodological decision.

Chapter Three

Research Approach and Methodology

3.1 Introduction

This chapter presents the definition of the study area, the navigation and surveying of data points, and an overview of the procedures and methodology used for selecting the optimal locations for tramway network components (routes and stations). The methodology is structured into six main steps.

The first step involves identifying the primary objectives and selection criteria for determining potential alternatives. The second step focuses on collecting data related to these criteria, which are essential for identifying the most suitable locations. The third step entails performing spatial analysis and geoprocessing to address the site selection problem. These procedures are implemented through a cartographic model, a criteria weighting process, and least-cost path analysis.

The fourth step involves the evaluation of alternatives, which includes identifying the criteria used for assessment and ranking the other options using the EDAS and CRITIC models. The final step consists of modeling the tram network using PTV VISSIM software and comparing two scenarios before and after the tram system's implementation in terms of LOS, average travel speed, average delay, traffic emissions, and noise levels. The percentage variations between the two scenarios are also determined. The overall methodology steps adopted in this study are illustrated in Figure (3.1).

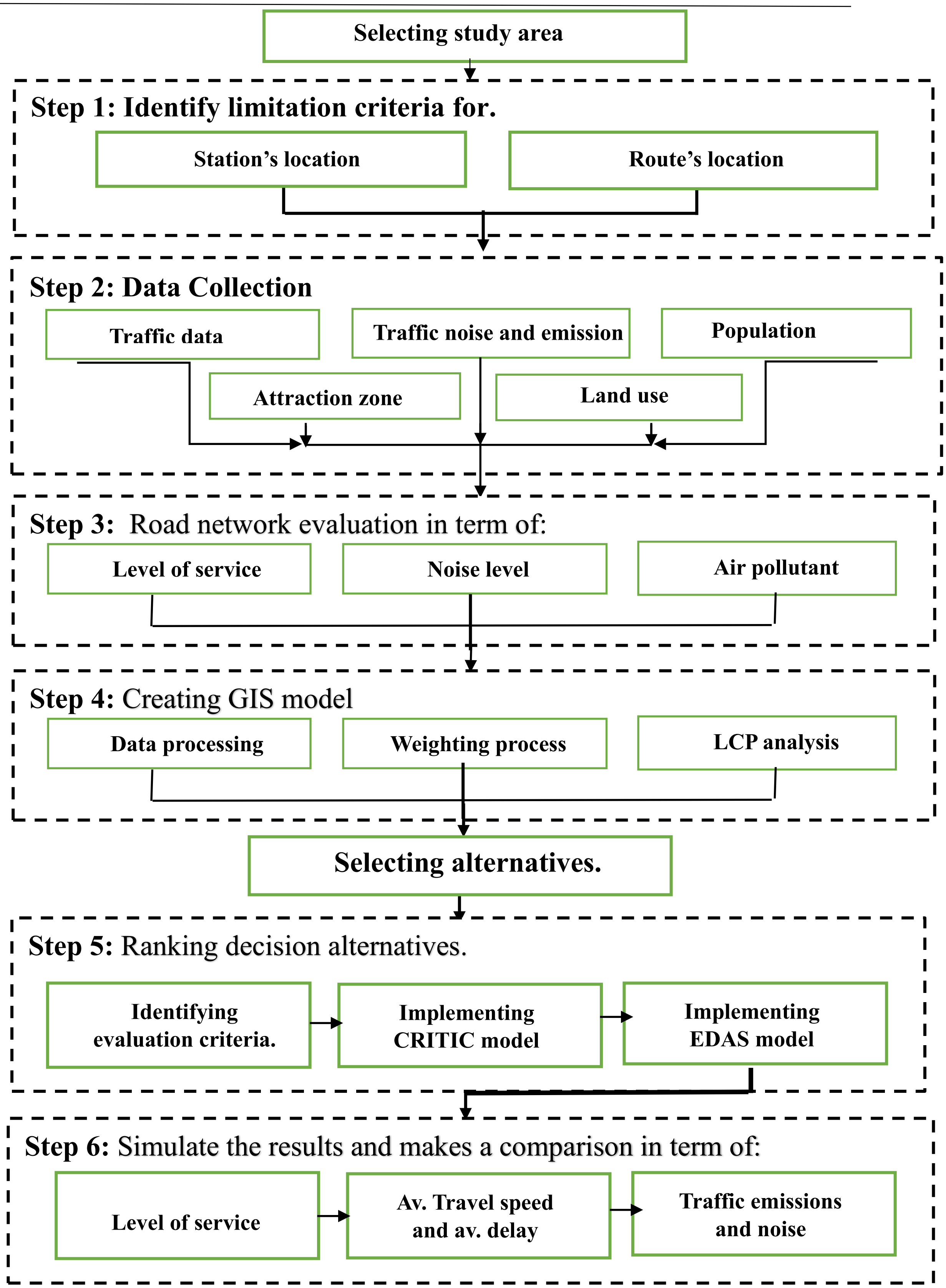

Figure (3.1): Methodology steps.

3.2 Study Area

Karbala City is situated at 32:60N, 44:00E, 110 kilometers southwest of the capital, Baghdad. The city's elevation above sea level is about 36 meters. There is a desert to the south and lush agricultural land to the north of the city. The city center, Al-Hur, AL-Husseiniya, Ein Al-Tamor, and AL-Hindiya districts are the five districts that make up the governorate. The closest town is Al-Hindiya, which is located roughly 22 kilometers from the Euphrates River's east bank. There is a direct road from Karbala to Saudi Arabia, Jordan, and Syria to the west. Karbala is connected to Baghdad in the North. Although the city does not yet have a railway, a new airport is being built. Beneath that there are layers of sand and clay up to 30 m depth and the bottom layer is a deep layer of compacted sand. Toward the desert, at depth of 50 m, water is sulfuric in nature. There is plenty of water at a depth of 20-30 m because Karbala is at the bottom of a basin in the region as vast as Iraq. The South area of Karbala is characterized by silica sand with high-quality gypsum. Figure (3.2) shows the study area.

3.3 Tram Routes Limitation Criteria

According to Ghani Ahmed and Moutaz Asmael (2015), El-Hallaq and Khalid (2017), the main limitations for route location are:

1. The proposed alternative should be located in a high-traffic volume and congestion area.
2. The proposed alternative should pass through main roads and intersections.
3. The proposed alternative should pass through attractive and generating areas (commercial, industrial, healthy, and educational areas).

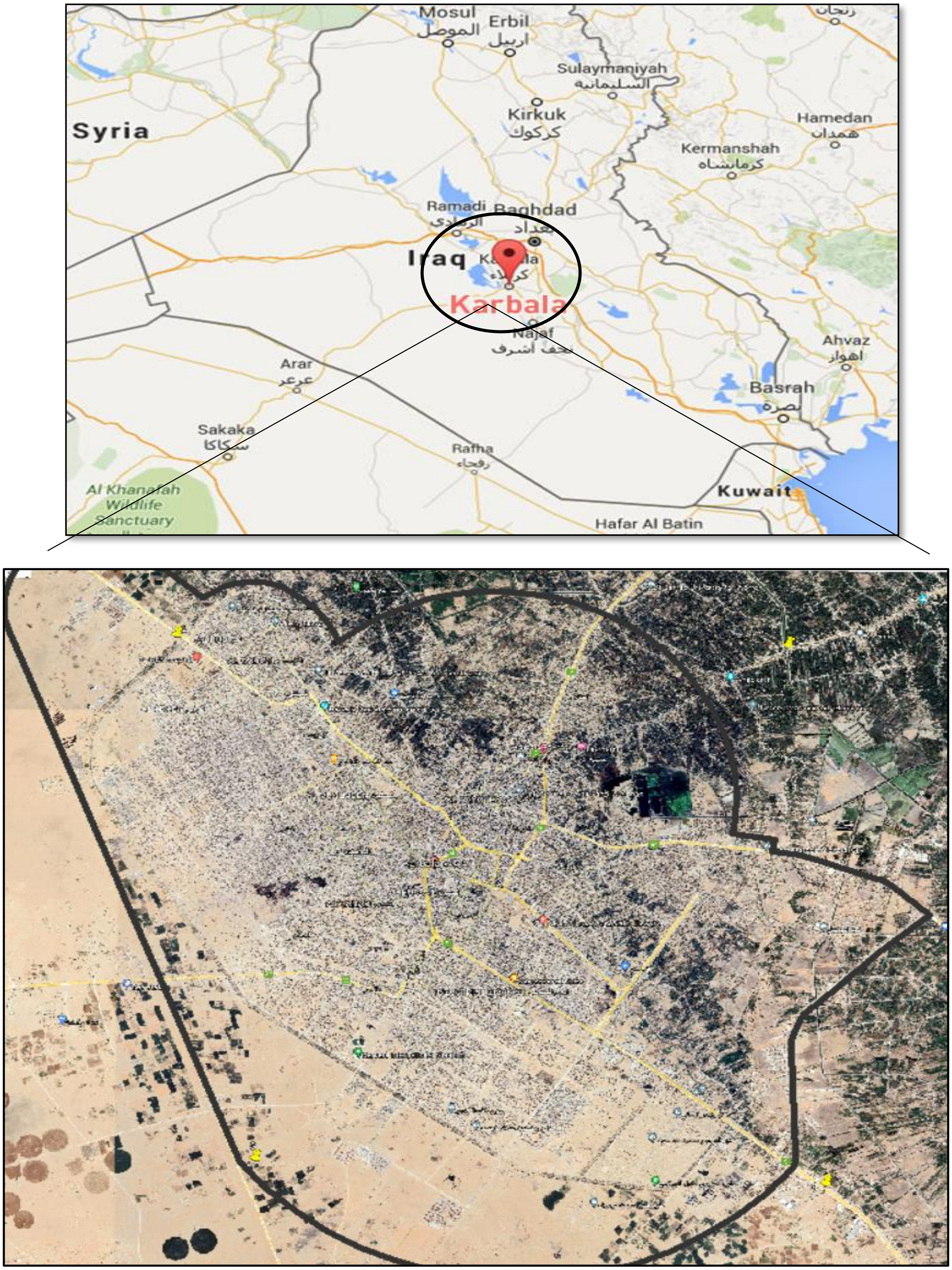

Figure (3.2): Area of study.

3.4 Tram Stations Limitations

According to Moutaz Asmael (2015), Shafik (2016), Savchuk and Nahornyi (2020), the main limitations for station locations are:

1. Stop stations should be near residential areas (generation zone), commercial areas (attraction zone), service areas (educational institutions, hospitals, governmental departments, industrial areas, and recreational areas).
2. It is preferable that station spacing ranges from 300 to 600 meters to maintain a balance between accessibility and efficiency. Very short distances may increase travel time due to frequent stops, while overly long distances can reduce accessibility and convenience for passengers.

3.5 Data Collection

The data was collected from various sources, including the General Directorate of Physical Planning, surveillance cameras, noise meters, and environmental sensors. A high-resolution (0.5 m) satellite image of Karbala's City center, taken in 2024, was used as a base map, The data regarded as the main criteria is listed in Table (3.1).

Table (3.1): Main data required.

Data required	Data source
Land use as GIS map layer	General Directorate of Physical Planning
Population	Directorate of Statics
Traffic speed data	Speed gun
Traffic volume data	Video camera
Traffic noise data	Noise level meter
Traffic emission data	Advanced sense environmental test meter

3.5.1 Land Use of Karbala City

The existing land use data were obtained from the General Directorate of Physical Planning. The land use of Karbala City was classified into 16 sectors: residential, commercial, agricultural, educational, healthy, tourist, archaeological, security, green, industrial, religious, athletes, transportation, recreation, government, and vacant. The detailed land use map would be presented in Chapter Five.

3.5.2 Population of Karbala City

The Directorate of Statics provided demographic information for each neighborhood for the year 2023. Figure (3.3) population in each neighborhood of Karbala city center.

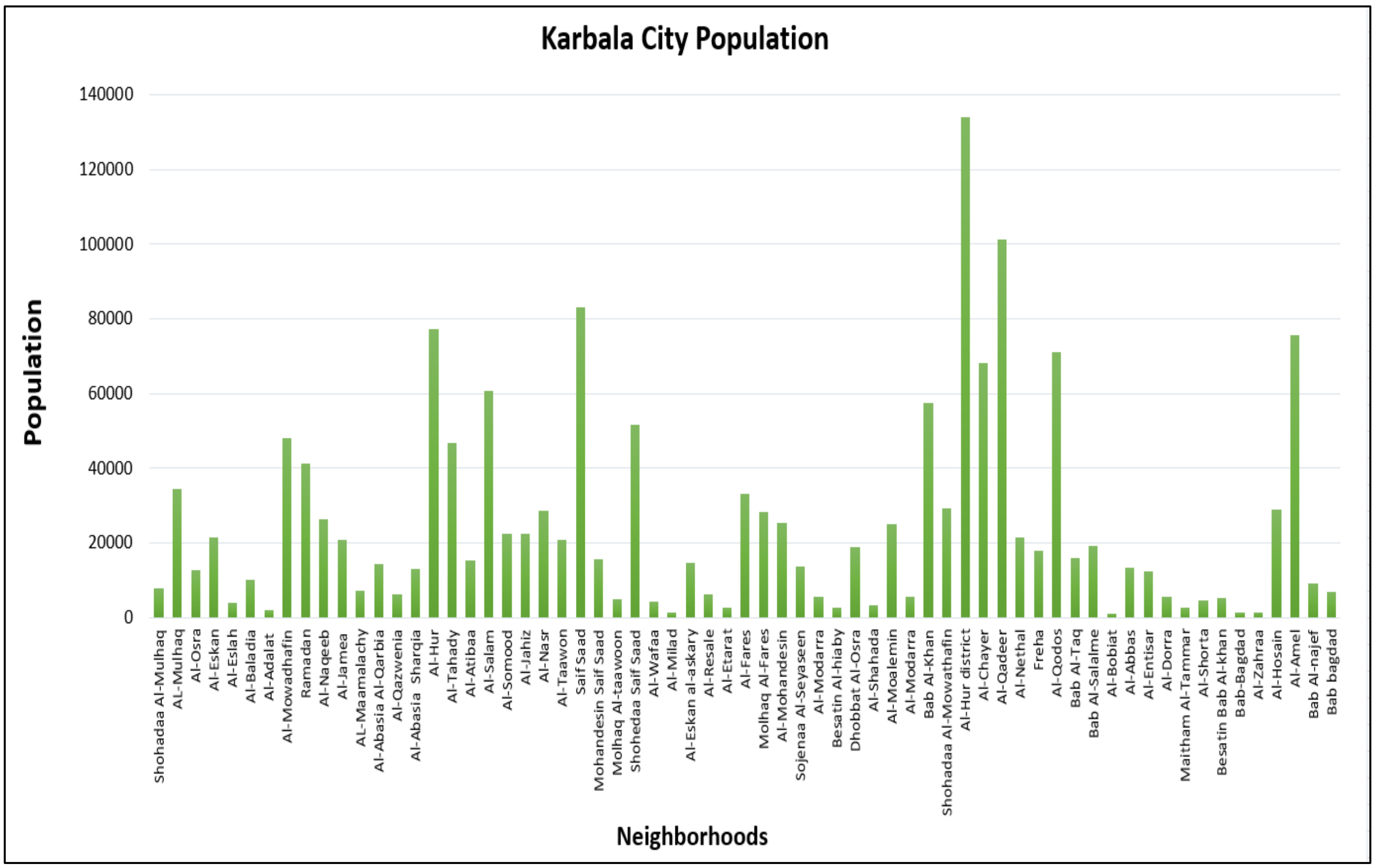

Figure (3.3): Karbala City neighborhood's population in 2023 (Directorate of Statics).

3.5.3 Traffic Data

There were thirty-eight urban streets in the research region. There are important varieties of activity centers in the area, such as government buildings, shopping areas, and educational institutions, which has resulted in increased traffic demand and congestion in this area. Figure (3.4) and Table (3.2) depict the study region.

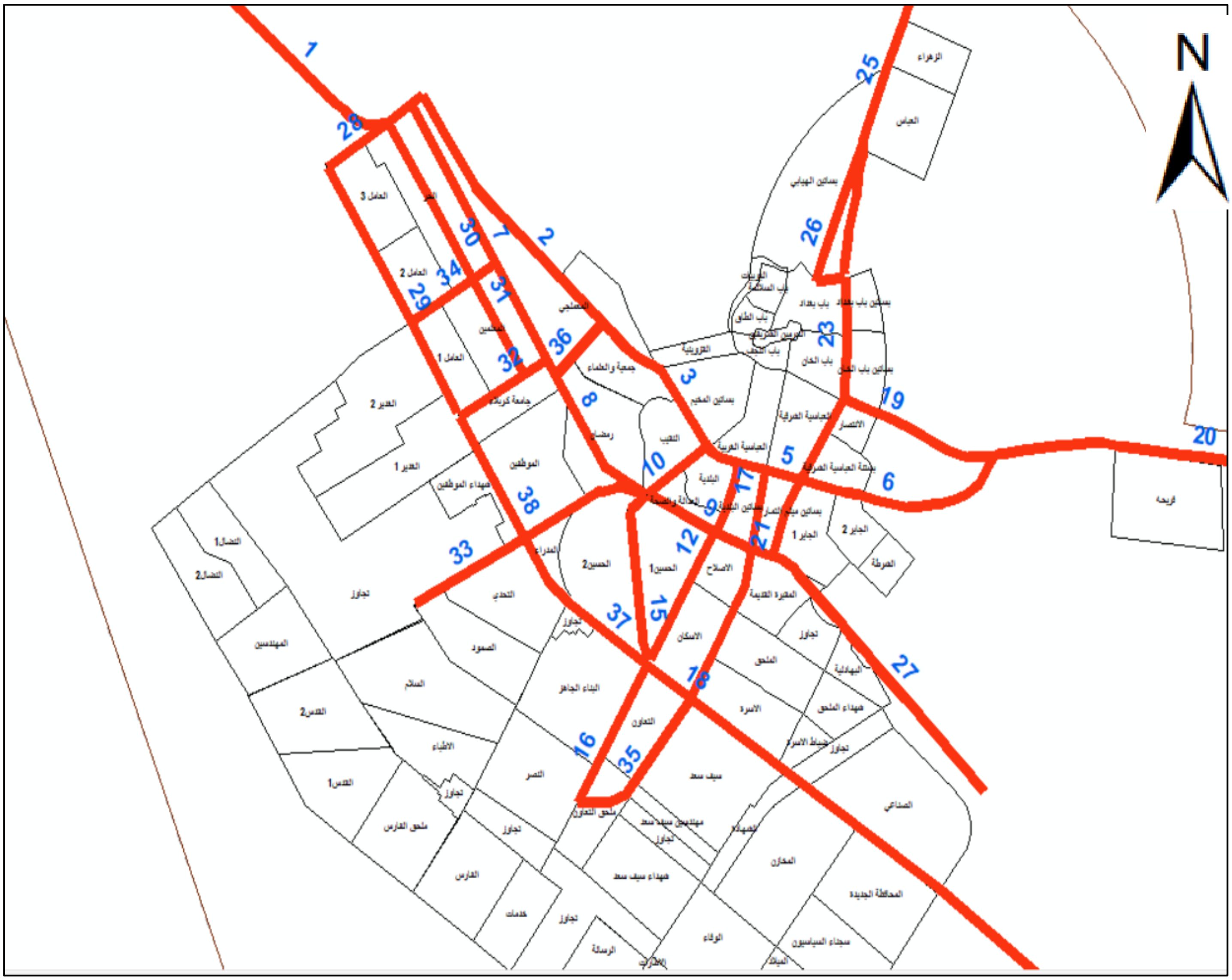

Figure (3.4): The studied urban streets.

Table (3.2): Urban Streets within the Study Area.

Street No.	Street name	Street No.	Street name
1	Hasan Al-Mojtaba	20	Karbala-Hindea
2	Al-Hur	21	Matham Al-Tammar 1
3	Bait Al-Mohafodh	22	Matham Al-Tammar 2
4	Al-Tarbea	23	Matham Al-Tammar 3
5	Nabi Mohmmad	24	Al-Qebla
6	Al-Hawly	25	Karbala- Bagdad 1
7	Sarie Al-Moalemin	26	Karbala- Bagdad 2
8	Sarie Ramadan	27	Abdolzahara Al-Kaaby
9	AL-Mojammaat	28	Al-Amel 2
10	Al-Dhariba	29	Al-Amel 1
11	Qorfat Al-Tijara	30	Hai Al-Hur
12	Al-Iskan	31	Hai Al-Moalemin
13	Ftima Al-Zahraa 1	32	Mostashfa Wilada
14	Ftima Al-Zahraa 2	33	Al-Mowadhfin
15	Haidar Al-karrar	34	Al-Markaz
16	Al-Nasr	35	Imam Ali
17	AL-Abbas	36	Al-Taalib
18	Karbala-Najaf	37	Al-Jahiz
19	Bab Twerige	38	Shohadaa Al-Mowadhafin

3.5.3.1 Traffic Volumes

The number of vehicles traversing the study locations was counted manually from recorded videos for both directions in the field throughout the day (24 hours). The peak periods were found to be from (7:00 to 9:00 AM) and from (4:00 to 6:00 PM), based on data collected during Monday (15/4/2024), Wednesday (17/4/2024), Tuesday (7/5/2024), and Wednesday (8/5/2024). These days were chosen due to their stable and consistent traffic patterns. Sunday and Thursday were excluded because of unusual congestion caused by the start of the workweek and increased pilgrim visits to the holy shrines, respectively. Friday and Saturday were also avoided as they are weekend days with irregular traffic flow. This selection ensures the data accurately reflects normal weekday operations. The traffic composition is classified as: private cars, taxis, minibuses, buses, trucks, three-wheelers (MTRs), and motorcycles. The following examples illustrate the volume data and flow rates in the study area. Volume data have been gathered in Appendix A.

A) Hasan Al-Mojtaba Street

Volume data have been measured on Monday (15/4/2024) from (7:00 to 9:00 A.M), for both directions as shown in Table (3.3) and Figure (3.5).

Table (3.3): Example of Hasan Al-Mojtaba Street direction 1 volumes data.

Time	Private	Taxi	MTR	Motor	Minibus	Bus	Truck	Volume	Flow (veh/hr.)
7:00-7:05	35	4	8	5	6	0	2	60	720
7:05-7:10	41	5	10	2	4	0	7	69	828
7:10-7:15	45	3	12	4	5	0	26	95	1140
7:15-7:20	46	6	8	5	8	2	14	89	1068

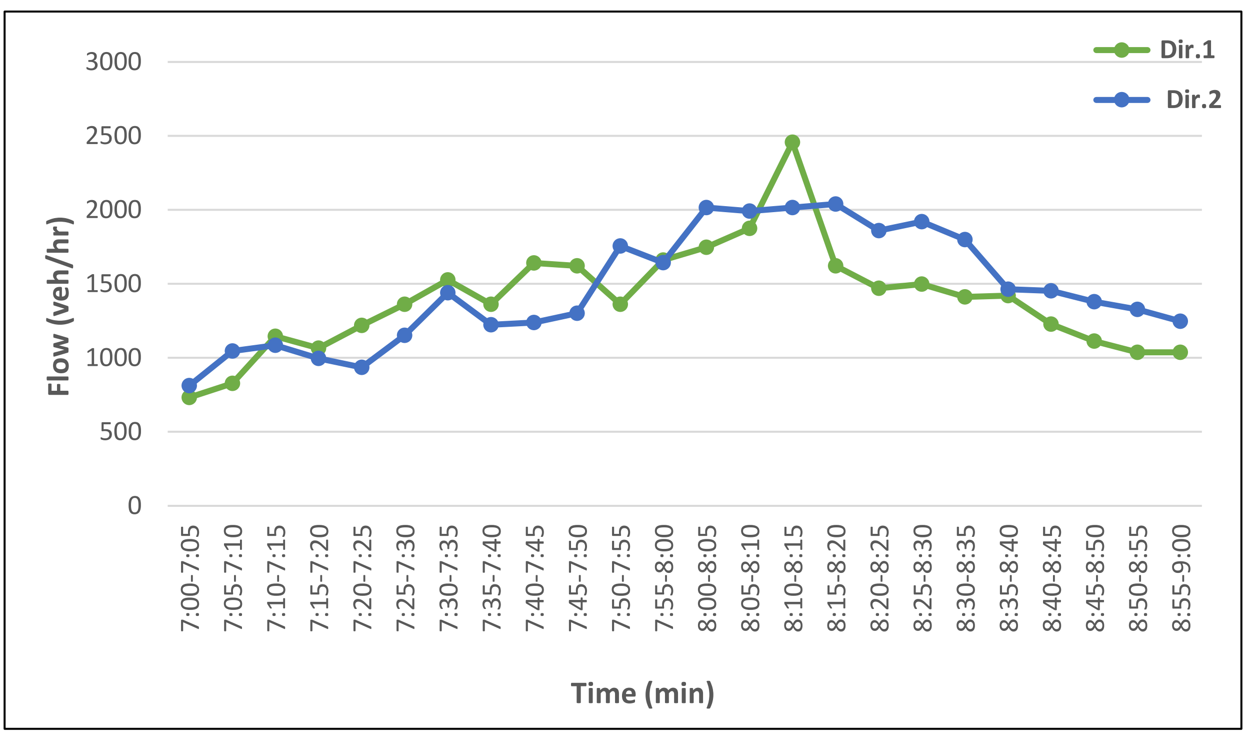

Figure (3.5): Hasn Al-Mojtaba Street traffic flow.

B) Nabi Mohammad Street

Volumes data have been measured on Monday (15/4/2024) from (7:00 to 9:00 A.M), as shown in Table (3.4) and Figure (3.6).

Table (3.4): Example of Nabi Mohammad Street at direction 1 volumes data.

Time	Private	Taxi	MTR	Motor	Minibus	Bus	Truck	Volume	Flow (veh/hr.)
7:45-7:50	94	14	31	22	10	5	19	195	2340
7:50-7:55	99	16	34	25	13	0	7	194	2328
7:55-8:00	104	19	39	28	12	3	19	224	2688
8:00-8:05	109	18	41	29	14	2	12	225	2700

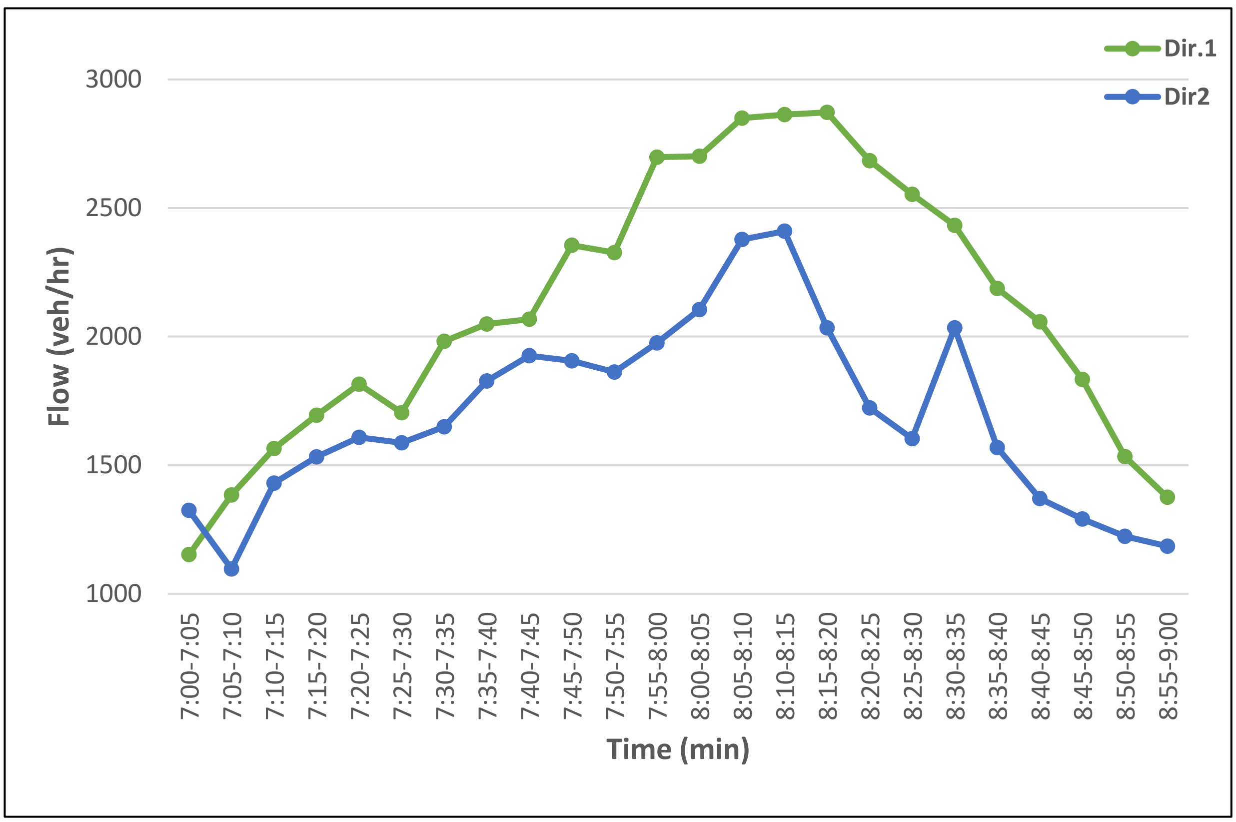

Figure (3.6): Nabi Mohammad Street traffic flow.

C) Al-Tarbea Street

Volumes data have been measured on Wednesday (17/4/2024) from (7:00 to 9:00 A.M), as seen in Figure (3.7) and Table (3.5).

Table (3.5): Example of Al-Tarbea Street at direction 1 volumes data.

Time	Private	Taxi	MTR	Motor	Minibus	Bus	Truck	Volume	Flow (veh/hr.)
7:45-7:50	74	16	53	46	31	5	3	228	2736
7:50-7:55	77	17	57	58	33	2	4	248	2976
7:55-8:00	80	18	58	54	39	3	3	255	3060
8:00-8:05	74	16	43	42	44	8	10	237	2844

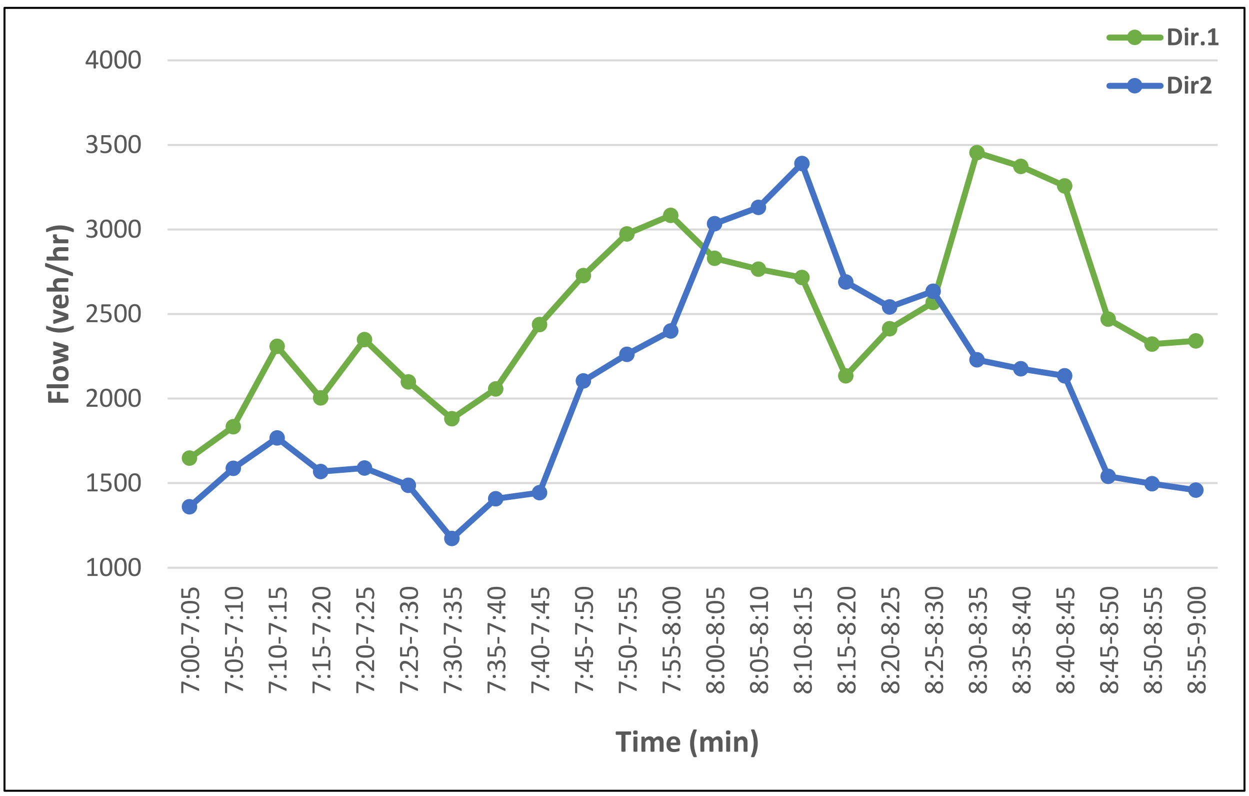

Figure (3.7): Al-Tarbea Street traffic flow.

D) AL-Hawly Street

Volumes data have been measured on Monday (8/5/2024) from (7:00 to 9:00 A.M), as shown in Table (3.6) and Figure (3.8).

Table (3.6): Example of Al-Hawly Street at direction 1 volumes data.

Time	Private	Taxi	MTR	Motor	Minibus	Bus	Truck	Volume	Flow (veh/hr.)
8:10-8:15	78	18	24	10	13	7	8	158	1896
8:15-8:20	79	15	26	9	12	4	6	151	1812
8:20-8:25	74	11	22	16	13	2	5	143	1716
8:25-8:30	70	13	14	10	6	1	3	117	1404

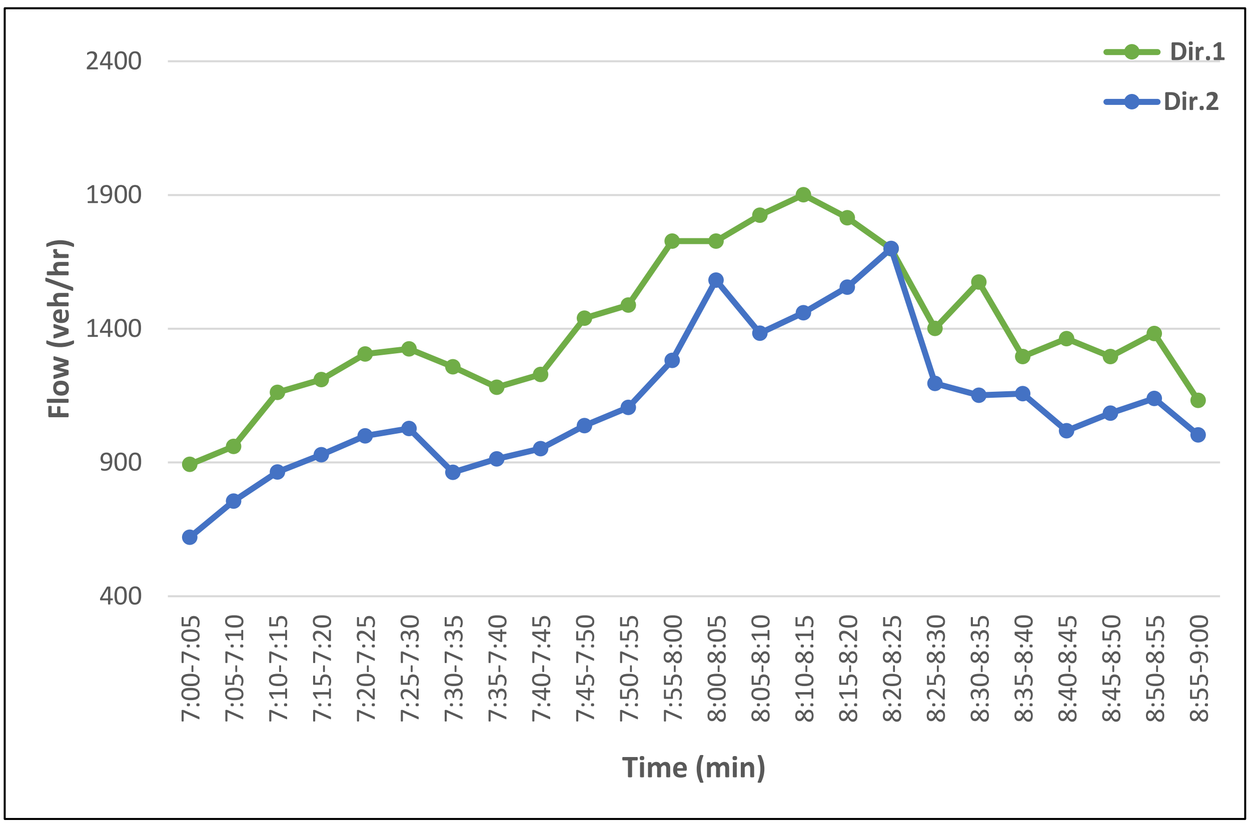

Figure (3.8): Al-Hawly Street traffic flow.

E) Sarie Al-Moalemin Street

Volume data have been measured on Tuesday (7/5/2024) from (7:00 to 9:00 A.M), as shown in Table (3.7) and Figure (3.9).

Table (3.7): Example of Sarie Al-Moalemin Street at direction 1 volumes data.

Time	Private	Taxi	MTR	Motor	Minibus	Bus	Truck	Volume	Flow (veh/hr.)
7:30-7:35	76	15	31	26	13	0	5	166	1992
7:35-7:40	82	16	23	20	17	2	2	162	1944
7:40-7:45	86	22	24	14	14	2	14	176	2112
7:45-7:50	94	17	30	27	14	2	13	197	2364

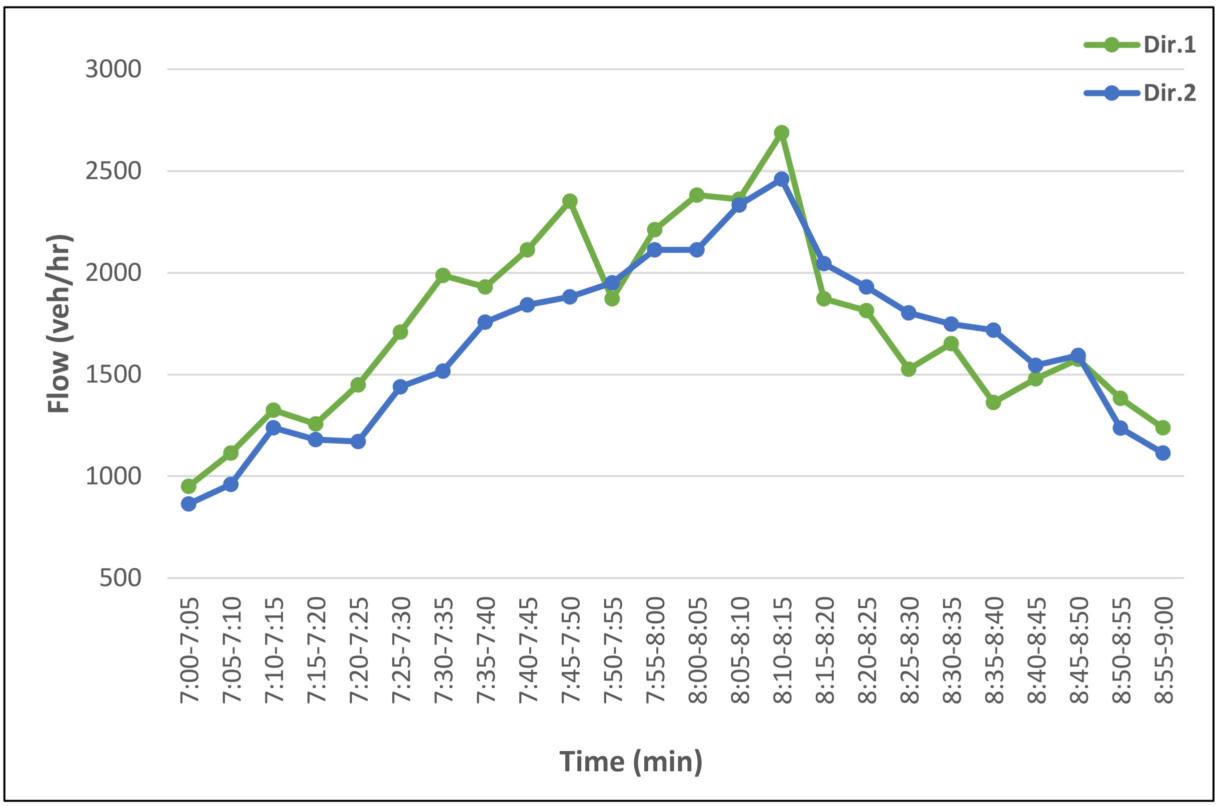

Figure (3.9): Sarie Al-Moalemin Street traffic flow.

F) Sarie Ramadan Street

Volume data have been measured on Tuesday (7/5/2024) from (7:00 to 9:00 A.M), as shown in Table (3.8) and Figure (3.10).

Table (3.8): Example of Sarie Ramadan at direction 1 Street volumes data.

Time	Private	Taxi	MTR	Motor	Minibus	Bus	Truck	Volume	Flow (veh/hr.)
8:05-8:10	110	37	41	62	24	0	19	293	3516
8:10-8:15	121	39	42	60	26	2	20	310	3720
8:15-8:20	130	42	44	61	27	1	22	327	3924
8:20-8:25	136	45	46	52	30	0	25	334	4008

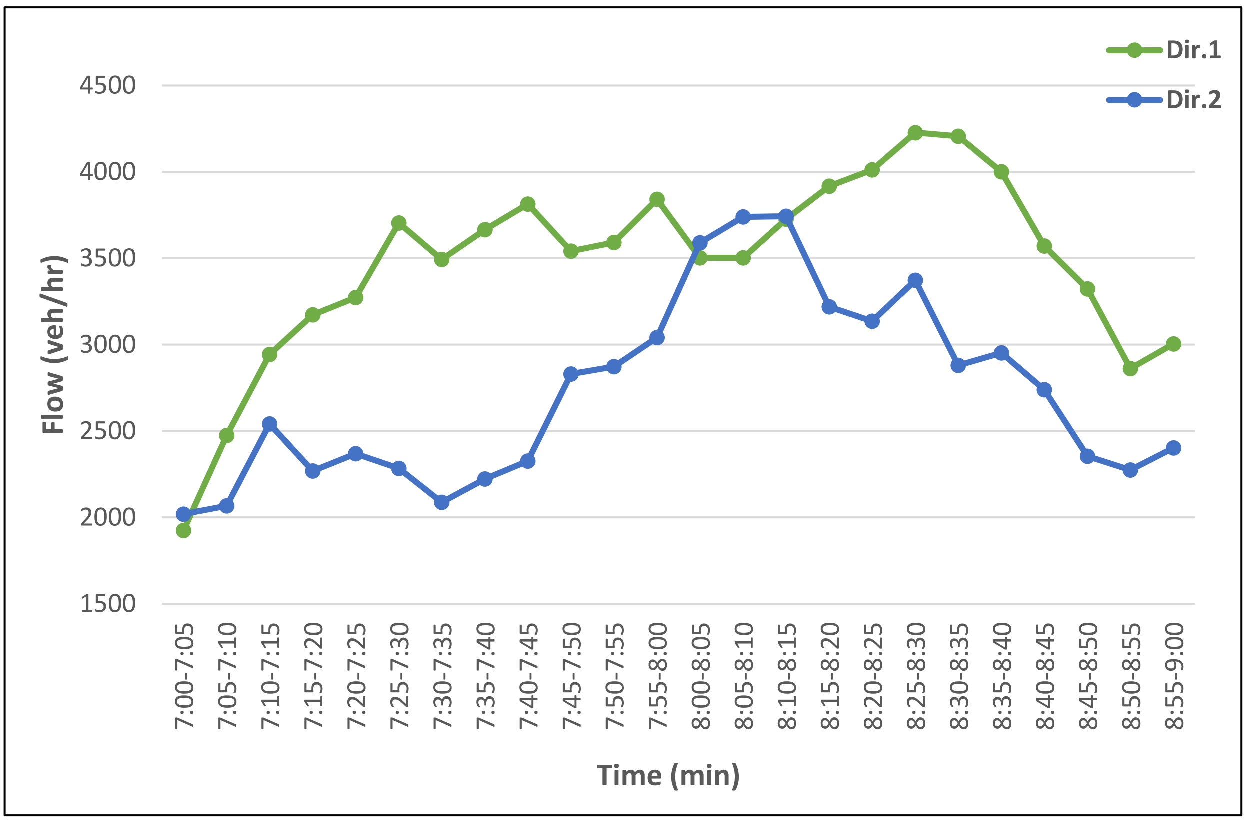

Figure (3.10): Sarie Ramadan Street traffic flow.

3.5.3.2 Traffic Speed Data

3.5.3.2.1 Free Flow Speed (FFS) Data

Free flow speed has been measured as an indicator of traffic performance during off-peak hours for all locations. It aims to state the maximum speed on the road, where drivers are free from the influence of others. A Speed Gun was used to calculate the free-flow speed. Devices called speed guns are used to gauge a running vehicle's speed. The device is shown in Figure (3-11).

Figure (3.11): Speed gun device.

3.5.3.2.2 Average Travel Speed Data

The average travel speed was estimated by dividing the total length of each street segment by the average travel time recorded during peak hours. The travel time data was obtained using the Floating Car Method, which involved conducting thirteen test runs along each segment and calculating the mean travel time. This method is widely recognized for its practicality in capturing real-time congestion patterns and variations in flow conditions. To enhance statistical reliability and account for variability in traffic behavior, a total of 30 observations were used for each case. This sample size was selected based on standard statistical conventions, where a minimum of 30 readings is often considered sufficient to approximate normal distribution properties and ensure robust estimation of central tendency and dispersion measures. Appendix (B) provides a set of values for these speeds. Figure (3.12) shows the FFS and average travel speed value for each street.

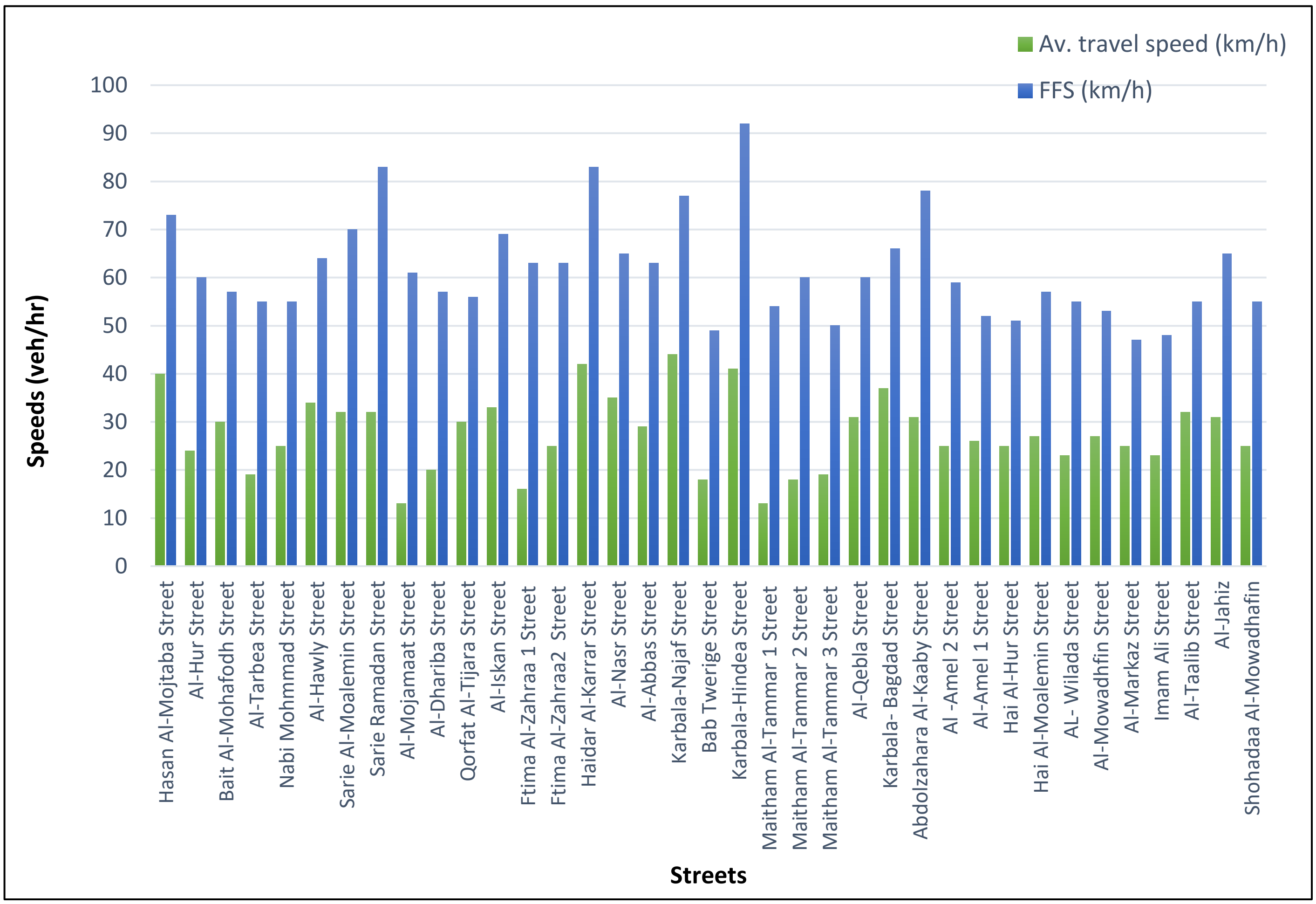

Figure (3.12): Average travel speed and free flow speed value for all streets.

3.5.3.3 Travel Time Data

The travel time was calculated for both off-peak and in-peak periods to estimate the overall delay experienced by vehicles. The off-peak travel time was computed by dividing the street segment length by the FFS, which has been previously measured using a handheld radar speed gun. During the peak period, travel time was measured using the Floating Car Method, based on 30 representative runs, to capture the actual conditions under congestion. Subsequently, the travel delay was obtained by subtracting the off-peak travel time from the observed peak-hour travel time. Figure (3.13) shows the travel time at off-peak and in-peak periods for each street.

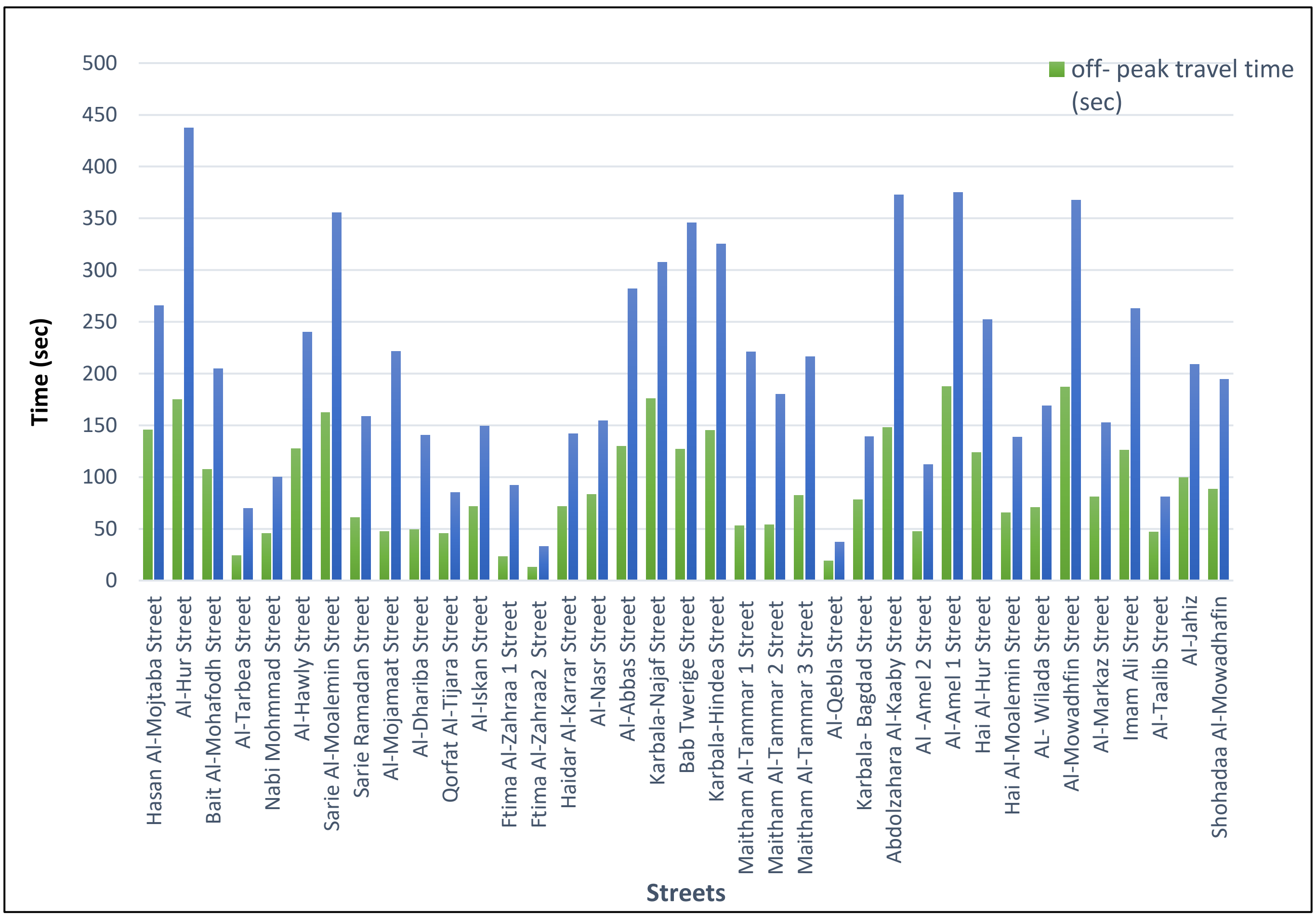

Figure (3.13): Travel time data for all streets.

3.5.3.4 Traffic Noise Data

Noise level data were measured at the study streets using a noise level meter during peak hours to assess the effect of traffic noise on the environment. Figure (3.14) shows the device. According to the WHO guideline, sound level meters were positioned at locations adjacent to the roadway, typically at a distance of 1.2 to 1.5 meters from the edge of the sidewalk, or at a distance of approximately 7 to 15 meters from the centerline of the traffic stream. Locations near intersections or other sources of non-traffic noise were also avoided. Tables (3.9) to (3.13) show the examples of noise level data in (dB) for each five minutes, and the data are in Appendix (C).

Figure (3.14): Noise level meter.

Table (3.9): Example of noise level at Hasan Al- Mujtaba Street.

Time	Noise (dB)
7:25-7:30	83.30
7:30-7:35	83.72
7:35-7:40	82.14

Table (3.10): Example of noise level at Bait Al-Mohafodh Street.

Time	Noise (dB)
8:30-8:35	79.86
8:35-8:40	75.07
8:40-8:45	80.58

Table (3.11): Example of noise level at Al-Hawly Street.

Time	Noise (dB)
7:00-7:05	67.87
7:05-7:10	70.15
7:10-7:15	71.19

Table (3.12): Example of noise level at Sarie Al-Moalemin Street.

Time	Noise (dB)
7:50-7:55	82.60
7:55-8:00	83.01
8:00-8:05	82.41

Table (3.13): Example of noise level at Haidar Al-Karrar Street.

Time	Noise (dB)
8:45-8:50	78.90
8:50-8:55	84.03
8:55-9:00	78.11

3.5.3.5 Traffic Emissions Data

Traffic pollution emissions such as CO, NO_2, CO_2, and $PM_{2.5}$ and PM_{10} were measured at study streets during morning peak hours using Gas met DX4040, which is a portable gas analyzer based on Fourier Transform Infrared (FTIR) spectroscopy, designed to detect and quantify a wide spectrum of emissions compounds in ambient or emission air samples. The evening peak periods were excluded from the emission measurement phase due to several influencing factors that could compromise the accuracy and representativeness of the data. First, atmospheric conditions during the late afternoon and evening, such as lower wind speeds, and temperature inversions, often lead to the accumulation of air pollutants near the ground level. Second, evening hours in urban areas typically involve additional emission sources beyond vehicular traffic, including increased activity from restaurants, street vendors, and other commercial operations, which may artificially elevate pollutant concentrations. Figure (3.15) shows the Gas met DX4040, Tables (3.14) to (3.18) illustrate the example of pollution emissions, and the data are listed in Appendix (D).

Figure (3.15): GAS MET DX4040.

Table (3.14): Example of pollution emissions at Al-Iskan Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:40-7:45	27.1	5.4	0.02	915	71	84
7:45-7:50	27.2	5.3	0.02	896	74	98
7:50-7:55	27.3	5.9	0.02	887	97	102
7:55-8:00	27.5	3.3	0.01	661	67	99

Table (3.15): Example of pollution emissions at Al-Nasr Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:05-7:10	19.5	1.4	0.00	410	16	23
7:10-7:15	19.8	1.7	0.00	466	24	37
7:15-7:20	20.3	1.2	0.00	487	39	43
7:20-7:25	20.5	2.1	0.01	377	48	34

Table (3.16): Example of pollution emissions at Al-Abbas Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
8:40-8:45	26.9	4.2	0.01	741	56	88
8:45-8:50	27.1	2.7	0.01	634	49	69
8:50-8:55	27.3	2.4	0.01	619	43	64
8:55-9:00	27.7	3.4	0.01	685	53	73

Table (3.17): Example of pollution emissions at Karbala-Najaf Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	24.6	0.5	0.00	476	25	76
7:05-7:10	25.1	0.8	0.00	582	31	74
7:10-7:15	25.3	2.0	0.01	661	79	142
7:15-7:20	25.5	2.1	0.01	696	63	149

Table (3.18): Example of pollution emissions at Bab Twerige Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:30-7:35	27.7	6.9	0.02	796	71	90
7:35-7:40	27.4	7.4	0.02	862	79	92
7:40-7:45	28.3	5.6	0.02	636	53	70
7:45-7:50	28.1	6.7	0.02	814	68	82

3.6 GIS Model Builder to Create Alternatives

Model builders are application tools in ArcGIS software packages to create, edit, and manage models. A model is a set of tools and data incorporated together in the workflow. The result of one step represents input data to another step of the workflow. Model builder can be seen as a visual programming language, (Cvetinović et al., 2014). Cvetinović et al., (2014) demonstrated that there are three basic elements of every model: tools, variables, and connectors.

Tools: for geoprocessing represent fundamental elements for creating workflows into models and performing various operations on geographic (spatial) and tabular data.

Variables: are model elements that contain values or data references that are stored on the disc. Two types of variables are available: data and values. Data variables contain descriptive information about data stored on the disc (field information, spatial reference, and path). Values are numbers, booleans, spatial references, etc.

Connectors: these elements are used for connecting variables with tools. Direction of connecting arrow represents the direction of workflow. There are four types of connectors: data connectors, environment connectors, precondition connectors, and feedback connectors. GIS model builder has been used to implement all processes of site selection automatically which include:

3.6.1 Data Processing: **Feature to Raster:** Each feature layer converted to raster layer by using feature to raster tool with 20 cell size, then each raster layer values were reclassified to new values from 1 to 10 depending on their importance by reclassify tool.

3.6.2 Weighting Criteria: AHP Weight Derivation

According to Sharma et al., (2008), AHP is a MCDA technique to make the operation of decision by decomposing a complex problem of objectives and criteria into a multi-level hierarchical structure. Saaty, (2008), explained that AHP is used to determine the priorities and relative critical criteria due to the comparison scale. Table (3.19) shows the nine-point comparison scales.

Table (3.19): Saaty comparison scale (Saaty, 2008).

Intensity of important	Definition	Explanation
1	Equally important	Both criteria contribute to the objective equally
3	Strictly more important	Moderate preference is given to each criterion over the other
5	Very strict, proven importance	Strict preference is given to one criterion over the other
7	importance	One criterion is strictly preferred over the other
9	Extreme importance	Each criterion is more preferred over the other has been considered to the highest confidence
2,4,6,8	Mid values	

3.6.3 Least Cost Model (LCP)

In the last part of the process of optimal site selection, the optimal, shortest, and cheapest routes were generated using the least cost path (LCP) model, this means the path that achieves the lowest cost, and expenses are chosen to be the best route. The LCP model consists of the output layer from the route weighted method that was explained previously and represented as the cost surface in the LCP model, as well as the origin and destination station. The cost of surfaces represents the calculated measure of costs. These cost values have an economic meaning and equal the cost of moving across the landscape. Its value ranged from 1 to 10, where 1 represents the lowest cost (equal to the base cost), and 10 represents the highest cost (virtually a barrier) (Djenaliev, 2007). This process was operated using the cost distance tool. The minimum cumulative cost distance per pixel from the original station to the destination station is calculated. The cost path tool was applied to calculate the minimum cost path from the origin station to the destination station; the output of this model is the best and cheapest route (Skaik, 2016).

3.7 Ranking Alternatives and Evaluating Criteria

The route alternatives that resulted from the GIS model must be ranked by using the evaluated criteria (traffic demand, accessibility, safety, economics, and environment) as demonstrated briefly in chapter two.

3.7.1 Proposed Models

1- Criteria Importance Through Intercriteria Correlation (CRITIC) Model. This model was used to calculate the weights of the selection criteria. Furthermore, many different disciplines, extremely complex issues with decision-making have been used (Görçün, 2021).

2- The Evaluation based on Distance from Average Solution (EDAS) Model, this model was used to determine the decision options' relative relevance values (Görçün, 2021). The EDAS strategy, a novel MCDM method, was introduced by Keshavarz et al. (2015) and is a promising approach. Although this approach has been used in only a few studies, its potential to yield highly beneficial outcomes for resolving decision-making issues across various sectors is evident from the evaluation of the results. The method's central claim is that a distance from the mean answer determines the optimal solution.

According to Görçün (2021), the basic procedure for conducting the analysis using this method and selecting the best alternative includes several steps, which are:

- Identifying alternatives, which depend upon the project's requirements.
- Identifying evaluation criteria, which includes the criteria that affect the project and what each criteria mean.
- Assigning weights, which means giving value to decision criteria, appropriate weights according to importance.
- Designing a scoring system.
- Rating the alternatives and totaling the scores that are made after multiplying the score for each decision criterion by its weighting factor.

Then, the total scores for each alternative are considered and analyzed. The alternative with a higher total represents the best alternative.

3.8 Summary

This chapter presented a comprehensive methodology for identifying the optimal locations of tram routes and stations in Karbala City. The study framework is structured into sequential phases, beginning with the definition of the study area and the establishment of limitation criteria for both tram routes and stations. A diverse set of spatial and traffic-related data was collected from multiple official and technical sources to support the subsequent analytical processes.

Traffic volume data were manually extracted from video recordings captured by video cameras installed at selected locations during peak periods. Noise levels were measured using a noise level meter, while free-flow speeds were recorded using a radar-based speed gun. Travel times were determined through the Floating Car Method, and environmental pollution indicators (CO, CO_2, NO_2, $PM_{2.5}$, PM_{10}) were measured using the Gas Met DX4040 portable gas.

In addition, geospatial datasets were collected and prepared. These include land use classifications and vital activity places (such as hospitals, universities, and recreational zones) provided by the General Directorate of Physical Planning. Population distribution data obtained from the Directorate of Statistics, and a detailed transportation network layer comprising streets, intersections, rail stations, paths, and terminals.

The methodology also outlines the use of GIS tools for data processing, including raster conversion and weight derivation using the AHP method. Route alternatives will be generated through the LCP model. These alternatives are to be evaluated and ranked using the CRITIC and EDAS multi criteria decision making models based on traffic performance, accessibility, environmental impact, and economic feasibility. Furthermore, a simulation step is proposed using PTV VISSIM software to assess anticipated performance metrics such as LOS, average speed, delay, emissions, and noise under scenarios before and after tram implementation.

Chapter Four

Data Analysis and Discussion

4.1 Introduction

This chapter presents the data analysis and statistical relationships among traffic and environmental variables (flow, speed, noise, and emissions) in the study streets, along with the models linking each dependent variable to its relevant predictors. In addition, the results of evaluation and analysis for the study area are presented in terms of LOS based on the v/c ratio. Furthermore, an evaluation of the public transportation system in the city is included.

4.2 Free Flow Speed (FFS)

Free flow speed was measured in the study area to classify the streets. Figure (4.1) shows the average FFS for each street. Most of the measurements follow a normal distribution, ranging from 92 km/hr on Karbala-Hindea Street to 47 km/hr on Al-Markaz Street, as illustrated in Figures (4.2 to 4.35).

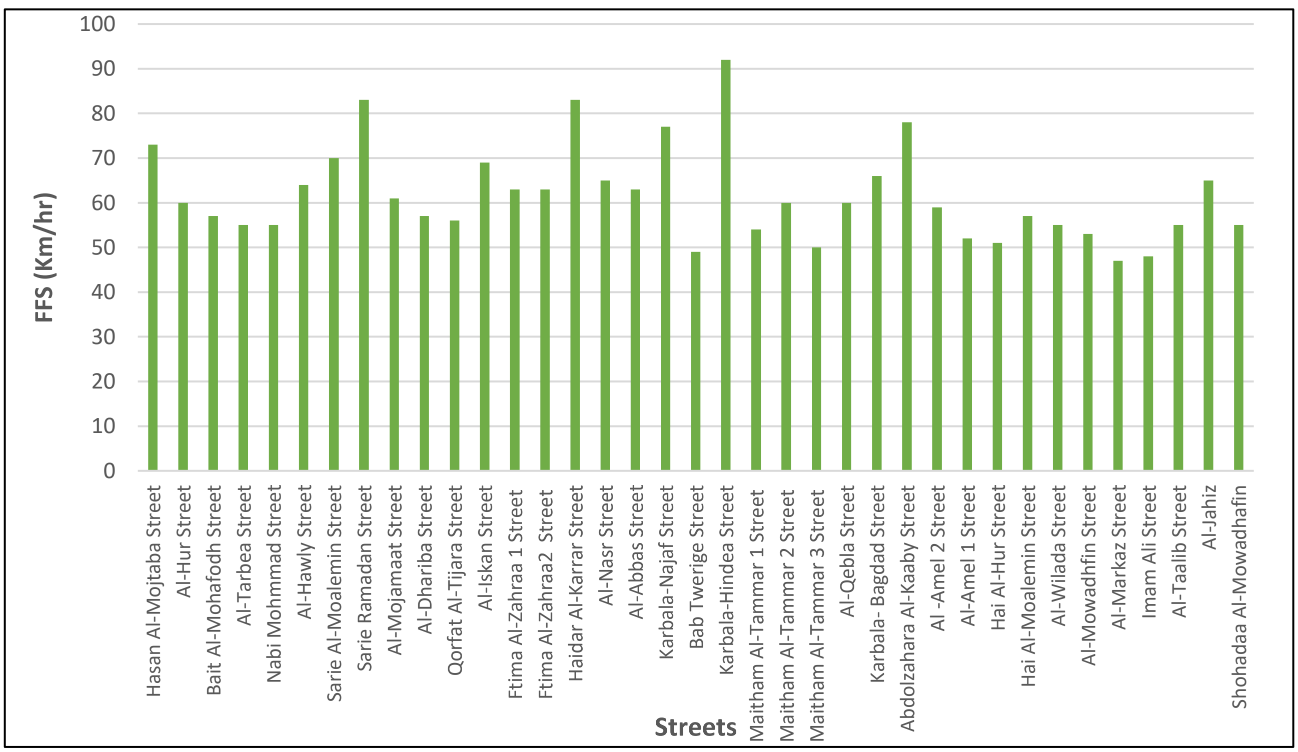

Figure (4.1): FFS for studied streets.

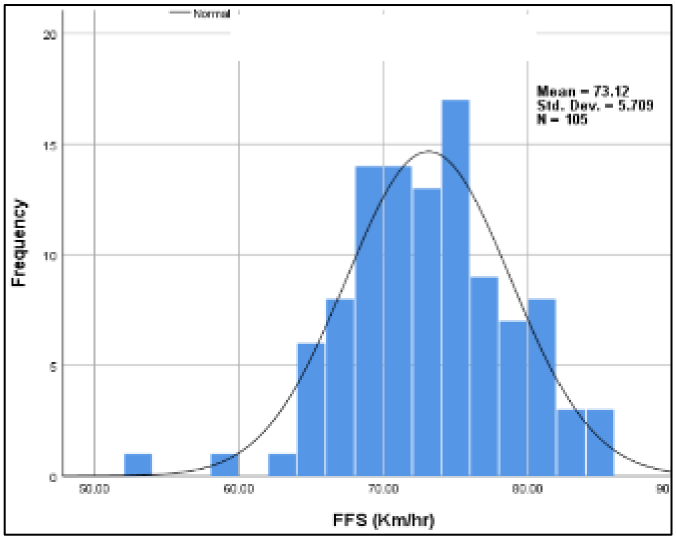

Figure (4.2): Average FFS at Hasan Al-Mujtaba Street.

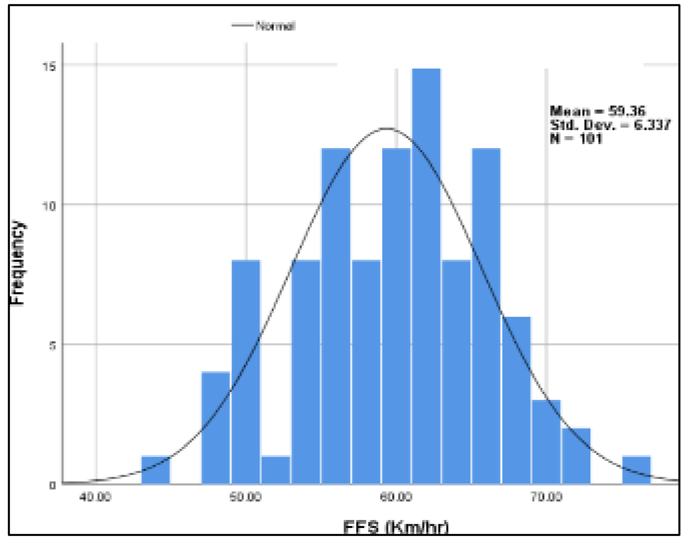

Figure (4.3): Average FFS at Al-Hur Street.

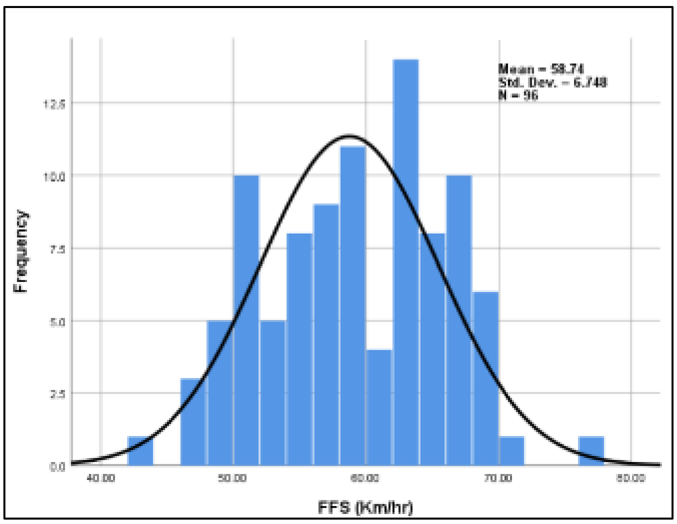

Figure (4.4): Average FFS at Bait Al-Mohafodh Street.

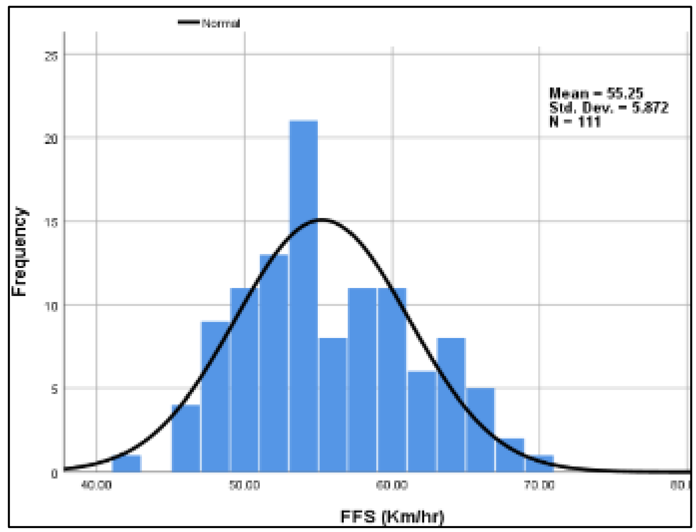

Figure (4.5): Average FFS at Al-Tarbea Street.

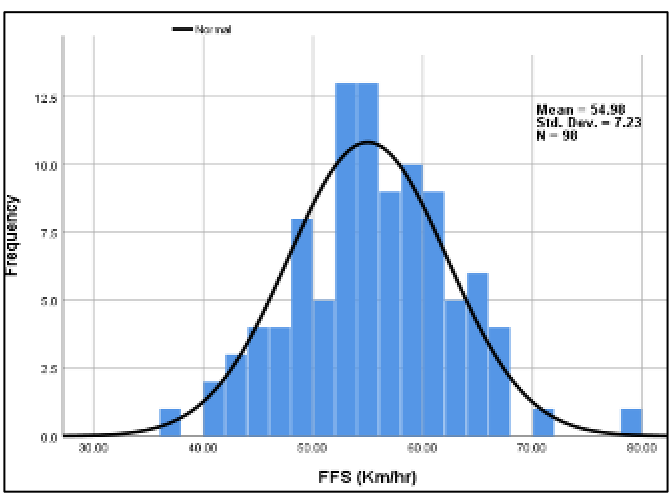

Figure (4.6): Average FFS at Nabi Street.

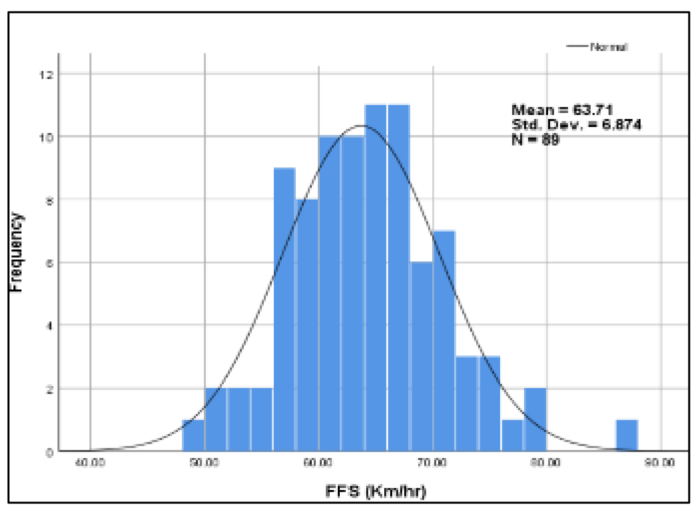

Figure (4.7): Average FFS at Al-Hawly

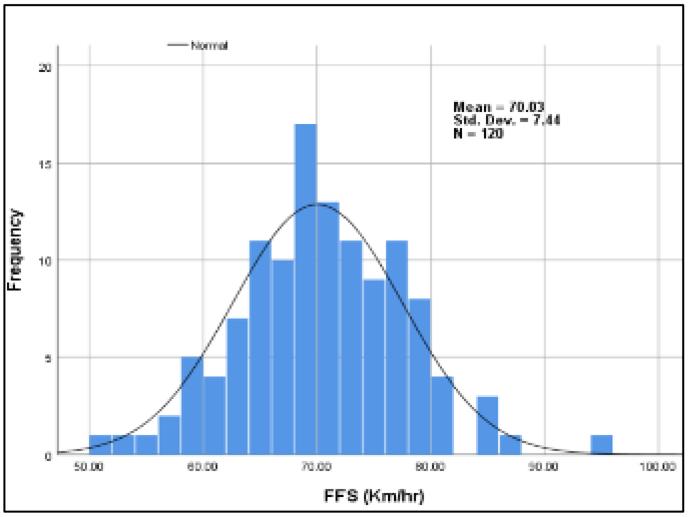

Figure (4.8): Average FFS at Saree Al-Moalemin Street.

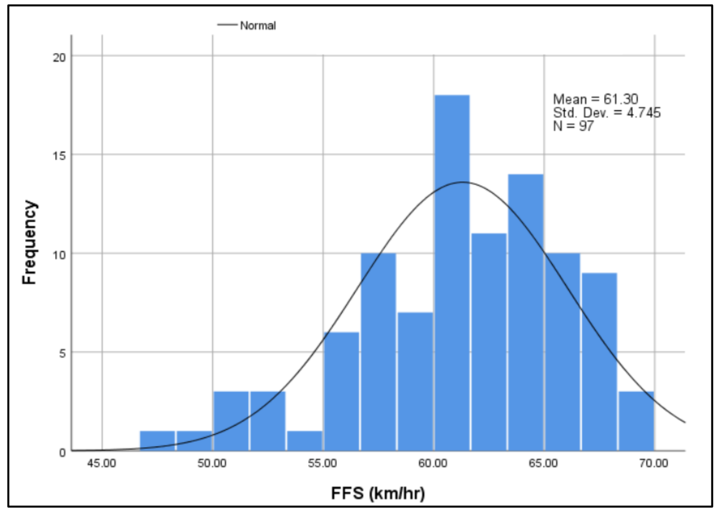

Figure (4.9): Average FFS at Al-Mojammat Street.

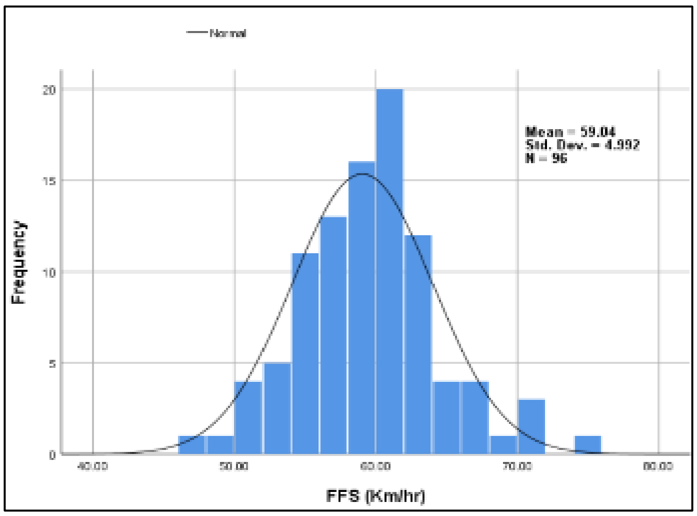

Figure (4.10): Average FFS at Al-Dhariba Street.

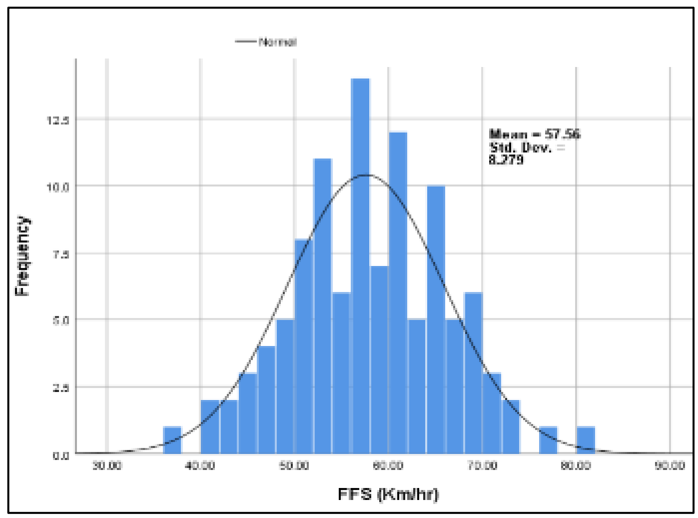

Figure (4.11): Average FFS at Qorfat Al-Tijara Street.

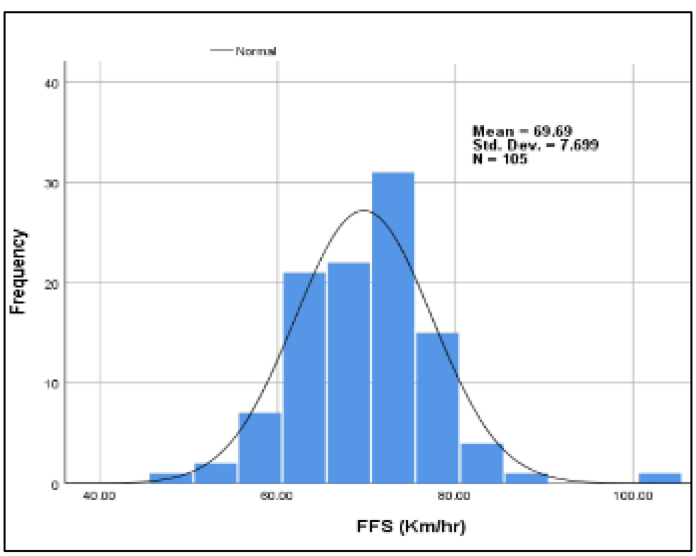

Figure (4.12): Average FFS at Al-Iskan Street.

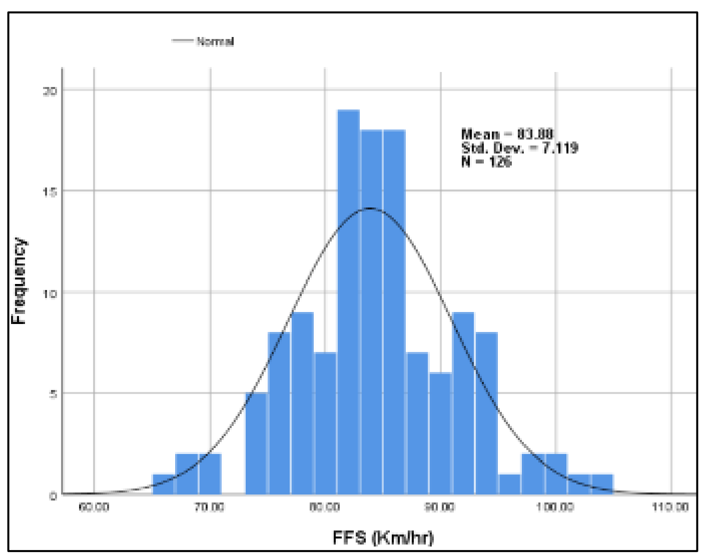

Figure (4.13): Average FFS at Haider Al-Karrar Street.

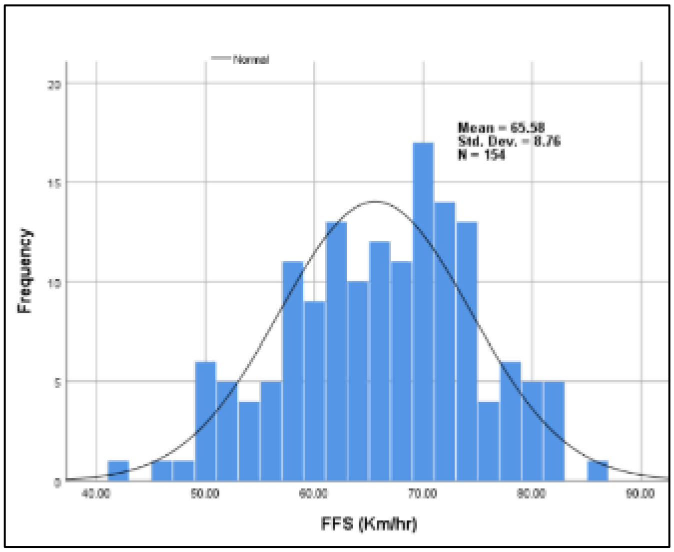

Figure (4.14): Average FFS at Al-Nasr Street.

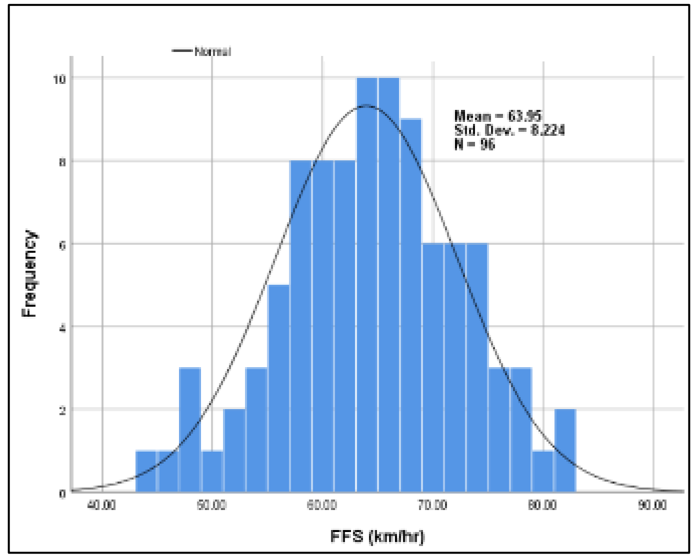

Figure (4.15): Average FFS at Al-Abbas Street.

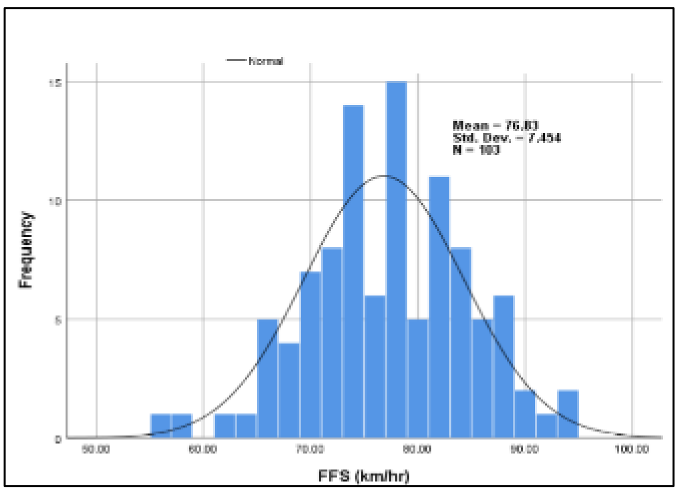

Figure (4.16): Average FFS at Karbala-Najaf Street.

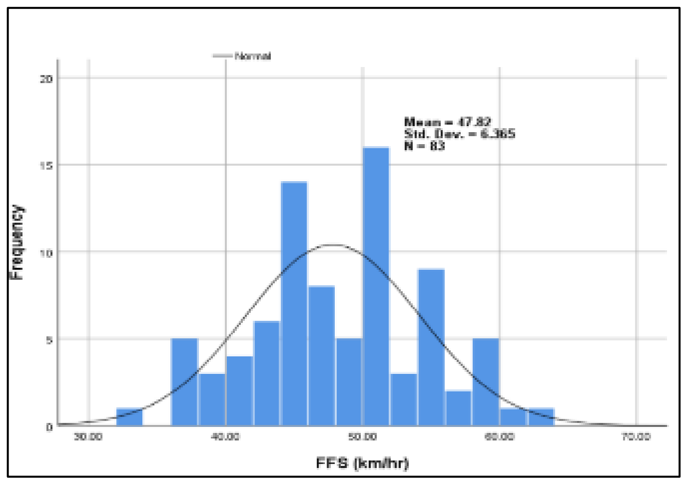

Figure (4.17): Average FFS at Bab Twerige Street.

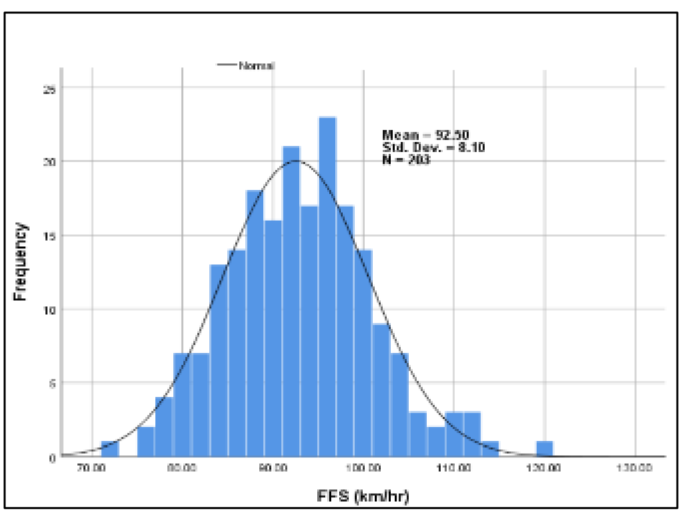

Figure (4.18): Average FFS at Karbala-Hindea Street.

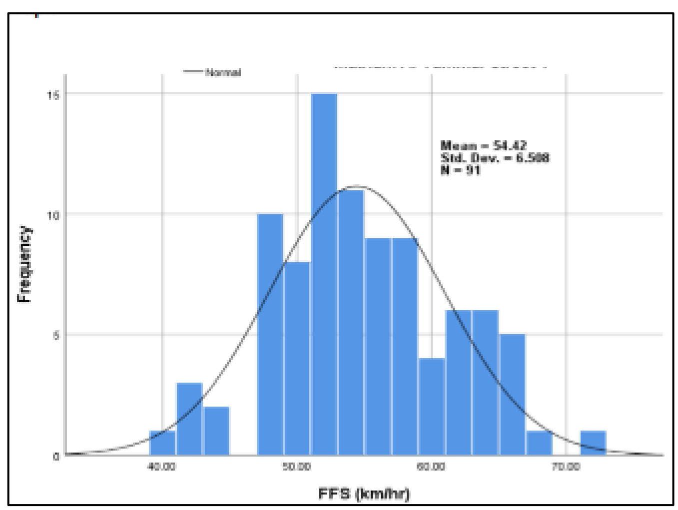

Figure (4.19): Average FFS at Maitham 1 Street.

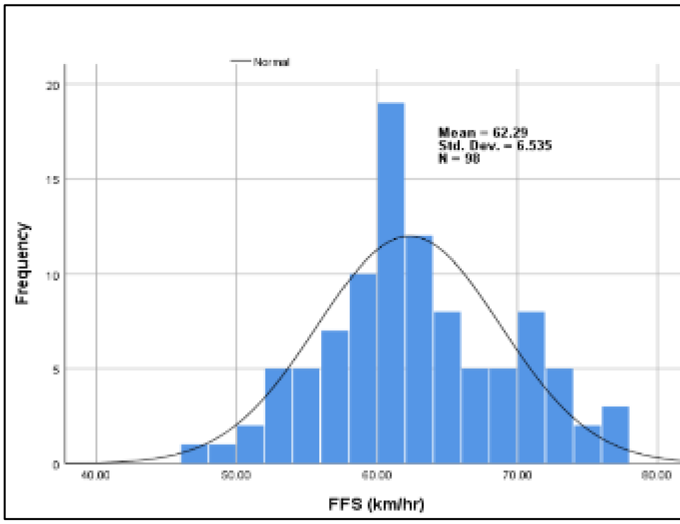

Figure (4.20): Average FFS at Maitham2 Street.

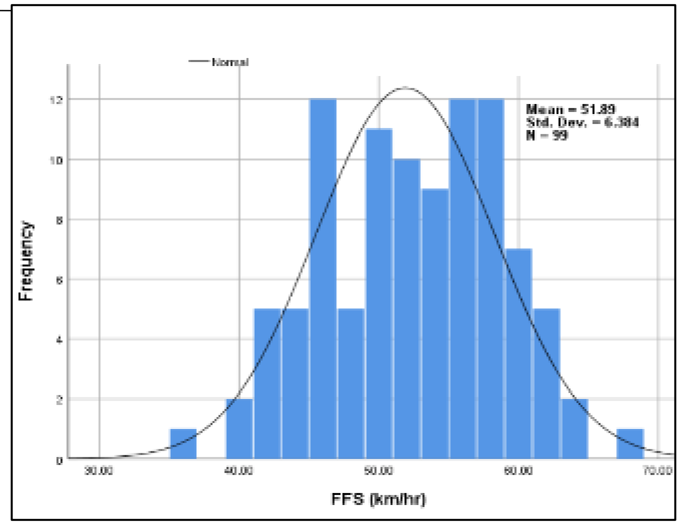

Figure (4.21): Average FFS at Maitham3 Street.

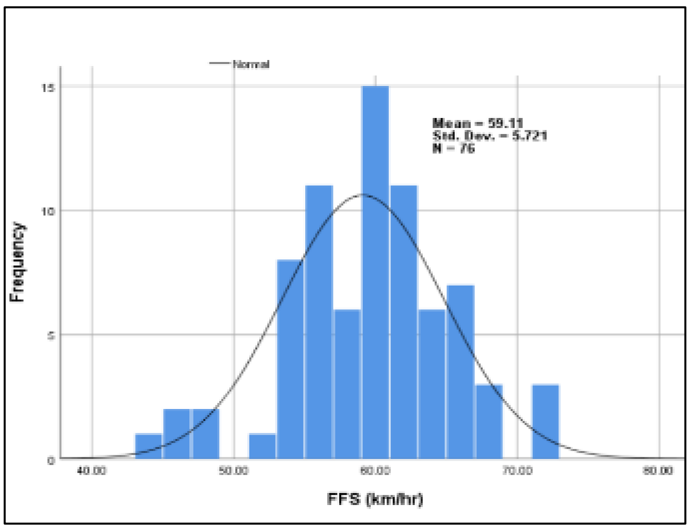

Figure (4.22): Average FFS at Al-Qebla Street.

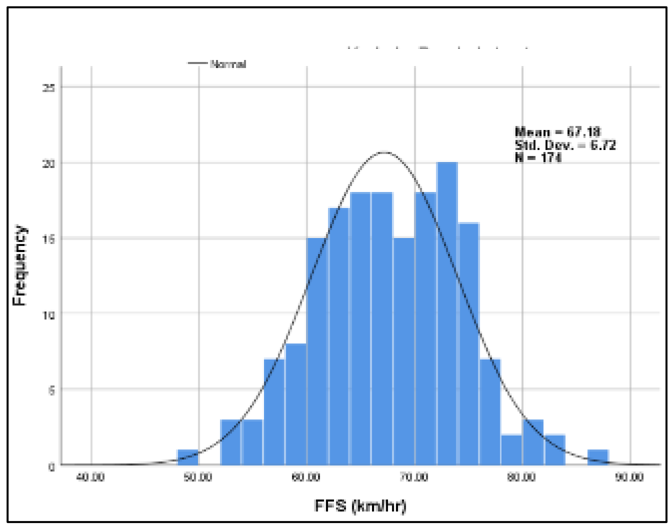

Figure (4.23): Average FFS at Karbala Bagdad Street.

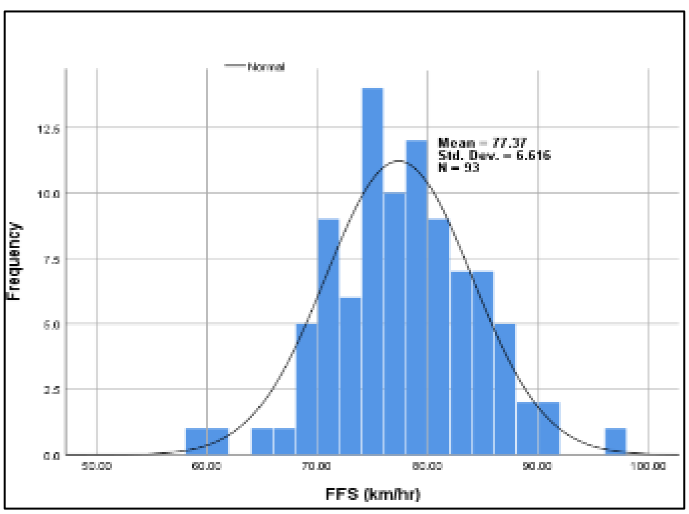

Figure (4.24): Average FFS at Abdolzahraa Street.

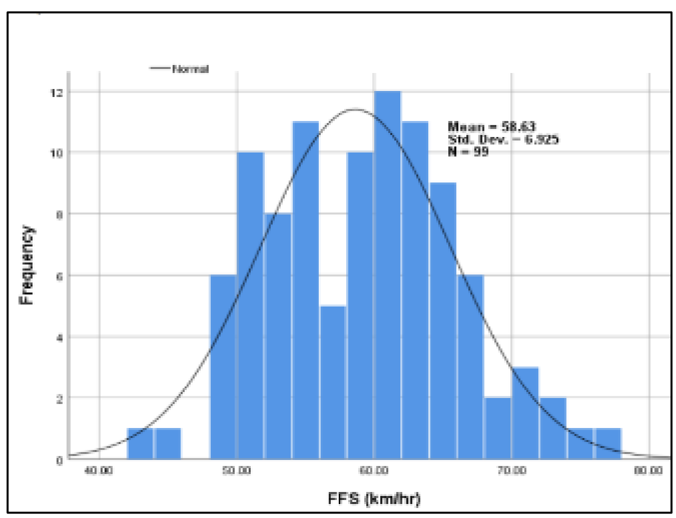

Figure (4.25): Average FFS at Al-Amel2 Street.

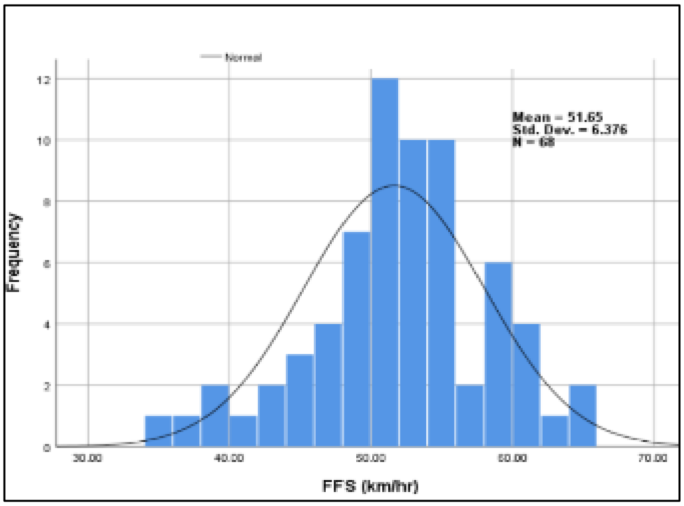

Figure (4.26): Average FFS at Al-Amel 1 Street.

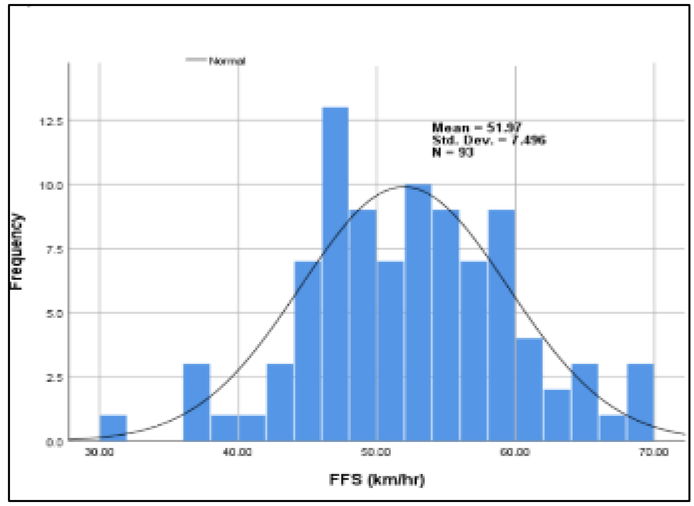

Figure (4.27): Average FFS at Hai Al-Hur Street.

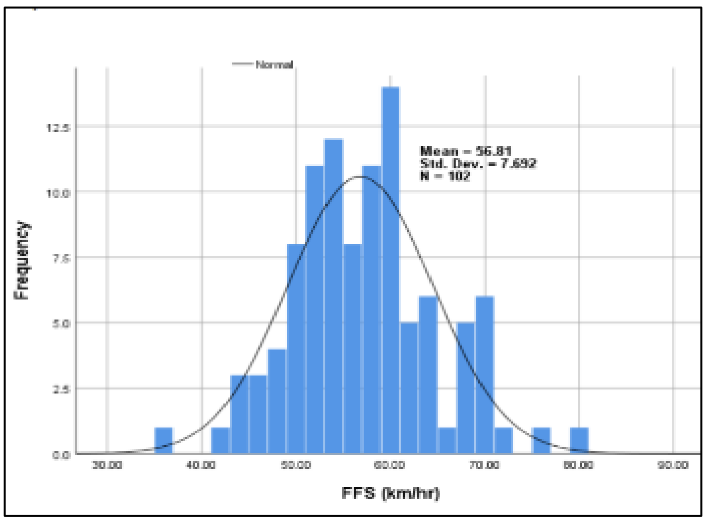

Figure (4.28): Average FFS at Al-Moalemin Street.

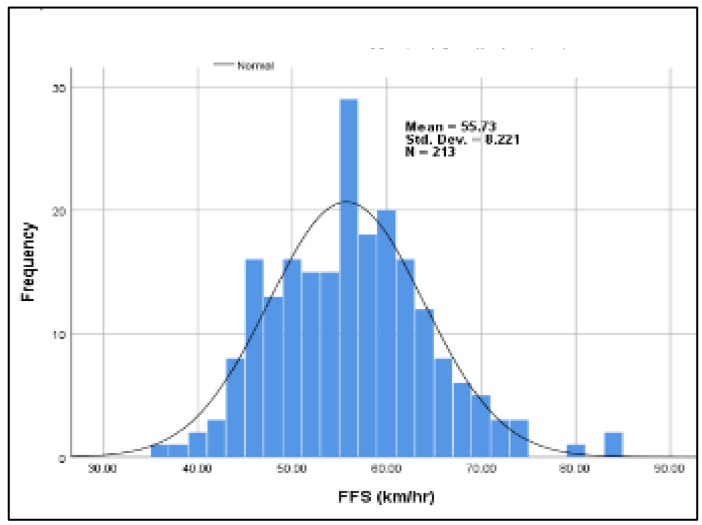

Figure (4.29): Average FFS at Mostashfa

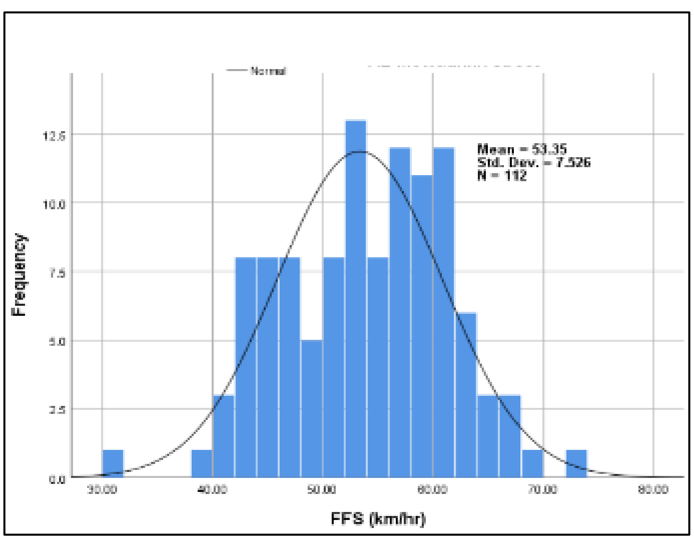

Figure (4.30): Average FFS at Al-Mowadhafin Street.

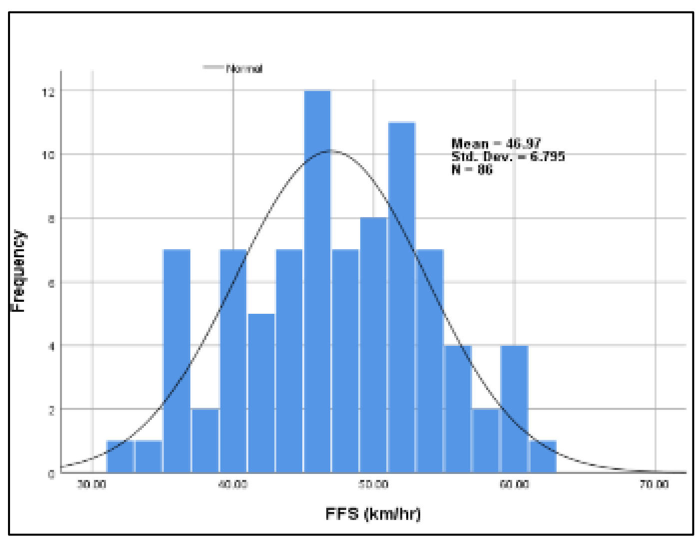

Figure (4.31): Average FFS at Al-Markaz Street.

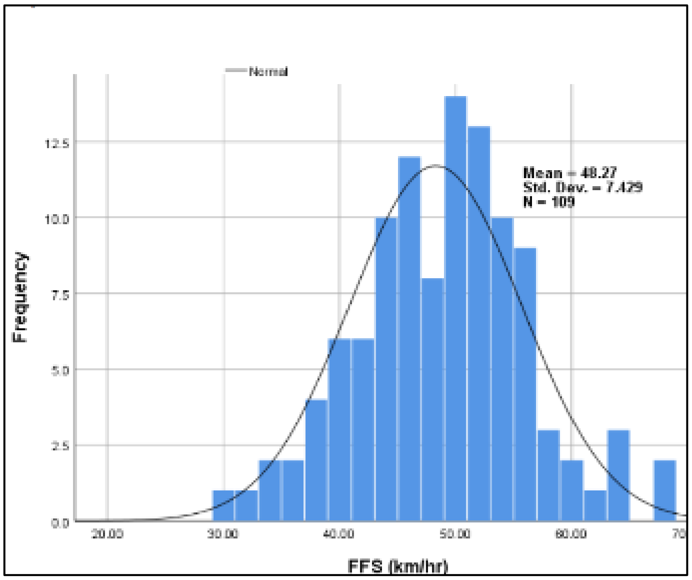

Figure (4.32): Average FFS at Imam Ali Street.

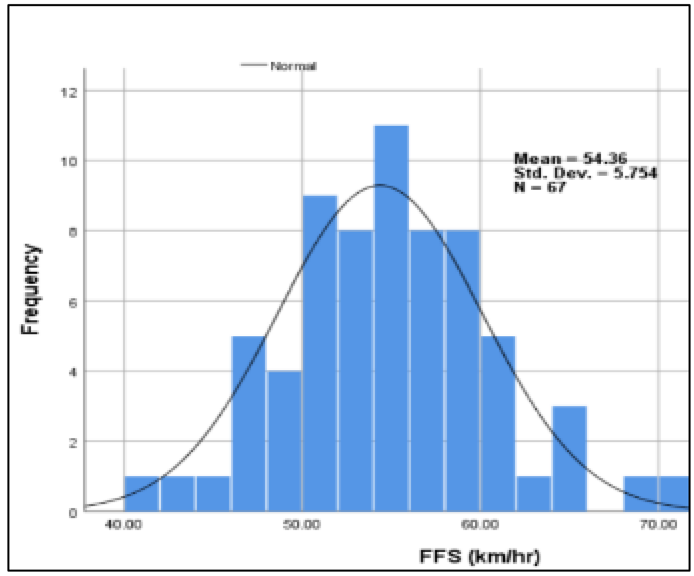

Figure (4.33): Average FFS at Al-Taalib Street.

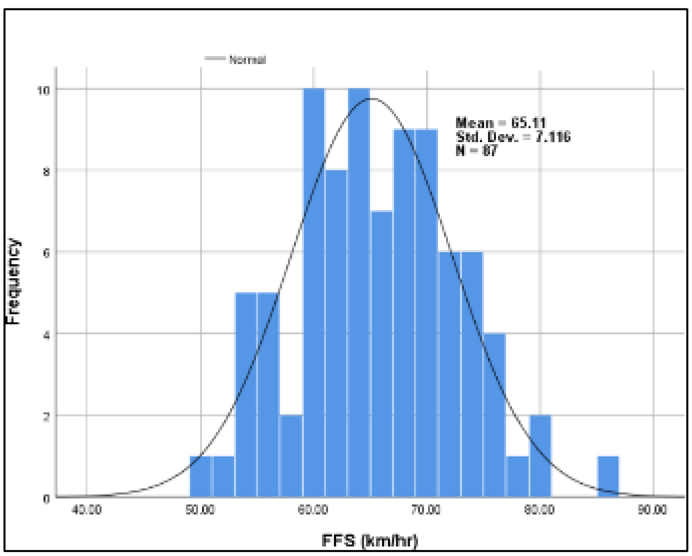

Figure (4.34): Average FFS at Al-Jahiz Street.

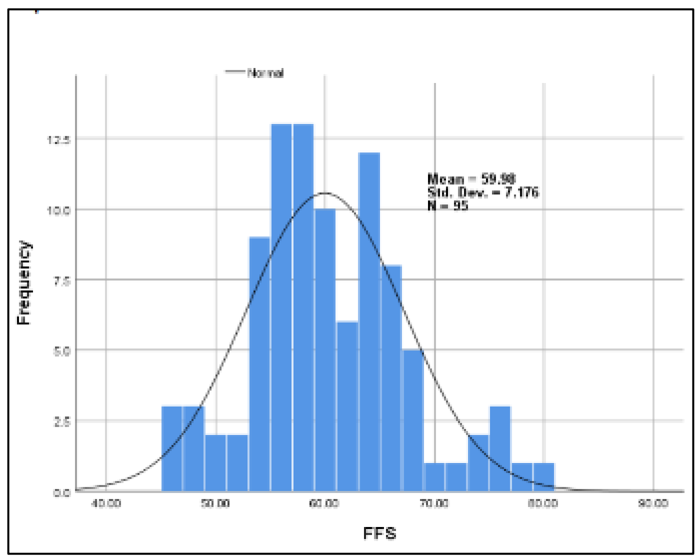

Figure (4.35): Average FFS at Shohadaa Al-Mowadhafin Street.

Based on FFS, street classifications have been obtained from Table (4.1), and the street class is illustrated in Table (4.2).

Table (4.1): Street class based on FFS (HCM, 2000).

Arterial road class	I	II	III	IV
Range of FFS	90 – 70 km/hr	70 – 55 km/hr	55 – 50 km/hr	55 – 40 km/hr
Typical FFS	80 km/hr	65 km/hr	55 km/hr	45 km/hr

Table (4.2): Casses based on FFS for selected streets.

Street	Class	Street	Class
Hasan Al-Mojtaba Street	I	Karbala-Hindea Street	I
Al-Hur Street	II	Matham Al-Tammar1 Street	III
Bait Al-Mohafodh Street	II	Maitham Al-Tammar2 Street	II
Al-Tarbea Street	II	Maitham Al-Tammar3 Street	III
Nabi Mohmmad Street	III	Al-Qebla Street	II
Al-Hawly Street	II	Karbala-Bagdad Street	II
Sarie Al-Moalemin Street	II	Abdolzahara Al-Kaaby Stree	I
Sarie Ramadan Street	I	Al-Amel 2 Street	II
Al-Mojamaat Street	II	Al-Amel 1 Street	III
Al-Dhariba Street	II	Hai AL-Hur Street	III
Qorfat Al-Tijara Street	II	Hai AL-Moalemin Street	II
Al-Iskan Street	II	Al-Wilada Street	II
Ftima Al-Zahraa1 Street	II	AL-Mowadhfin Street	III
Ftima Al-Zahraa 2 Street	II	AL-Markaz Street	IV
Haidar Al-Karrar Street	I	Imam Ali Street	IV
Al-Nasr Street	II	AL-Taalib Street	III
ALl-Abbas Street	II	Al-Jahiz Street	II
Karbala-Najaf Street	I	Shohadaa Al-Mowadhafin Sreet	III
Bab Twerige Street	IV		

The classification results revealed that most of the streets (approximately 55%) fell under Class II, which corresponds to FFS values typically ranging from 55 to less than 70 km/hr. These roads represent a moderate level of mobility and accessibility, often found in mixed-use urban corridors with balanced traffic flow and land access. A smaller yet significant portion of the streets, around 21%, were classified as Class III. These streets generally have lower FFS values (between 40 and 55 km/hr) and are commonly influenced by higher access point density, signalization, and pedestrian activity. Such roadways often function within commercial or residential zones where traffic interruptions are more frequent. Conversely, only 6 roads (approximately 16%) were classified as Class I. These represent high-performance arterials with free flow speeds equal to or greater than 70 km/hr. Roads in this category provide superior mobility, fewer access points, and typically serve as major city connectors or bypass routes. Lastly, 3 streets (about 8%) fell into Class IV, indicating very low free flow speeds, generally less than 40 km/hr. These streets are likely constrained by dense urban infrastructure, high pedestrian volumes, or geometric limitations.

4.3 Operational Capacity and LOS

The actual traffic capacity has been measured for the streets under study, which is meant to be the maximum flow rate within the peak hours. These values have been compared to the maximum theoretical capacity used by HCM (2000) based on road class, as shown in Table (4.3). The LOS can be extracted using a volume-to-capacity ratio (v/c) using Table (4.4). The LOS for the segments in the study area can be calculated based on the mentioned procedure, as illustrated in Table (4.5).

Table (4.3): Traffic capacity based on road class (HCM, 2000).

Lanes	Service volumes (veh/hr)				
	A	B	C	D	E
Class I					
1	N/A	740	920	1010	1110
2	N/A	1490	1780	1940	2120
3	N/A	2210	2580	2790	3040
4	N/A	2970	3440	3750	4060
Class II					
1	N/A	N/A	620	820	860
2	N/A	N/A	1290	1590	1650
3	N/A	N/A	1920	2280	2370
4	N/A	N/A	2620	3070	3190
Class III					
1	N/A	N/A	600	790	840
2	N/A	N/A	1250	1530	1610
3	N/A	N/A	1870	2220	2310
4	N/A	N/A	2580	2960	3080
Class IV					
1	N/A	N/A	270	690	790
2	N/A	N/A	650	1440	1520
3	N/A	N/A	1070	2110	2180
4	N/A	N/A	1510	2820	2900

Table (4.4): LOS based on (v/c) (HCM, 2000).

Class	A	B	C	D	E	F
I	N/A	≤ 0.75	0.76 - 0.81	0.82 - 0.89	0.90 - 1.0	> 1
II	N/A	N/A	≤ 0.85	0.86 - 0.95	0.96 - 1.0	> 1
III	N/A	N/A	≤ 0.61	0.62 - 0.95	0.96 - 1.0	> 1
IV	N/A	N/A	≤ 0.79	0.80 - 0.97	0.98 - 1.0	> 1

Table (4.5): LOS for streets based on (v/c) (HCM, 2000).

Street	Dir.	Class	Max. flow (vph)	Capacity	v/c	LOS
Hasan Al-Mojtaba	1	I	2026	3040	0.67	B
	2		1606	3040	0.53	B
Al-Hur	1	II	2364	2370	1.00	E
	2		2296	2370	0.97	E
Bait Al-Mohafodh	1	II	2211	2370	0.93	D
	2		1853	2370	0.78	C
Al-Tarbea	1	II	3360	3190	1.05	F
	2		3184	3190	1.00	E
Nabi Mohmmad	1	III	3160	3080	1.03	E
	2		3076	3080	1.00	E
Al-Hawly	1	II	1818	2370	0.77	C
	2		1754	2370	0.75	C
Sarie Al-Moalemin	1	II	2477	2370	1.05	F
	2		2301	2370	0.97	E
Sarie Ramadan	1	I	4144	3040	1.36	F
	2		3456	3040	1.14	F
Al-Mojamaat	1	I	3664	3040	1.21	F
	2		3629	3040	1.19	F
Al-Dhariba	1	II	2694	2370	1.14	F
	2		3147	2370	1.33	F
Qorfat Al-Tijara	1	II	1956	2370	0.83	C
	2		2116	2370	0.89	D
Al-Iskan	1	II	2016	2370	0.860	D
	2		2005	2370	0.86	D
Ftima Al-Zahraa 1	1	II	3501	2370	1.48	F
	2		2384	2370	1.01	F

Table (4.5): Continued.

Street	Dir.	Class	Max. flow (vph)	Capacity	v/c	LOS
Ftima Al-Zahraa 2	1	II	2854	2370	1.20	F
	2		2291	2370	0.97	E
Haidar Al-Karrar	1	I	3589	4060	0.88	D
	2		3146	4060	0.77	C
Al-Nasr	1	II	3104	3190	0.97	E
	2		2792	3190	0.88	D
AL-Abbas	1	II	2534	2370	1.07	F
	2		2797	2370	1.18	F
Karbala-Najaf	1	I	2474	3040	0.81	C
	2		2620	3040	0.86	D
Bab Twerige	1	IV	2419	2180	1.11	F
	2		2531	2180	1.16	F
Karbala-Hindea	1	I	2972	3040	0.98	E
	2		2942	3040	0.97	E
Matham Al-Tammar1	1	III	2672	2310	1.16	F
	2		2608	2310	1.13	F
Matham Al-Tammar2	1	II	2312	2370	0.98	E
	2		2396	2370	1.01	F
Matham Al-Tammar3	1	III	2304	2310	1.00	E
	2		2280	2310	0.99	E
Al-Qebla	1	II	2014	1650	1.22	F
Karbala- Bagdad	1	II	2022	2370	0.85	C
	2		2302	2370	0.97	E
Abdolzahara Al-Kaaby	1	I	2871	3040	0.94	E
	2		3024	3040	0.99	E
Al-Amel 2	1	II	1619	2370	0.68	C
	2		1620	2370	0.68	C
Al-Amel 1	1	III	2026	3040	0.67	B
	2		1606	3040	0.53	B
Hai Al-Hur	1	III	2364	2370	1.00	E
	2		2296	2370	0.97	E
Hai Al-Moalemin	1	II	2211	2370	0.93	D
	2		1853	2370	0.78	C
Al-Wilada	1	II	3360	3190	1.05	F
	2		3184	3190	1.00	E
Al-Mowadhafin	1	III	3160	3080	1.03	E
	2		3076	3080	1.00	E

Table (4.5): Continued.

Street	Dir.	Class	Max. flow (vph)	Capacity	v/c	LOS
Al-Markaz	1	IV	1818	2370	0.77	C
	2		1754	2370	0.75	C
Imam Ali	1	IV	2477	2370	1.05	F
	2		2301	2370	0.97	E
Al-Taalib	1	III	4144	3040	1.36	F
	2		3456	3040	1.14	F
Al-Jahiz	1	II	3664	3040	1.21	F
	2		3629	3040	1.19	F
Shohadaa Al-Mowadhafin	1	III	2694	2370	1.14	F
	2		3147	2370	1.33	F

The LOS assessment across 73 street directions highlighted consistent signs of operational inefficiency. According to HCM (2000), LOS criteria, a significant portion of the evaluated directions operates under lower service levels. Specifically, 40% of the directions fall under LOS F, representing severe congestion where demand exceeds capacity, often resulting in stop-and-go conditions and high travel delays. 30% operate at LOS E, indicating saturated flow conditions with limited maneuverability and unstable speeds. Additionally, 10% of the directions were classified as LOS D, which, although still within acceptable limits for urban operations, signals a critical transition toward unstable conditions. In contrast, only 16% of the directions achieved LOS C, denoting stable flow but with restricted freedom to maneuver 4% of segments operated at LOS B, reflecting relatively smooth traffic conditions with minimal restrictions. Notably, no direction was observed under LOS A, which typically corresponds to free-flow conditions rarely achievable in dense urban environments. These results suggest that over 80% of those who studied street directions within LOS (D, E, and F combined) experience moderate to severe congestion, highlighting. Figure (4.36) shows the LOS percentages.

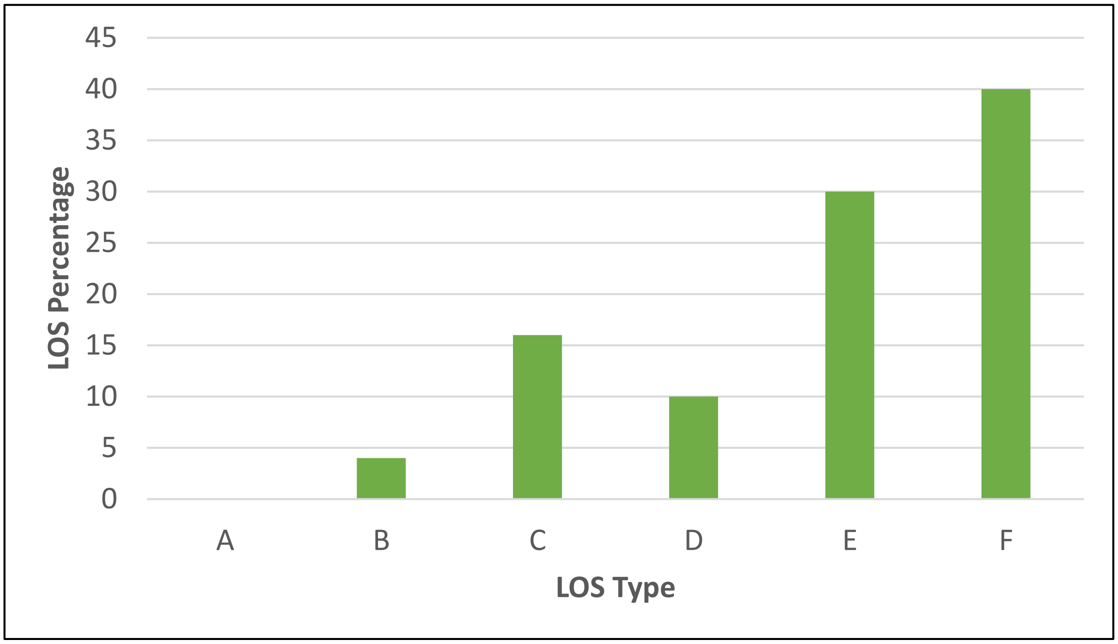

Figure (4.36): LOS percentages for streets.

4.4. Travel Speed and Flow Relationship

The relationship between traffic flow and travel speed is a key aspect of traffic performance analysis. As traffic volume increases, clear changes in speed patterns emerge, which can be used to evaluate roadway efficiency and levels of congestion.

A) Al-Wilada Street

Figure (4.37) represents the relationship between flow rate and speed for each 5-minute interval at peak period in Al-Wilada Street. The figure illustrates how travel speed on Al-Wilada Street decreases as traffic flow increases. This trend reflects a typical real-world pattern in urban traffic behavior, where higher vehicle volumes gradually lead to reduced speeds due to congestion buildup and increased interaction between vehicles. As flow continues to rise, the speed starts to decline more noticeably. Around 2000 veh/hr, the average speed drops to approximately 27–30 km/hr, suggesting the beginning of unstable flow, where minor disturbances in traffic can start to cause significant slowdowns. Beyond 2500 veh/hr, the decline becomes more pronounced, and speeds fall below 20 km/hr, indicating saturated or over-saturated conditions. At this stage, the road operates near or above its capacity, and even small increases in traffic volume cause disproportionate losses in speed. These conditions are often associated with frequent stop-and-go movement, reduced safety margins, and heightened driver stress. The shape of the curve clearly highlights that the relationship between flow and speed is not linear; the speed does not decrease at a constant rate. Instead, as traffic approaches capacity limits, the rate of speed reduction accelerates, which is a key characteristic of congested urban streets.

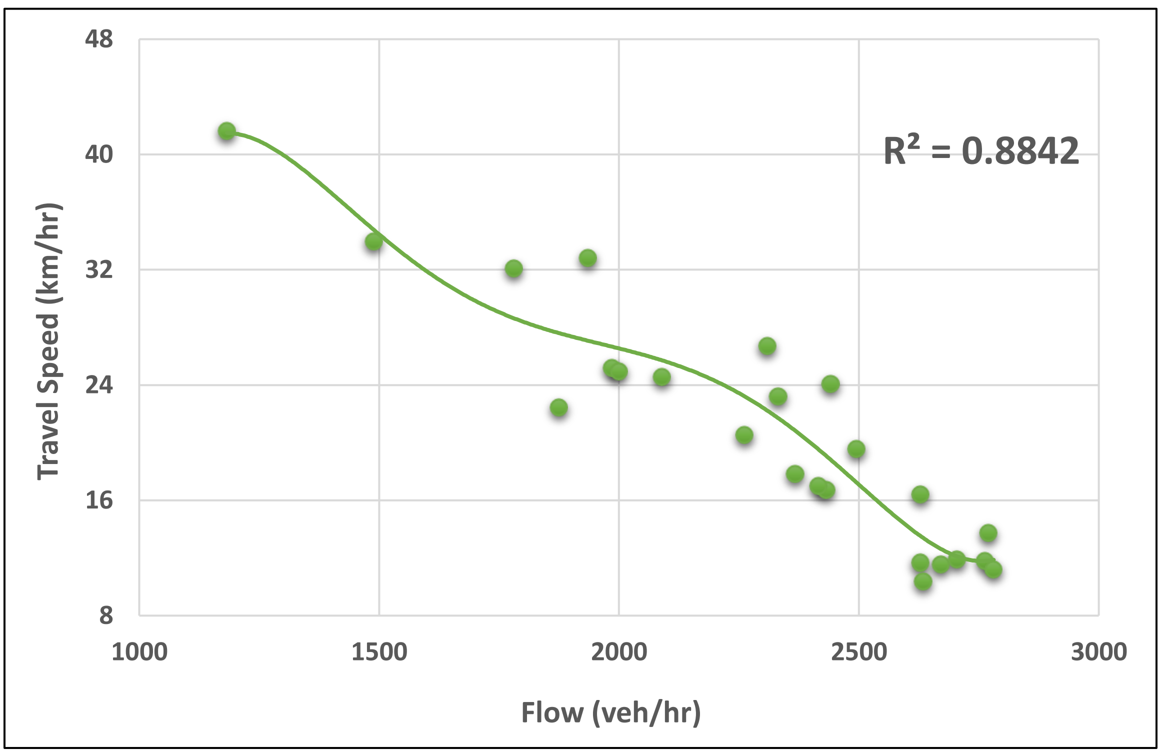

Figure (4.37): Flow-speed relationship curve for Al-Wilada Street.

B) Al-Mojamaat Street

For Al-Mojamaat Street Figure (4.38) shows a clear nonlinear inverse relationship between traffic flow and travel speed. As flow increases from 1900 to over 3000 veh/hr, the speed drops significantly from around 22 km/h to 10-12 km/h, indicating high congestion levels.

The curve flattens at higher volumes, suggesting that speed stabilizes at a low level once the street is saturated. This behavior reflects heavy traffic conditions where additional vehicles no longer significantly worsen speed but maintain severe delay. The coefficient of determination ($R^2 = 0.7149$) reflects a moderate-to-strong correlation, which may be influenced by frequent pedestrian activity, mainly due to the presence of a pedestrian crossing in this area.

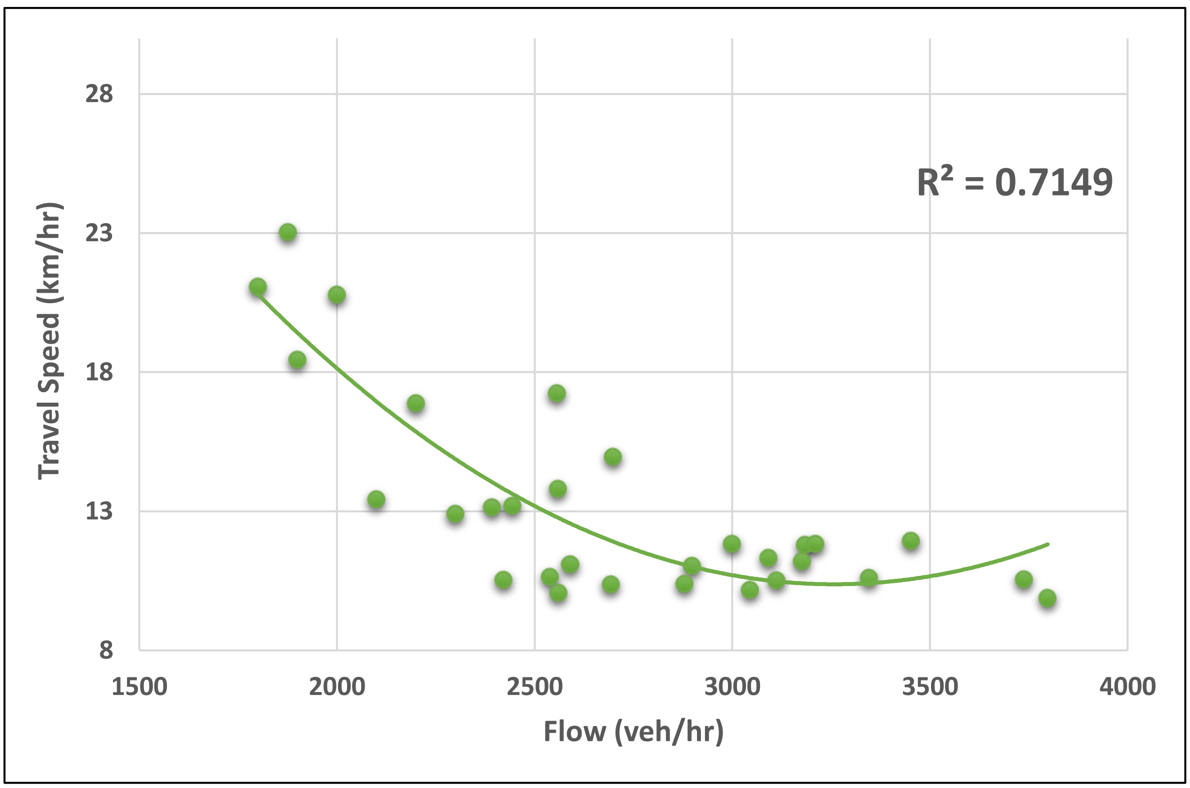

Figure (4.38): Flow-speed relationship curve for AL-Mojammat Street.

C) Sarie Al-Moalemin Street

At Sarie Al-Moalemin Street, Figure (4.39) demonstrates a strong inverse nonlinear relationship between traffic flow and travel speed. When flow is low around 1000 veh/hr vehicles travel at high speeds exceeding 40 km/h. However, as the flow increases toward 2700 veh/hr, speed drops sharply below 20 km/h, indicating significant congestion. The curve shows a steady and almost linear decline in speed, which suggests consistent traffic buildup as volume rises. This pattern reflects a street under growing pressure, where higher volumes steadily degrade traffic performance. The correlation coefficient (R^2 = 0.851) indicates a strong fit, supporting the reliability of the observed trend in this location.

Figures (4.40 to 4.47) show the speed-flow relationship for other main streets.

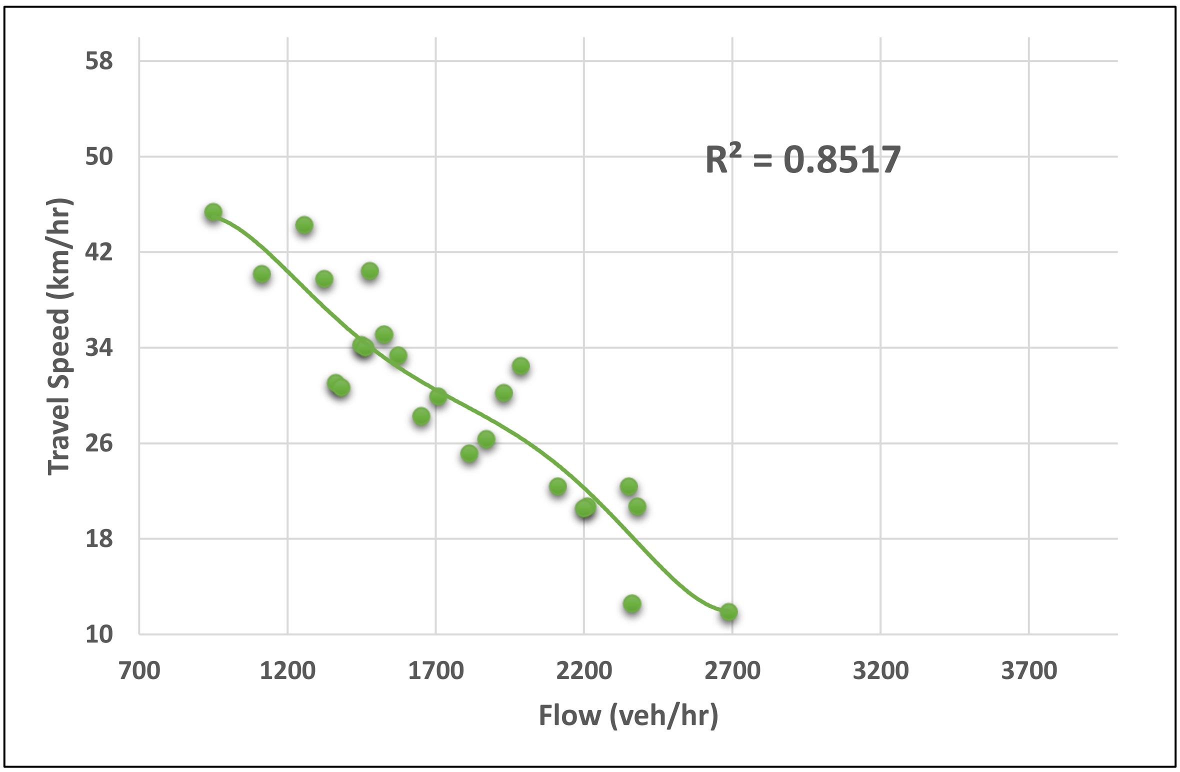

Figure (4.39): Flow-speed relationship curve for Sarie Al-Moalemin Street.

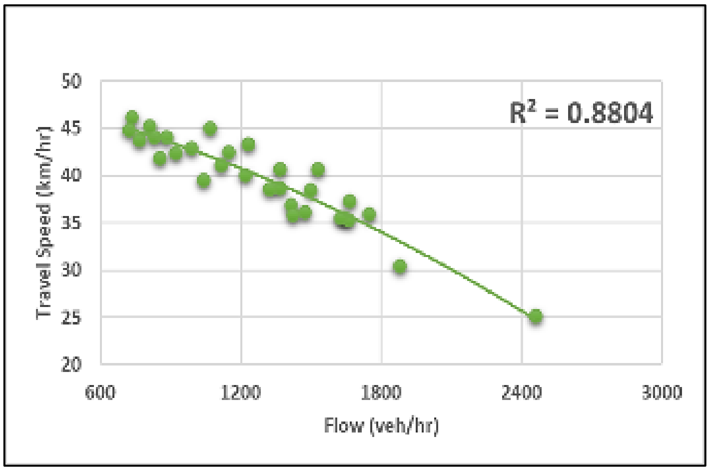

Figure (4.40): Flow-speed relationship for Hasan Al-Mojtaba Street.

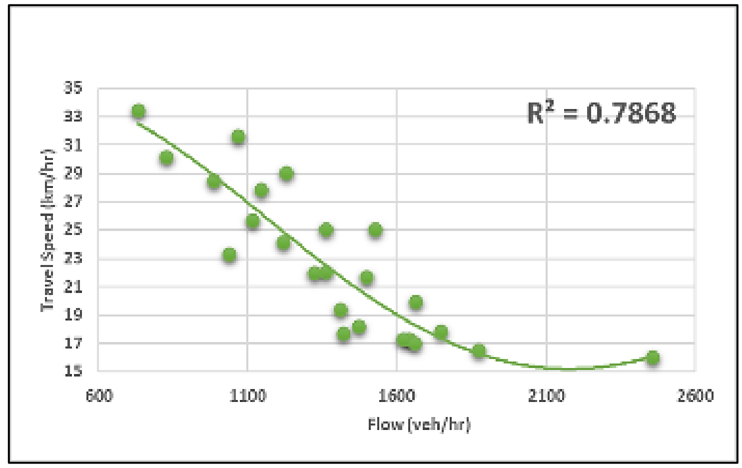

Figure (4.41): Flow-speed relationship AL-Hur Street.

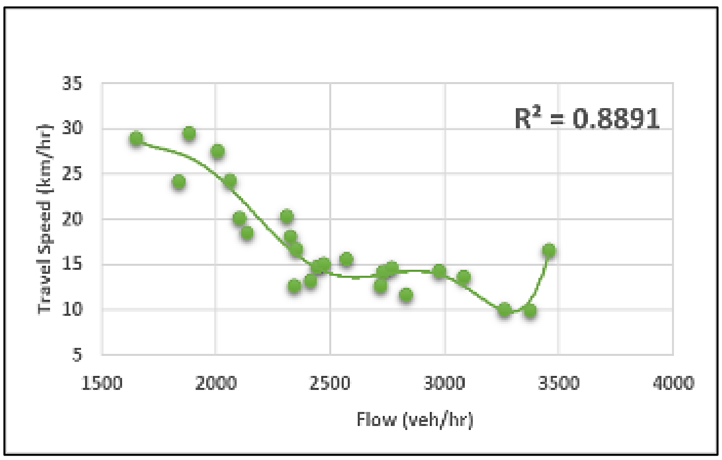

Figure (4.42): Flow-speed relationship Al-Tarbea Street.

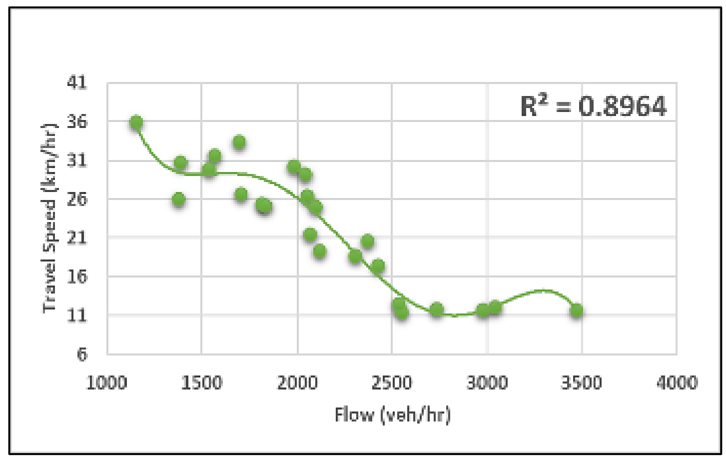

Figure (4.43): Flow-speed relationship for Nabi Street.

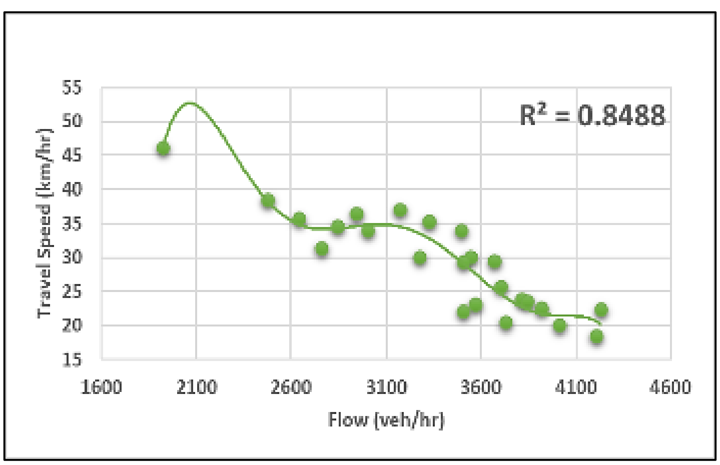

Figure (4.44): Flow-speed relationship for Ramadan Street.

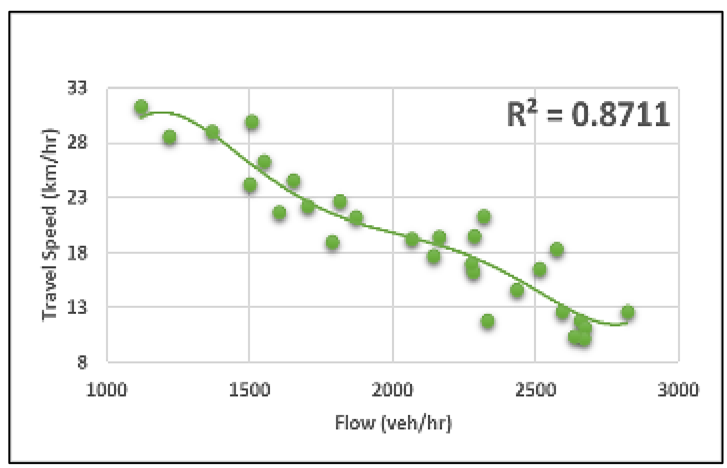

Figure (4.45): Flow-speed relationship for Al-Dhariba Street.

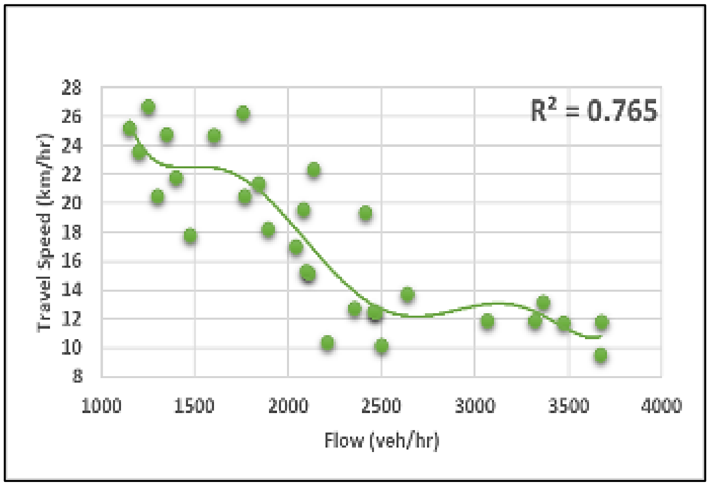

Figure (4.46): Flow-speed relationship for Fatima 1 Street.

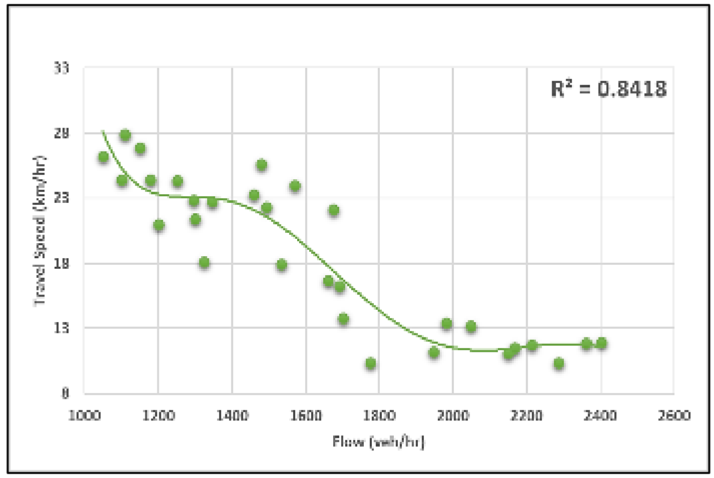

Figure (4.47): Flow-speed relationship for Maitham2 Street.

Generally, the flow-speed diagrams for all streets consistently demonstrate a nonlinear inverse relationship between traffic flow and travel speed. As vehicle flow increases, the average travel speed declines across all locations, which aligns with established traffic flow theory and real-world urban congestion behavior. However, as the flow increases, a sharper drop in speed is observed. In several streets such as Al-Tarbea, Nabi Mohmmad, and Fitma Al-Zahraa the curves show a steep decline after flow exceeds 2500–3000 veh/hr, suggesting the onset of saturation and reduced roadway performance. The curvature in many plots confirms that the relationship is not linear; speed reduction is initially gradual but becomes more severe at higher volumes. Additionally, most R^2 values (ranging from 0.765 to 0.896) indicate a strong correlation, supporting the reliability of the modeled trends. Minor differences in curved shape and steepness across streets likely result from variations in physical design and pedestrian activity.

4.5 Traffic Noise Analysis

Noise values in the study streets have been measured at morning peak hours by a noise level meter, and the average noise level for each street is represented in Figure (4.48). The Figure shows the variation in average noise levels, which range between 74 dB and 93 dB. Several streets, such as Ftima Al-Zahraa 2 (91.55 dB), Sarie Ramadan (90.33 dB), and Maitham Al-Tammar1 (90.03 dB), exhibit markedly higher noise levels. This is likely attributed to a combination of factors, including high traffic volumes, high percentages of heavy vehicles, and possibly the presence of commercial or industrial activities. Such areas typically experience higher engine load, braking activity, and idling noise, especially during peak hours. Furthermore, geometric constraints like narrow road sections or dense built environments may intensify sound reflections and contribute to higher noise readings. In contrast, streets such as AL-Taalib Street (74.8 dB) and Al-Nasr Street (74.92 dB) recorded relatively lower noise levels. These streets are generally characterized by lower traffic volume, a more homogeneous fleet with fewer heavy trucks, or smoother traffic flow conditions. It's also plausible that urban design elements, such as tree-lined boulevards or acoustic barriers, have contributed to noise mitigation in those segments. Interestingly, the majority of streets cluster within the 80-88 dB range, suggesting a common exposure level in typical urban road networks under medium-to-heavy traffic conditions. It can also be concluded that the noise level exceeded the limits of the Central Pollution Control Board and World Health Organization, which are 65 dB and 70 dB, respectively.

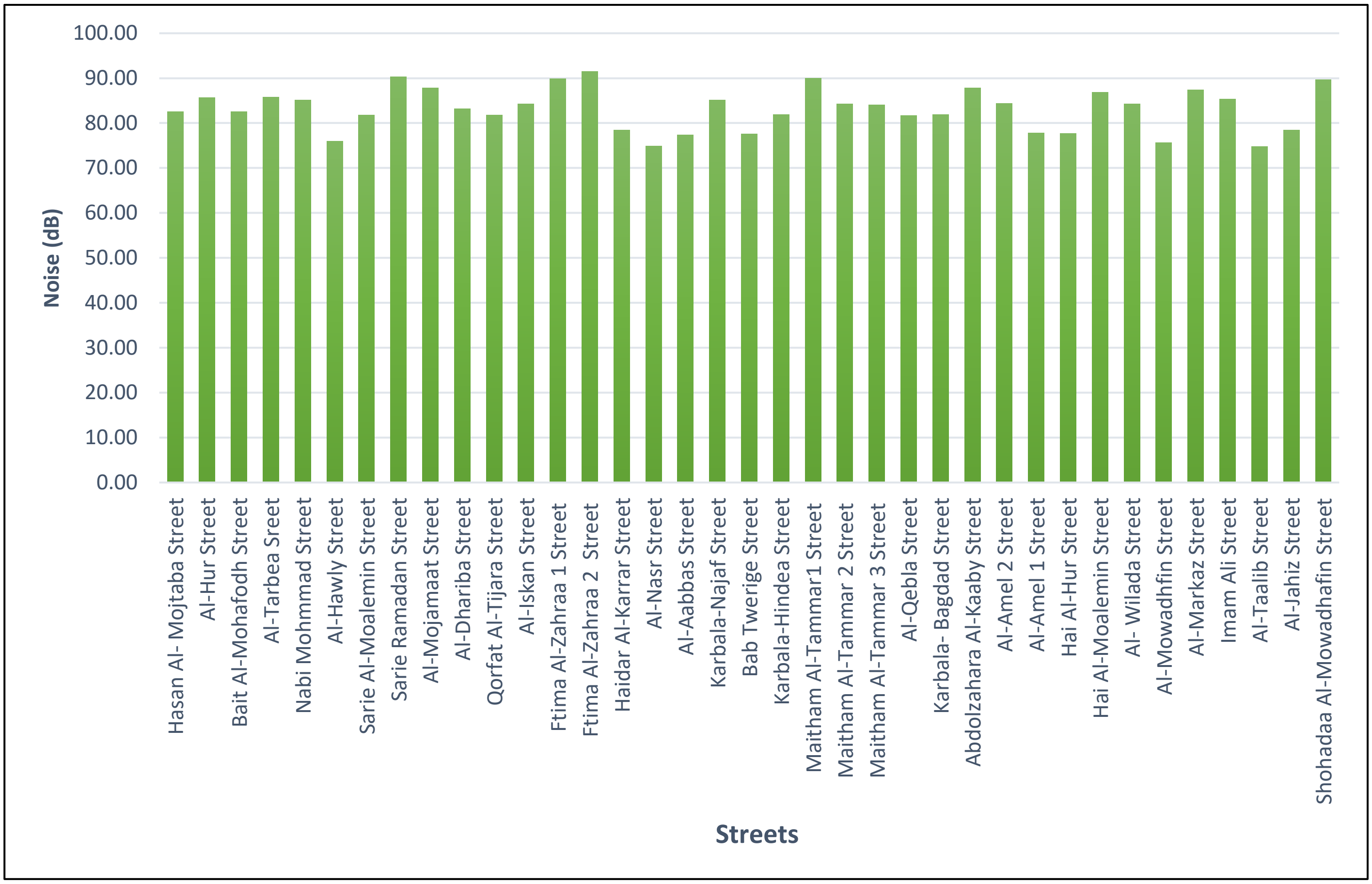

Figure (4.48): Average noise level in streets.

4.5.1 Modeling Strategy for Traffic Noise Analysis

Noise pollution has become a major environmental problem in urban transportation environments, with substantial effects on quality of life and public health. Developing successful mitigation methods requires an understanding of the fundamental causes of traffic noise. In this case, the association between noise levels and important traffic parameters, namely, vehicle speed, traffic volume, and the percentage of heavy vehicles, was investigated using a multiple regression modeling technique. This model aims to estimate how much these factors affect the decibel (dB) level of noise across main roads during peak hours. Through the integration of statistical analysis and real traffic data, the model offers a framework for evaluating each factor's predictive relevance. The nonlinear regression model used is expressed as:

Noise = a × $Volume^{b}$ × $Speed^{c}$ × Heavy $vehicles\%^{d}$

A) Sarie Rmadan Street

A nonlinear regression model was developed to estimate traffic noise levels for this street segment, using traffic volume, speed, and heavy vehicle percentage as predictor variables. The resulting equation is as follows:

$$Noise = 53.515 \times Volume^{(0.579)} \times Speed^{(-0.052)} \times H.V\%^{(0.283)}$$

The model achieved a coefficient of determination (R^2) of 0.860, indicating that the model explains 86% of the variation in observed noise levels. This suggests a strong model fit and confirms the effectiveness of the included traffic parameters in capturing the primary contributors to noise in this environment. The volume coefficient (0.579) shows a moderately strong positive relationship, implying that increased vehicle flow significantly raises noise levels. The speed coefficient is negative but relatively small (-0.052), suggesting a weak inverse relationship; higher speeds slightly reduce noise, likely due to less stop-and-go driving. The heavy vehicle percentage shows a notable coefficient (0.283), highlighting that heavy vehicles play a considerable role in generating traffic noise, consistent with their larger engines and higher mechanical output. The remaining 14% of unexplained variance may be attributed to factors not included in the model, such as the presence of nearby buildings, surface roughness, land use type, or driver behavior. These results reinforce the value of integrating additional contextual and environmental variables in future modeling efforts to enhance predictive accuracy. Figures (4.49 to 4.51) illustrate the relationship between noise and flow, speed, and heavy vehicles. Figure (4.49) shows a tight alignment between the proportion of heavy vehicles and noise levels throughout the observation period. This reinforces the regression outcome regarding the dominant role of heavy vehicles. Figure (4.50) illustrates an inverse trend, where noise tends to rise when speed dips, particularly evident between 8:00 and 8:25 AM. In Figure (4.51), although volume generally increases in tandem with noise, the relationship is not consistent or steep enough to achieve statistical significance in the regression.

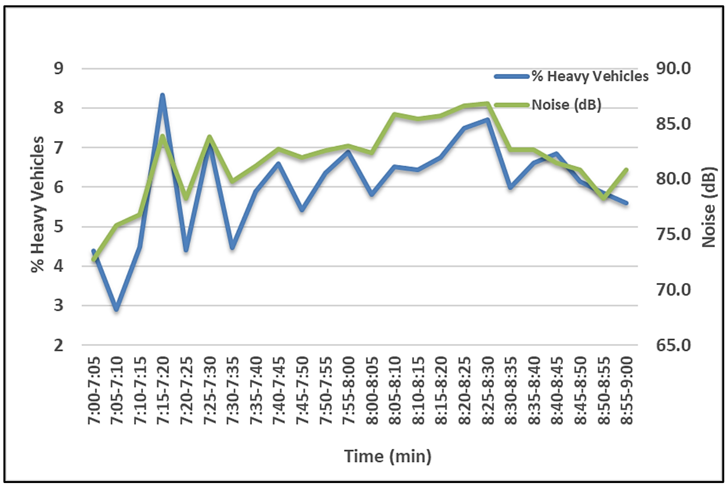

Figure (4.49): Noise and H.V% relationship on Ramadan Street.

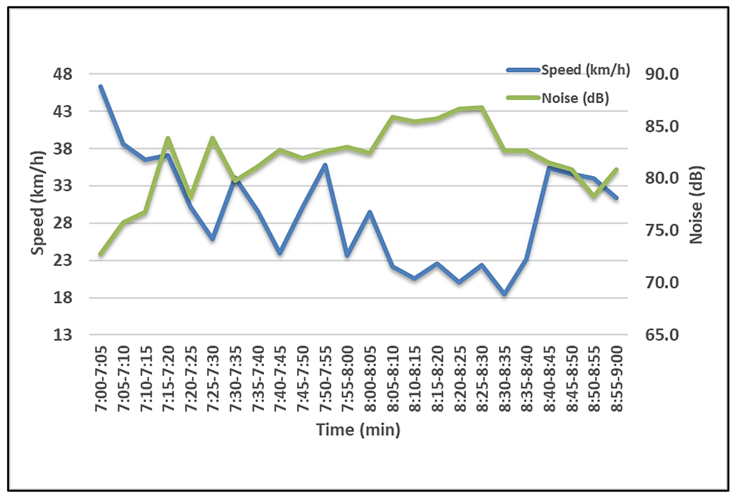

Figure (4.50): Noise and speed relationship on Ramadan Street.

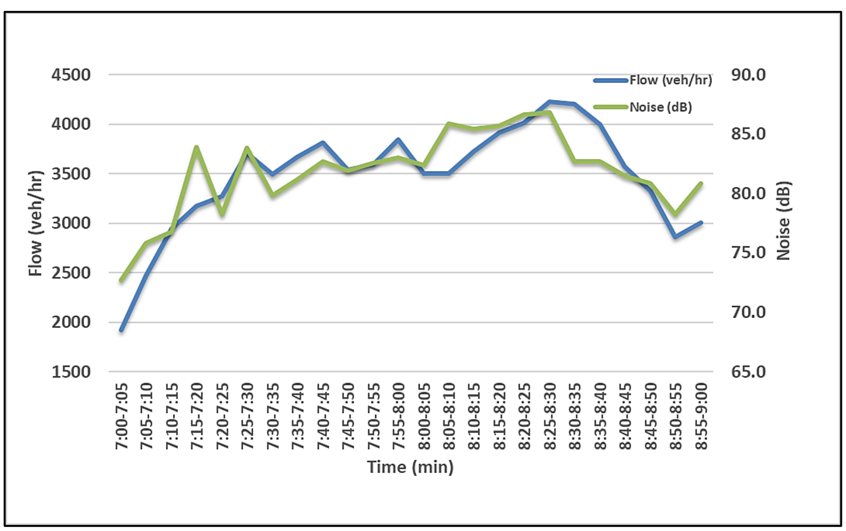

Figure (4.51): Noise and flow relationship on Ramadan Street.

B) Al- Dhariba Street

The nonlinear regression model was developed to estimate traffic noise levels as a function of traffic volume, average speed, and the percentage of heavy vehicles. The model takes the form of a power function:

Noise = 70.406 × $Volume^{(0.65)}$× Speed $^{(-0.15)}$× Heavy $Vehicle\%^{(0.033)}$

Each coefficient in the model provides insight into the relative influence of its associated predictor variable. The volume coefficient (0.65) indicates a relatively strong positive impact, suggesting that increased traffic volume leads to higher noise levels due to more engine activity, tire-road interaction, and horn usage.

The negative coefficient of the speed variable (-0.15) reflects an inverse relationship with noise levels, indicating that as average vehicle speed increases, noise levels tend to decrease. This behavior is typical in congested urban areas, where reduced speeds are linked to stop-and-go conditions, frequent braking, and acceleration.

The heavy vehicles coefficient (0.033) is positive but small, indicating that heavy vehicles contribute to noise levels, though their effect is modest. Despite the low value, their impact remains relevant, as heavy vehicles typically generate more noise than light vehicles due to their larger engines, heavier weight, and louder mechanical systems.

The coefficient of determination (R^2) for the model is 0.870, indicating that approximately 87% of the variability in the observed noise data is explained by the model. This high value reflects a strong fit and confirms the model's capability to reliably represent the relationship between the selected traffic parameters and noise levels. Figures (4.52 to 4.54) illustrate the relationship between noise and flow, speed, and heavy vehicles.

In Figure (4.52), a clear inverse relationship is observed between speed and noise. As vehicle speed decreases from approximately 30 km/h at 7:00 to below 15 km/h around 8:00, noise levels increase from 83 dB to nearly 90 dB. Figure (4.53) demonstrates a positive relationship between heavy vehicle percentage and noise levels. The proportion of heavy vehicles increases from around 3% to 5.5%**,** corresponding to a rise in noise from 85 - 89 dB**.** In Figure (4.54)**,** noise levels tend to follow the pattern of traffic flow, which peaks at around 2500 veh/hr between 7:35 and 7:50. During this peak, noise levels reach up to 90 dB, suggesting a direct correlation where increased traffic volume intensifies overall noise emissions.

Figure (4.52): Noise and H.V% relationship on Al-Dhariba Street.

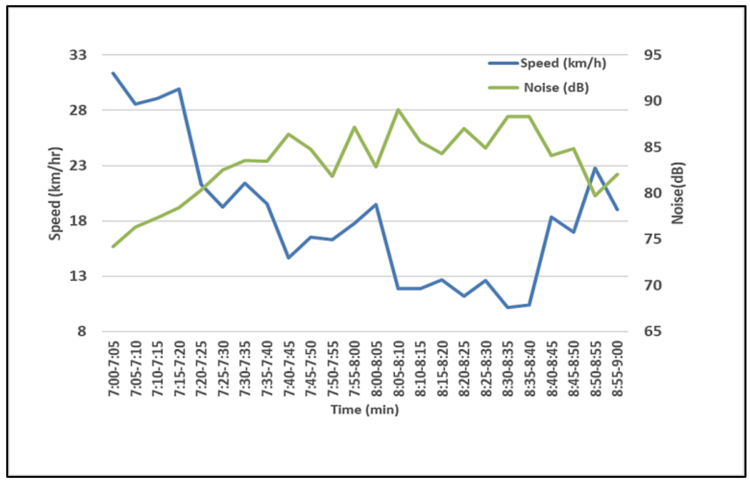

Figure (4.53): Noise and speed relationship on Al-Dhariba Street.

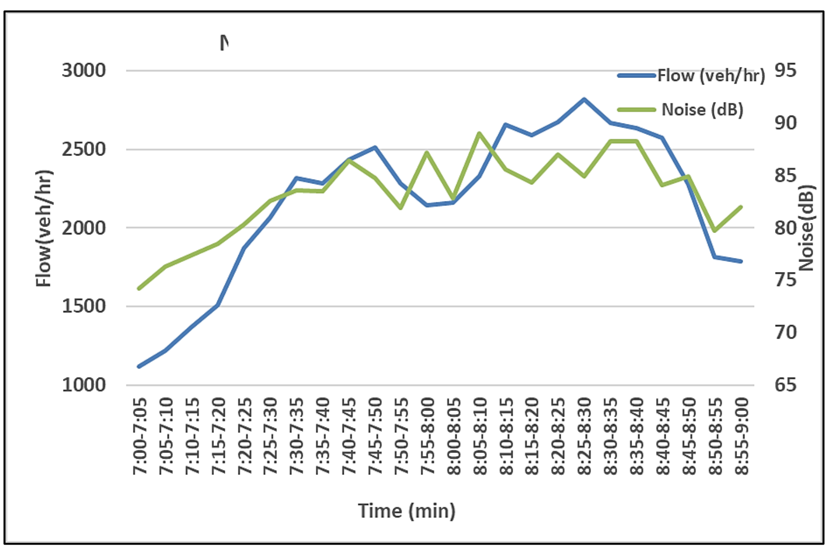

Figure (4.54): Noise and flow relationship on Al-Dhariba Street.

C) Al-Tarbea Street

In this scenario, the model produced a multiple correlation (R^2 of 0.828), indicating that about 82.8% of the variation in noise levels can be explained by the three variables.

The regression equation is:

$$Noise = 33.62 \times Volume^{(0.8197)} \times Speed^{(-0.305)} \times H.V\%^{(0.1830)}$$

The volume coefficient (0.819) is relatively high compared to other models, indicating a strong positive relationship between traffic volume and noise. The speed coefficient (-0.305) is moderately negative, reflecting an inverse relationship; as vehicle speed increases, noise tends to decrease. The heavy vehicle percentage has a positive exponent (0.1830), signifying a meaningful contribution to noise levels. The remaining 17.2% of unexplained noise variation could be attributed to additional real-world factors that were not included in the regression. Several external elements can significantly affect traffic noise levels beyond speed, flow, and heavy vehicle percentage. For instance, the type and condition of road pavement can influence noise, as rough or worn-out surfaces generate more tire friction sound. Similarly, roadside geometry, barriers, and land use (e.g., presence of buildings or vegetation) can affect how sound propagates. Furthermore, driver behavior such as sudden braking, honking, or aggressive acceleration can introduce noise variation that is not captured by average speed or flow rates. Environmental conditions, including temperature, wind, and humidity, also impact sound levels but are not reflected in traffic datasets. Therefore, the moderately lower R^2 value should be interpreted as an indication that while traffic variables are essential, they are not the sole contributors to noise. The presence of unmeasured external factors likely explains part of the residual variation in noise levels. Figures (4.55 to 4.57) illustrate the relationship between noise and flow, speed, and heavy vehicles. Figure (4.55) reveals a moderate alignment between fluctuations in truck percentage and noise levels. Notably, at certain moments when the heavy vehicle percentage drops, noise also slightly dips, reinforcing the variable's importance. Figure (4.56) shows a clear inverse trend, with noticeable noise increases coinciding with lower speed intervals, particularly between (7:20–8:20 AM). Figure (4.57) illustrates a steady upward trend for both flow and noise, although the relationship is less synchronized compared to the other variables.

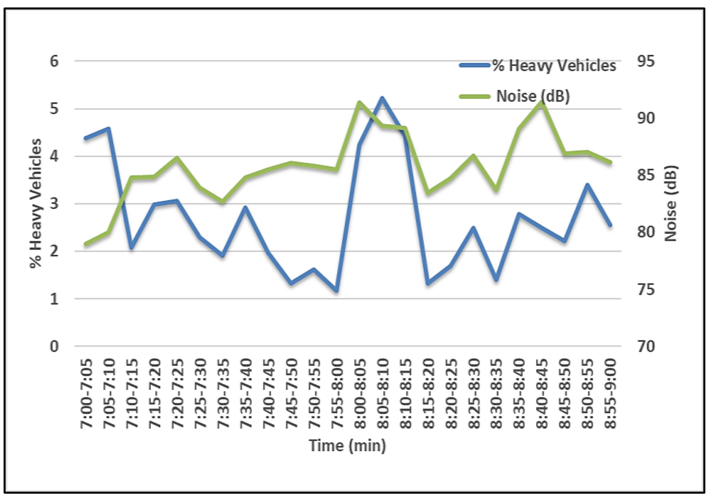

Figure (4.55): Noise and H.V% relationship on Al-Tarbea Street.

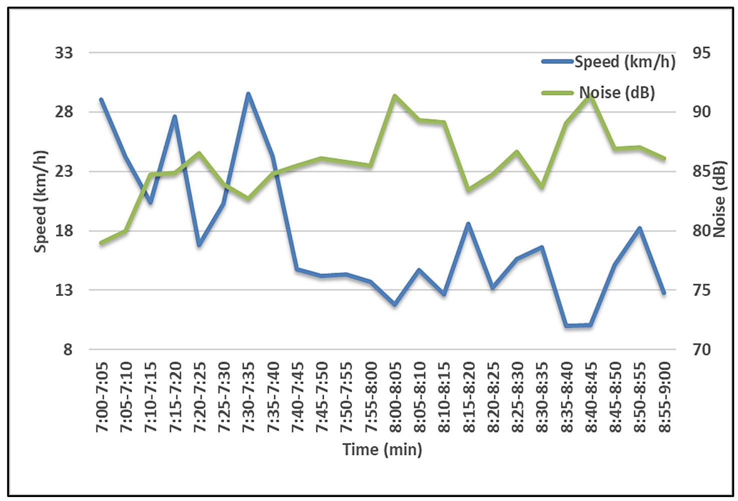

Figure (4.56): Noise and speed relationship on Al-Tarbea Street.

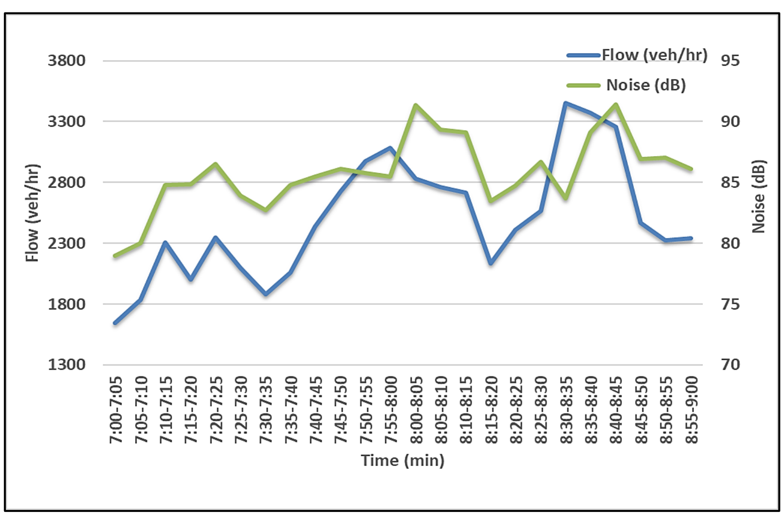

Figure (4.57): Noise and flow relationship on Al-Tarbea Street.

D) Maitham Al-Tammar2 Street

In this scenario, the regression analysis yielded compelling results, highlighting a strong and statistically significant relationship between traffic noise levels and the explanatory variables: vehicle speed, traffic volume, and the percentage of heavy vehicles. The coefficient of determination (R^2 = 0.895) indicates that approximately 89.5% of the variance in noise levels can be explained by the selected traffic parameters. This reflects a strong model fit.

The regression equation formulated from the data is as follows:

$$Noise = 48.713 \times Volume^{(0.48)} \times Speed^{(-0.149)} \times Heavy\ Vehicle\%^{(0.118)}$$

Figures (4.58 to 4.60) represent the relationship between noise and traffic flow, travel speed, and heavy vehicle percentages. The noise trend closely follows fluctuations in the percentage of heavy vehicles, particularly between 7:10 and 8:15 AM. Similarly, the Noise-Speed curve illustrates an increase in noise levels as speeds decline, indicating an inverse trend that strengthens the regression findings. As for the flow-noise relationship, the visual pattern shows a general alignment, though with less intensity, supporting the statistical outcome that flow plays a supplementary role relative to speed and heavy vehicle share. Table (4.6) represents the summary of regression equations and R^2 for main streets.

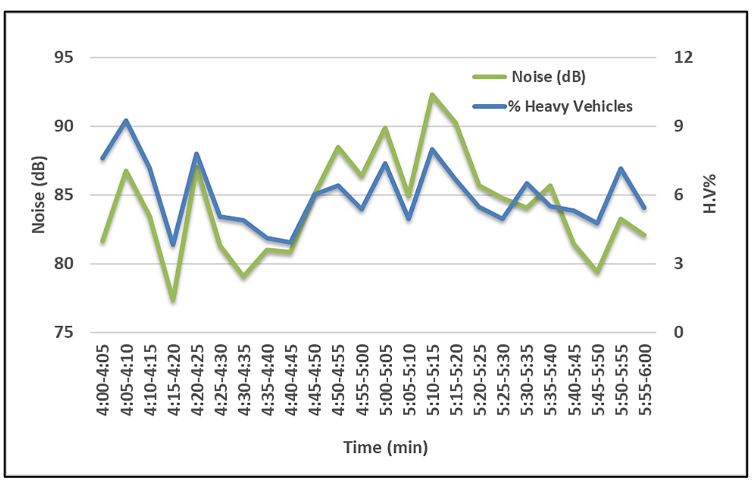

Figure (4.58): Noise and H.V% relationship on Maitham2 Street.

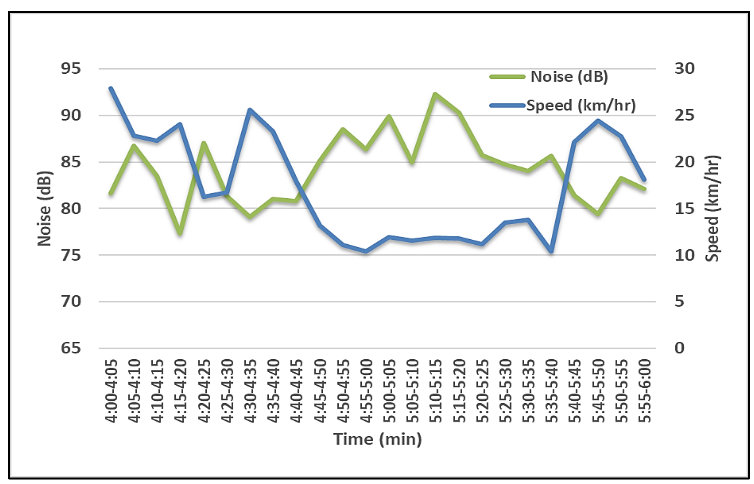

Figure (4.59): Noise and speed relationship on Maitham2 Street.

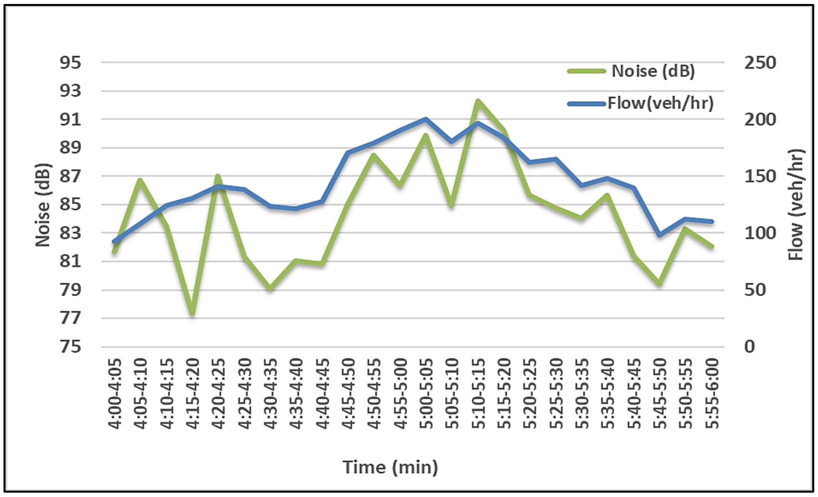

Figure (4.60): Noise and flow relationship on Maitham2 Street.

Table (4.6): Regression equations and R^2 for main streets.

Street	Regression Equation	R^2
Sarie Ramadan	53.515 × Volume $^{(0.579)}$ × Speed $^{(-0.052)}$ × Heavy Vehicle % $^{(0.283)}$	0.860
Al-Dhariba	70.406 × Volume$^{(0.65)}$× Speed $^{(-0.15)}$× Heavy Vehicle%$^{(0.033)}$	0.87
Fatima 1	47.531 × Volume $^{(0.073)}$ × Speed $^{(0.018)}$ × Heavy Vehicle% $^{(0.104)}$	0.885
Tarbea	33.62 × Volume $^{(0.8197)}$ × Speed $^{(-0.305)}$ × Heavy Vehicle % $^{(0.1830)}$	0.819
Maitham2	48.713 × Volume $^{(0.48)}$ × Speed $^{(-0.149)}$ × Heavy Vehicle% $^{(0.118)}$	0.895
Mojamaat	55.499 × Volume $^{(0.270)}$ × Speed $^{(-0. 34)}$ × Heavy Vehicle% $^{(0.075)}$	0.747
Naby Mohammad	78.953 × Volume $^{(0. 34)}$ × Speed $^{(-0.078)}$ × Heavy Vehicle% $^{(0.096)}$	0.845
SarieAl- moelemin	61.88 × Volume $^{(0. 787)}$ × Speed $^{(-0.134)}$ × Heavy Vehicle $^{(0.069)}$	0.860
Al-Hur	62.129 × Volume $^{(0.55)}$ × Speed $^{(0.278)}$ × Heavy Vehicle% $^{(0.054)}$	0.92
Hasan Al-Mojtaba	16.880 × Volume $^{(0.390)}$ × Speed $^{(0.062)}$ × Heavy Vehicle% $^{(0.35)}$	0.918
Al-Wilada	19.275 × Volume $^{(0.421)}$ × Speed $^{(-0.287)}$ × Heavy Vehicle% $^{(0.061)}$	0.803

4.6 Traffic Flow Emissions Analysis

Traffic pollution emissions have been measured at study streets, maximum values for CO and CO_2 were noticed at Fatima Al-Zahraa1 Street, which were 14.7 (ppm) and 1090 (ppm) respectively. Figures (4.61 to 4.64) illustrate the average values for CO, CO_2, NO_2, $PM_{2.5}$, and PM_{10} for each street. The maximum average value for CO was at Mostashfa Wilada Street, which was 7.8 ppm, and the maximum average value for CO2 was at Sarie Ramadan Street. A higher average for NO2 was at Shohadaa Al-Mowadhafin, which was 0.066 ppm, as well as PM2.5, which was equal to 85.9 mg/m^3. Finally, the maximum average for PM_{10} was at Karbala-Najaf Street.

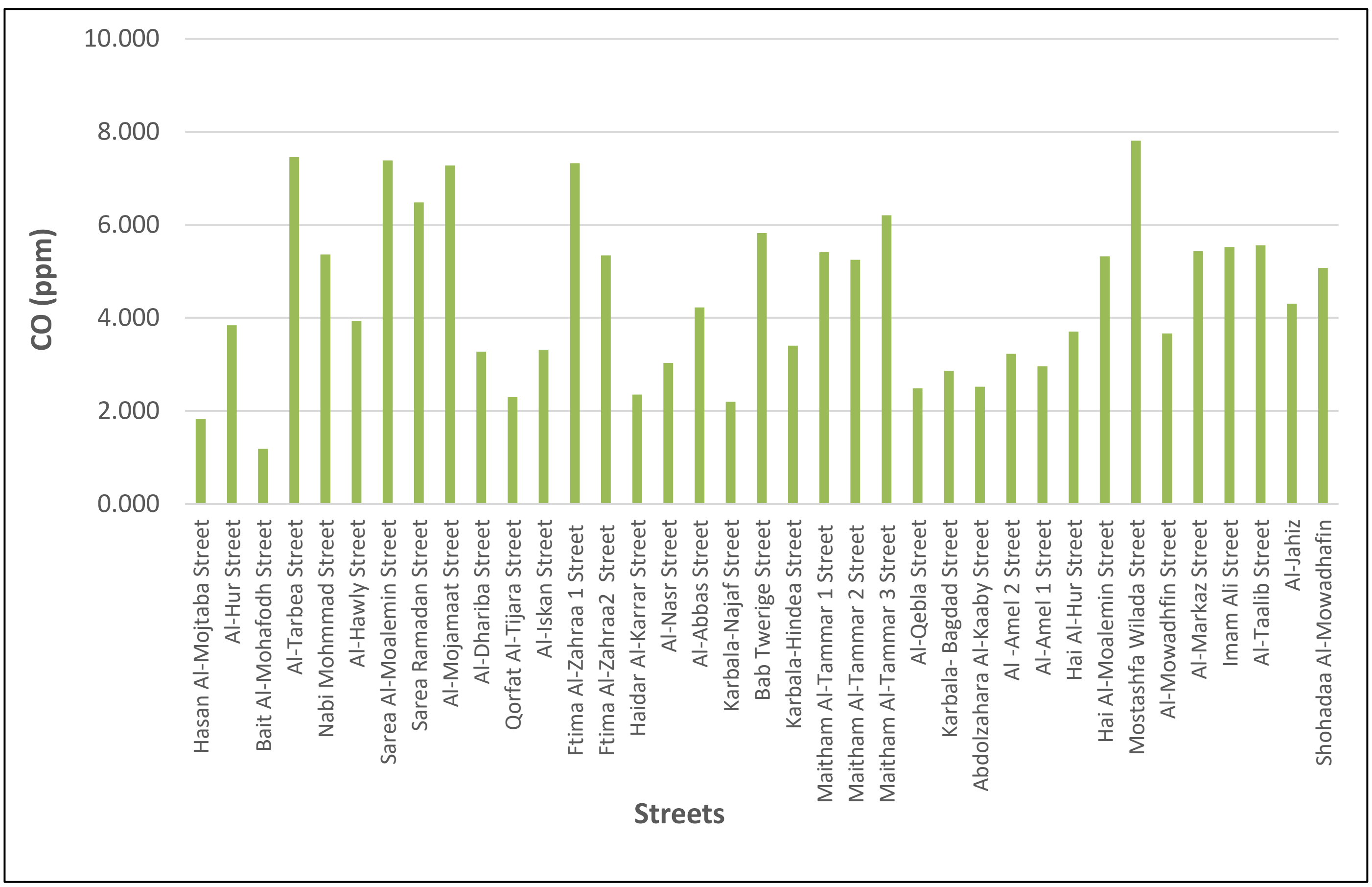

Figure (4.61): Average CO for streets.

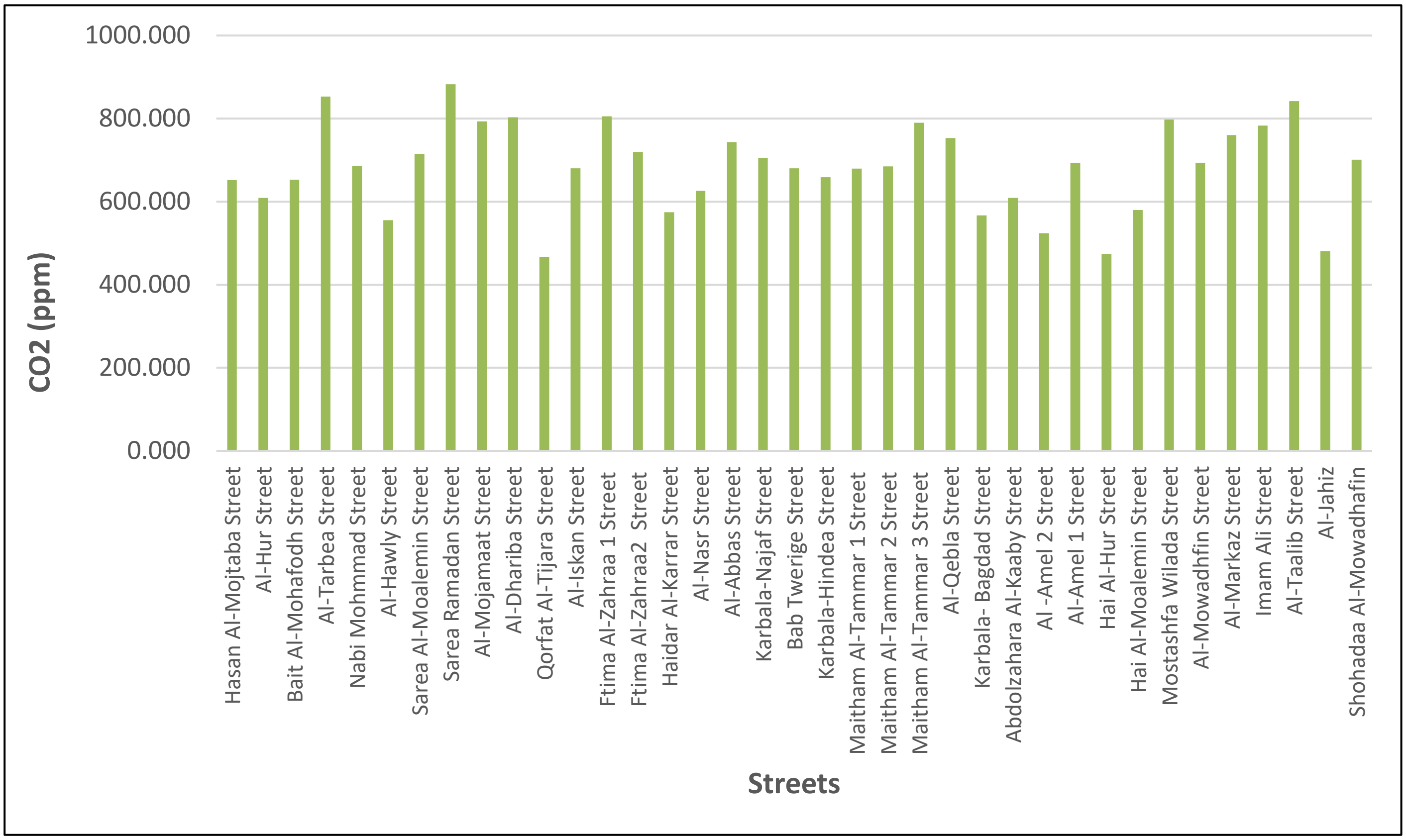

Figure (4.62): Average CO_2 for streets.

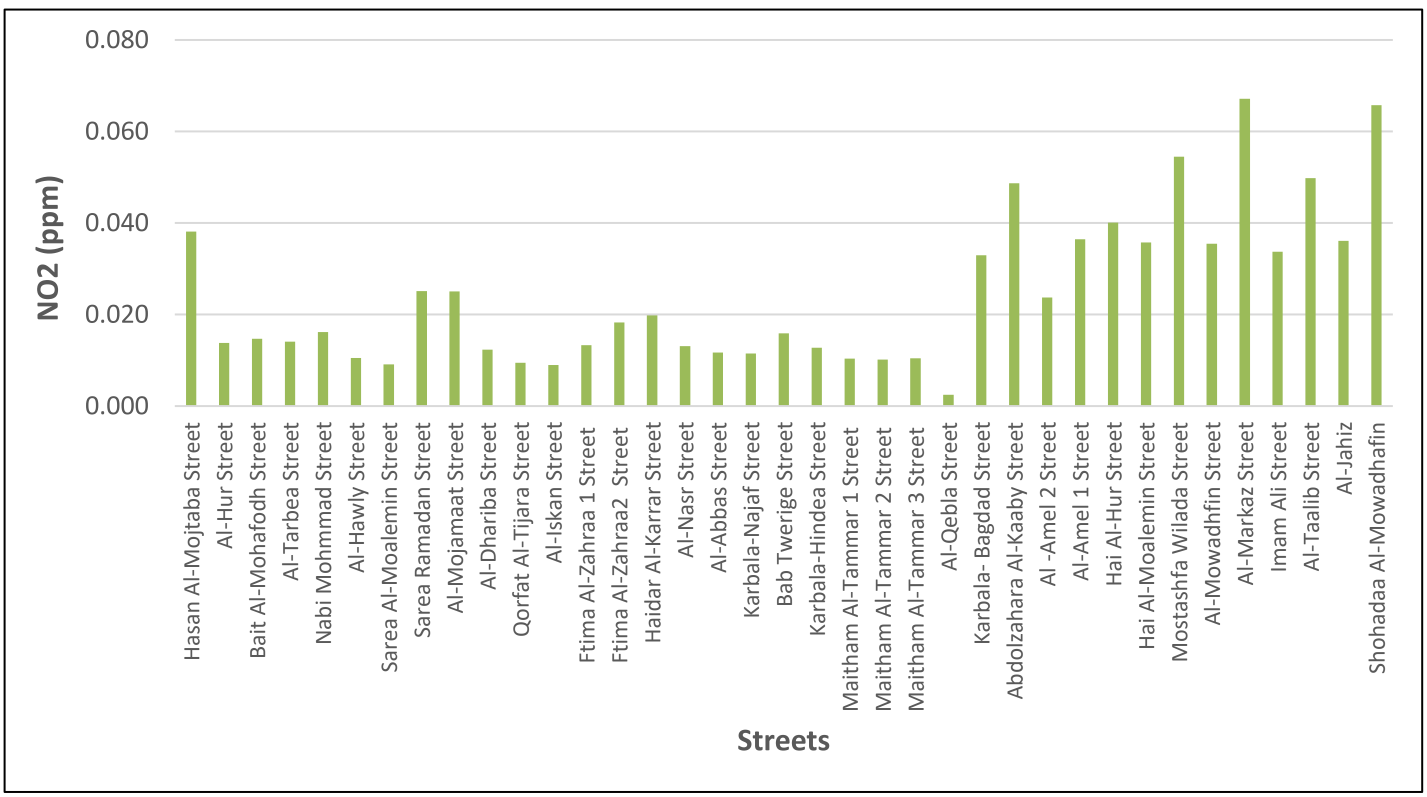

Figure (4.63): Average NO_2 for streets.

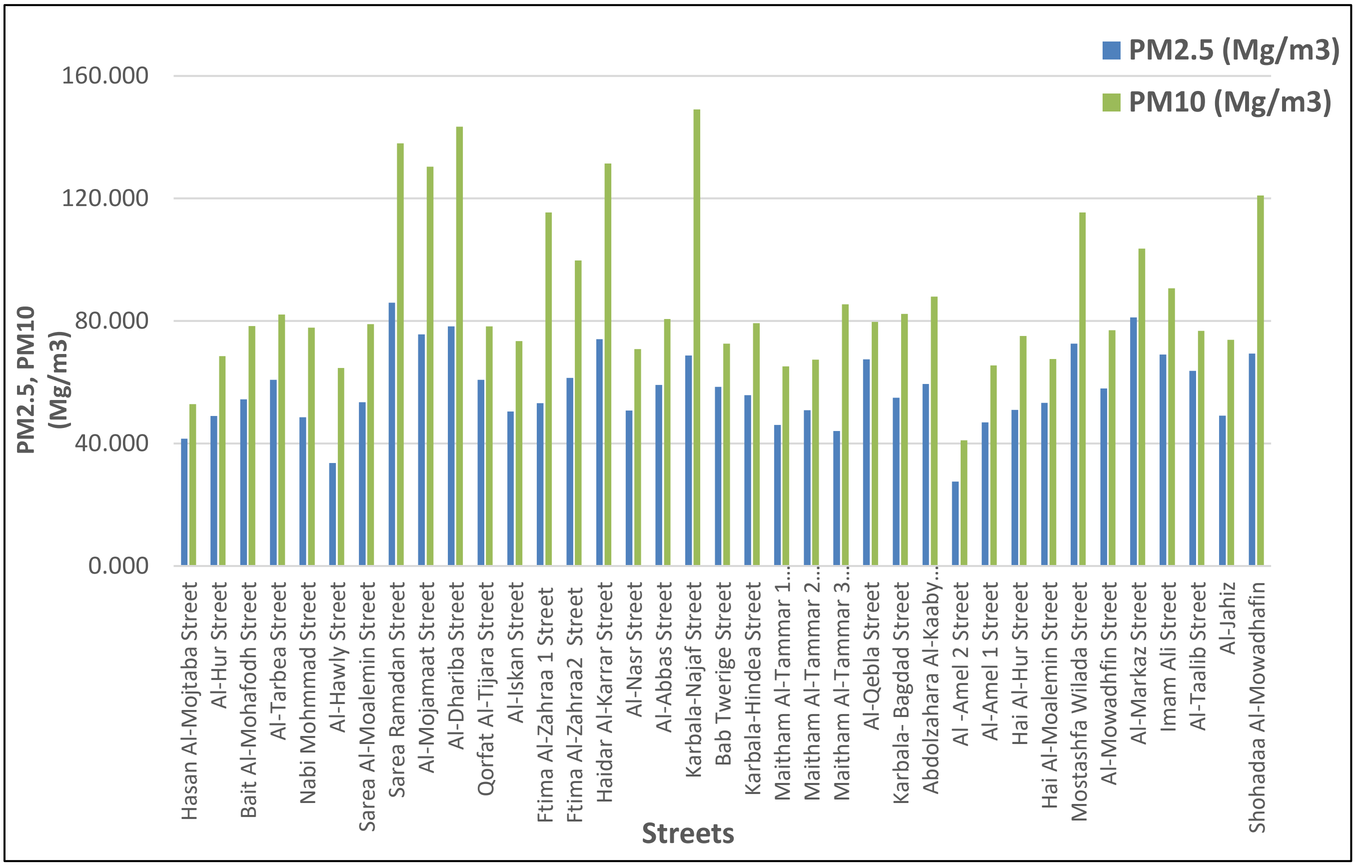

Figure (4.64): Average $PM_{2.5}$, PM_{10} for streets.

Table (4.7) represents the AQI and its values according to the Environmental Protection Agency (EPA) for each street.

An analysis of AQI data from 38 urban streets revealed critical insights into the environmental health conditions across the studied area.

Nineteen streets (51.35%) fall under unhealthy categories, including "Unhealthy" and "Unhealthy for certain individuals". Eighteen streets (48.65%) were classified as "Moderate", representing acceptable air quality conditions for the general population. The high proportion of streets falling into unhealthy AQI ranges suggests elevated exposure to harmful pollutants, particularly in dense urban corridors. This situation poses significant health risks, especially for sensitive groups such as children, the elderly, and individuals with respiratory conditions.

Table (4.7): AQI for streets.

Street	AQI values	Result
Hasan Al-Mojtaba Street	82	Moderate
Al-Hur Street	95	Moderate
Bait Al-Mohafodh Street	58	Moderate
Al-Tarbea Street	134	Unhealthy for certain individua
Nabi Mohmmad Street	93	Moderate
Al-Hawly Street	62	Moderate
Sarie Al-Moalemin Street	148	Unhealthy for certain individua
Sarie Ramadan Street	97	Moderate
Al-Mojamaat Street	159	Unhealthy
Al-Dhariba Street	55	Moderate
Qorfat Al-Tijara Street	51	Moderate
Al-Iskan Street	67	Moderate
Ftima Al-Zahraa1 Street	188	Unhealthy
Ftima Al-Zahraa 2 Street	90	Moderate
Haidar Al-Karrar Street	75	Moderate
Al-Nasr Street	66	Moderate
AL-Abbas Street	76	Moderate
Karbala-Najaf Street	61	Moderate
Bab Twerige Street	192	Unhealthy
Karbala-Hindea Street	179	Unhealthy
Maitham Al-Tammar1 Street	198	Unhealthy
Maitham Al-Tammar2 Street	185	Unhealthy
Maitham Al-Tammar3 Street	195	Unhealthy

Table (4.7): Continued.

Street	AQI values	Result
Al-Qebla Street	134	Unhealthy for certain individual
Karbala-Bagdad Street	138	Unhealthy for certain individual
Abdolzahara Al-Kaaby Street	171	Unhealthy
Al-Amel 2 Street	93	Moderate
Al-Amel 1 Street	134	Unhealthy for certain individual
Hai Al-Hur Street	135	Unhealthy for certain individual
Hai Al-Moalemin Street	113	Unhealthy for certain individual
Al-Mowadhfin Street	113	Unhealthy for certain individual
Al-Markaz Street	86	Moderate
Imam Ali Street	125	Unhealthy for certain individual
Al-Taalib Street	82	Moderate
Al-Jahiz Street	83	Moderate
Shohadaa Al-Mowadhafin Street	171	Unhealthy
Al-Wilada Street	154	Unhealthy

4.6.1 Pollution Prediction Model Description

To evaluate the impact of traffic conditions on air quality, a regression-based model was developed to estimate pollutant levels based on vehicle speed and flow rate. This model aims to quantify the contribution of traffic dynamics to urban air pollution levels. The results of the multivariate regression analysis on pollutant emissions (CO, CO_2, NO_2, $PM_{2.5}$, and PM_{10}) in connection with traffic volume and speed during the morning peak hour at main streets are thoroughly discussed in this part. The following sections explain the values of R^2, scatter diagrams, and regression equations, which shed light on how pollutants behave in different traffic scenarios for each main street.

A) Fatima Al-Zahraa1 Street

The nonlinear regression models developed for Fatima Al-Zahraa Street illustrate statistically significant relationships between traffic volume (V), vehicle speed (S), and pollutant concentrations. The power-form equations highlight how each pollutant reacts to variations in flow and speed, with R^2 values ranging from 0.6959 to 0.9142, indicating good model fit overall. Among the pollutants, CO_2 exhibits the strongest correlation ($R^2 = 0.9142$), followed by PM_{10} and CO, suggesting that changes reliably influence these emissions in traffic conditions.

NO_2, however, shows the weakest fit ($R^2 = 0.6959$), possibly due to unmodeled influences like localized emissions or atmospheric reactions. For most pollutants, traffic volume has a more dominant effect than speed. In contrast, the speed exponents are negative and moderate, indicating that higher speeds tend to reduce emission rates slightly, likely due to improved engine efficiency and reduced idling. Overall, these models support the use of nonlinear formulations in predicting air pollution levels under real traffic dynamics.

Table (4.8) represents the regression equations and R^2, while Figures (4.65 to 4.70) show the scatter plots. The nonlinear model is:

Gas = a × **V**$^{(b)}$ × **S**$^{(c)}$ Where: **V** represents traffic volume (veh/hr), **S** is the average vehicle speed (km/h), a**, b, and c** are the regression coefficients.

Table (4.8): Regression equations and R^2 for Ftima Al-Zahra1 Street.

Pollutant	Regression Equation	R^2
CO	$0.00058 \times V^{(1.388)} \times S^{(-0.524)}$	0.989
NO_2	$0.00006 \times V^{(2.559)} \times S^{(-0.261)}$	0.930
CO_2	$0.66378 \times V^{(0.845)} \times S^{(0.192)}$	0.920
$PM_{2.5}$	$0.00044 \times V^{(1.537)} \times S^{(-0.126)}$	0.839
PM_{10}	$0.00010 \times V^{(1.781)} \times S^{(-0.008)}$	0.900

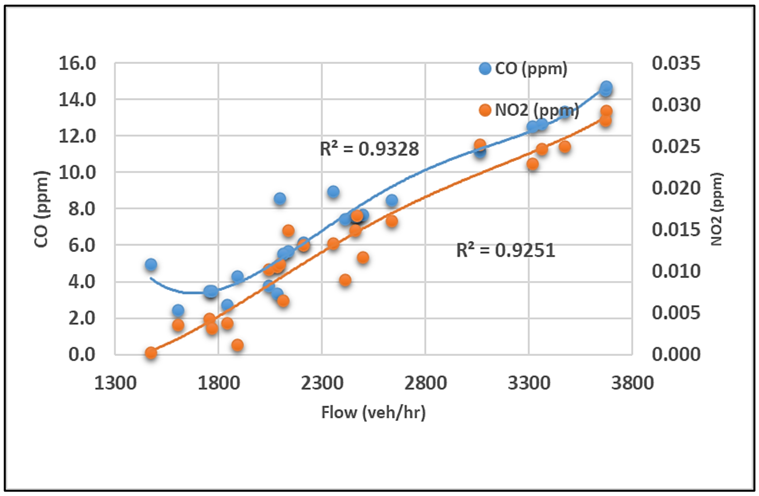

Figure (4.65): Relation of CO and NO_2 with flow on Fatima 1 Street.

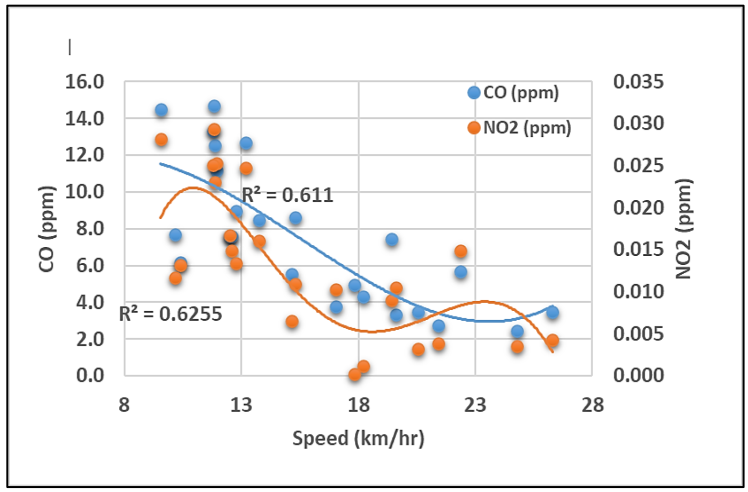

Figure (4.66): Relation of CO and NO_2 with speed on Fatima 1 Street.

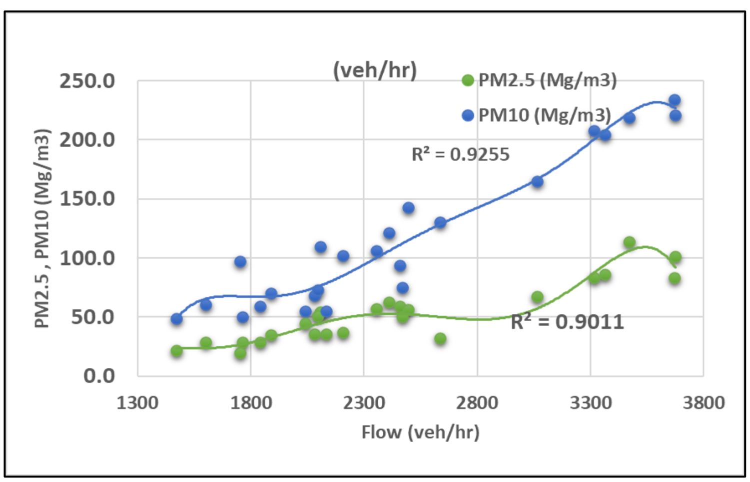

Figure (4.67): Relation of $PM_{2.5}$ and PM_{10} with flow on Fatima 1 Street.

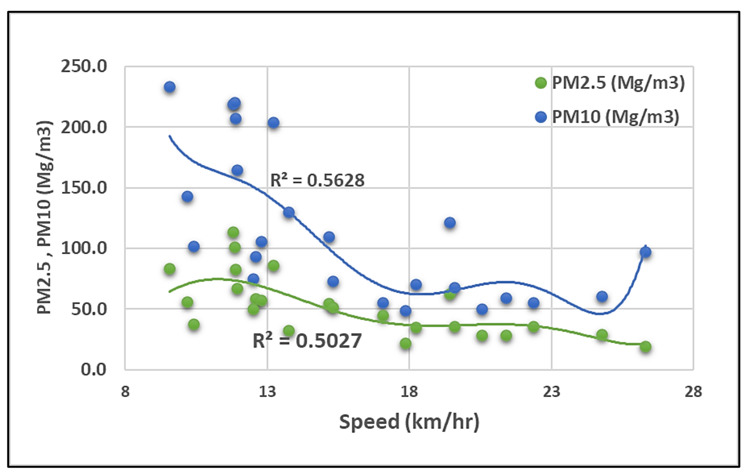

Figure (4.68): Relation of $PM_{2.5}$ and PM_{10} with speed on Fatima 1 Street.

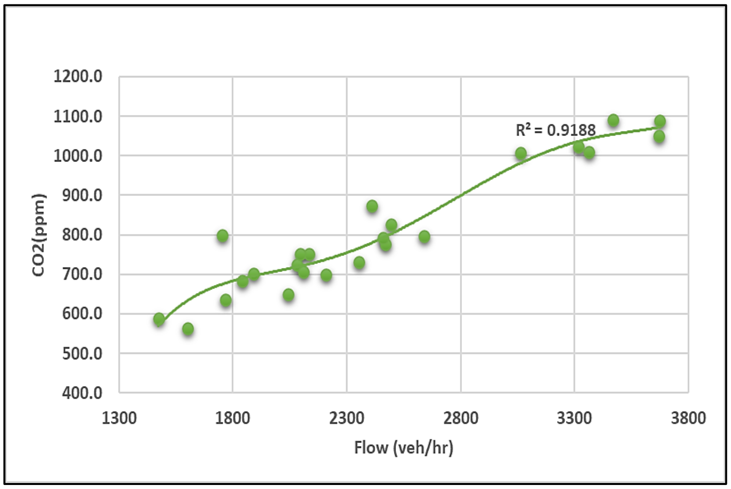

Figure (4.69): Relation of CO_2 with flow on Fatima 1 Street.

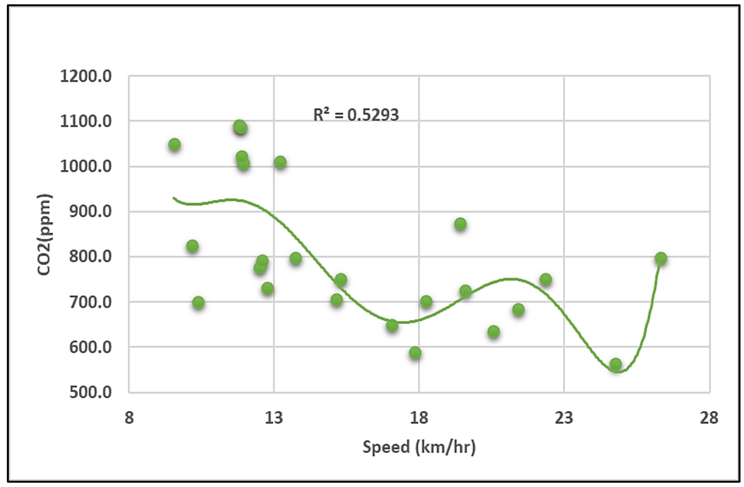

Figure (4.70): Relation of CO_2 with speed on Fatima 1 Street.

B) Sarie Al-Moalemin Street.

The regression results for Sarie Al-Moalemin Street reveal that CO and CO_2 have strong relationships with traffic parameters, with R^2 values above 0.90. This indicates that over 90% of the variability in their concentrations is explained by changes in traffic flow and speed. CO is more positively associated with both flow and speed than other pollutants, suggesting it increases significantly with traffic intensity and faster driving conditions.

Pollutants scatter diagram, however, demonstrates inverse relationships with speed, indicating that lower speeds (typically during congestion) correlate with higher concentrations. The model for $PM_{2.5}$, with an R^2 of 0.800, is weaker compared to the other pollutants, possibly due to external influences such as wind, road dust resuspension, or nearby land use, followed by PM_{10} and NO_2 with an R^2 of 0.837 and 0.862, respectively.

Table (4.9) represents the nonlinear regression equations and R^2, while Figures (4.71 to 4.76) show the scatter plots.

Table (4.9): Regression equations and R^2 for Sarie Al-Moalemin Street.

Pollutant	Regression Equation	R^2
CO	$0.00004 \times V^{(2.096)} \times S^{(0.223)}$	0.9335
NO_2	$0.00003 \times V^{(2.990)} \times S^{(0.314)}$	0.8628
CO_2	$10.49633 \times V^{(0.616)} \times S^{(-0.113)}$	0.9229
$PM_{2.5}$	$0.03187 \times V^{(1.042)} \times S^{(-0.114)}$	0.8005
PM_{10}	$0.03067 \times V^{(1.085)} \times S^{(-0.080)}$	0.8376

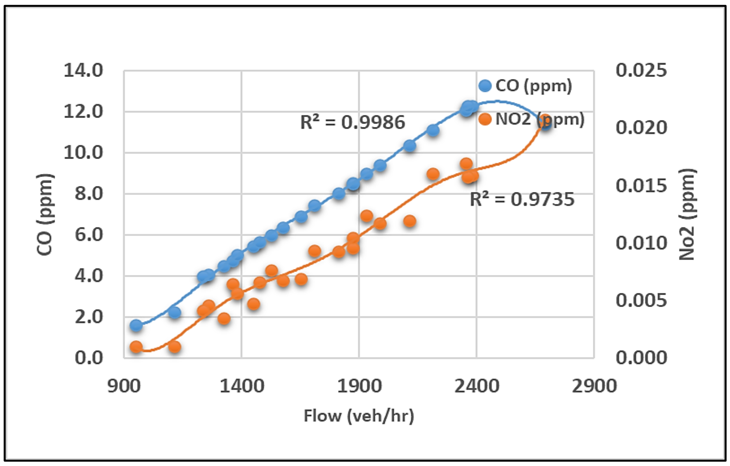

Figure (4.71): Relation of CO and NO_2 with flow on Saree Al-Moalemin Street.

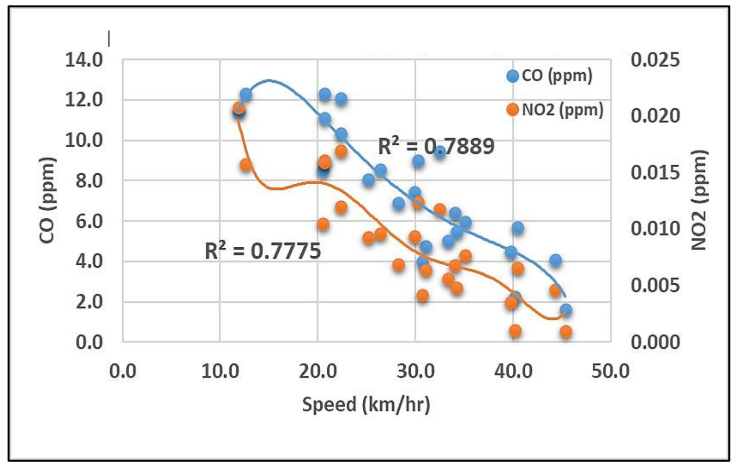

Figure (4.72): Relation of CO and NO_2 with speed on Saree Al-Moalemin Street.

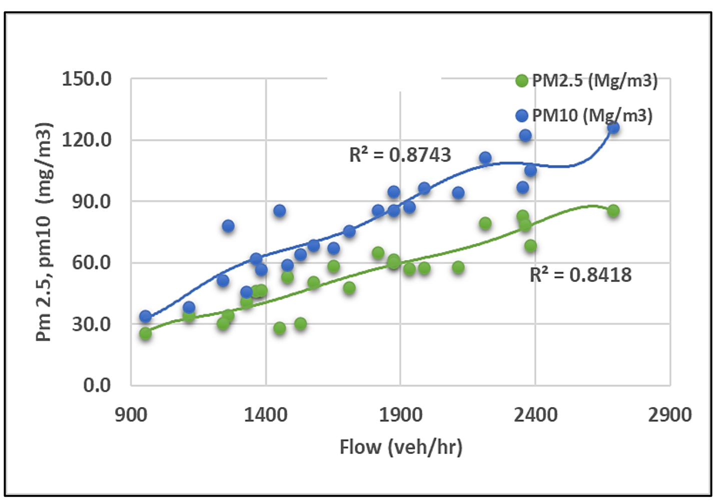

Figure (4.73): Relation of $PM_{2.5}$ and PM_{10} with flow on Saree Al-Moalemin Street.

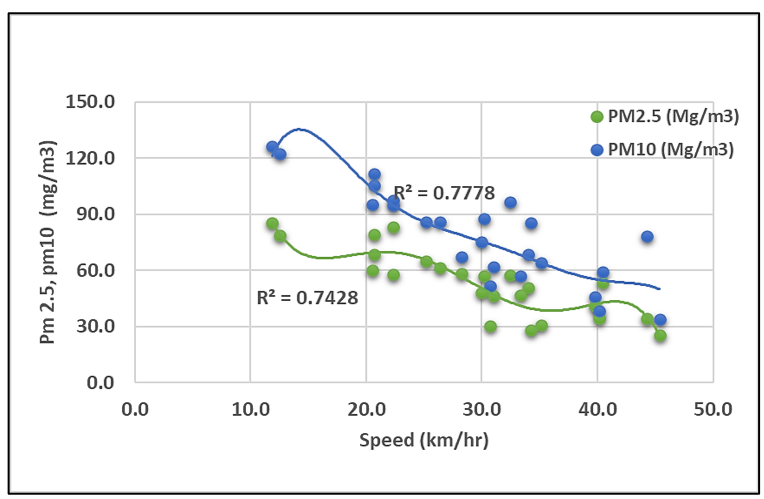

Figure (4.74): Relation of $PM_{2.5}$ and PM_{10} with speed on Saree Al-Moalemin Street.

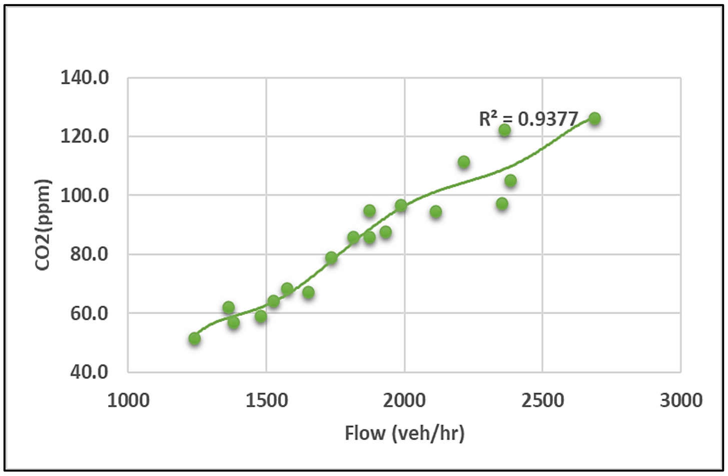

Figure (4.75): Relation of CO_2 with flow on Saree Al-Moalemin Street.

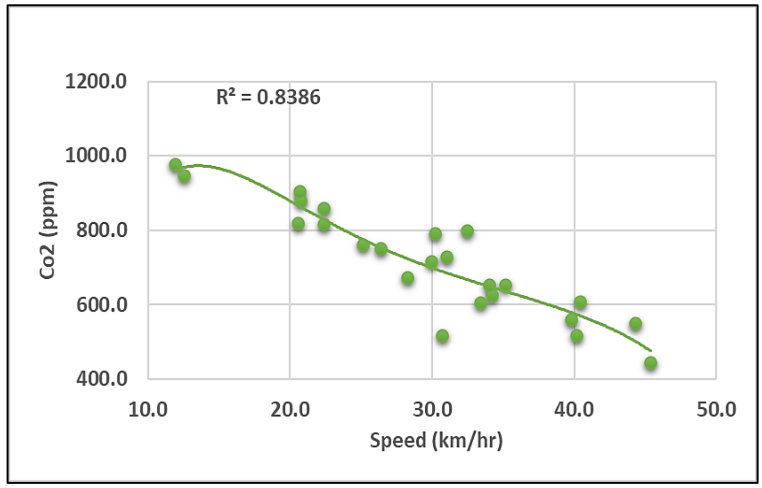

Figure (4.76): Relation of CO_2 with speed on Saree Al-Moalemin Street.

C) Al-Dharriba Street

The model results reveal that NO_2 and CO_2 exhibit the strongest correlations, with R^2 values of 0.950 and 0.917, respectively. This suggests that these gases are highly sensitive to traffic conditions, especially to volume increases. In contrast, CO and PM_{10} show moderately strong relationships, with R^2 values of 0.77-0.79, indicating some variability likely influenced by other environmental factors. Across all pollutants, traffic flow shows a significant impact of speed, as evidenced by higher exponents for flow and more minor (often negative) exponents for speed. This confirms that increased traffic flow is the dominant factor contributing to pollution buildup, while higher speeds may slightly reduce emissions due to improved engine efficiency and reduced idling. These equations are statistically significant and can be used in predictive modeling for future traffic scenarios or urban environmental assessments. Their form allows for dynamic estimation of emissions based on real-time or simulated flow-speed data. Table (4.10) represents the regression equations and R^2, while Figures (4.77 to 4.82) display the scatter plots. Tables (4.11 to 4.17) show the regression equations for other streets.

Table (4.10): Regression equations and R^2 for Al-Dhariba Street.

Pollutant	Regression Equation	R^2
CO	$0.00005 \times V^{(2.102)} \times S^{(-0.061)}$	0.7712
NO_2	$0.00003 \times V^{(2.816)} \times S^{(0.017)}$	0.9509
CO_2	$2.29509 \times V^{(0.777)} \times S^{(-0.038)}$	0.9176
$PM_{2.5}$	$0.00151 \times V^{(1.499)} \times S^{(-0.245)}$	0.8716
PM_{10}	$0.00016 \times V^{(1.828)} \times S^{(-0.134)}$	0.7980

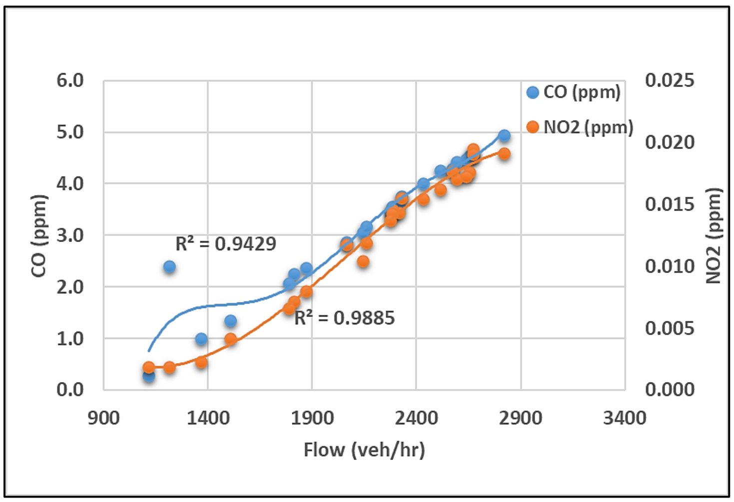

Figure (4.77): Relation of CO and NO_2 with flow on Al-Dhariba Street.

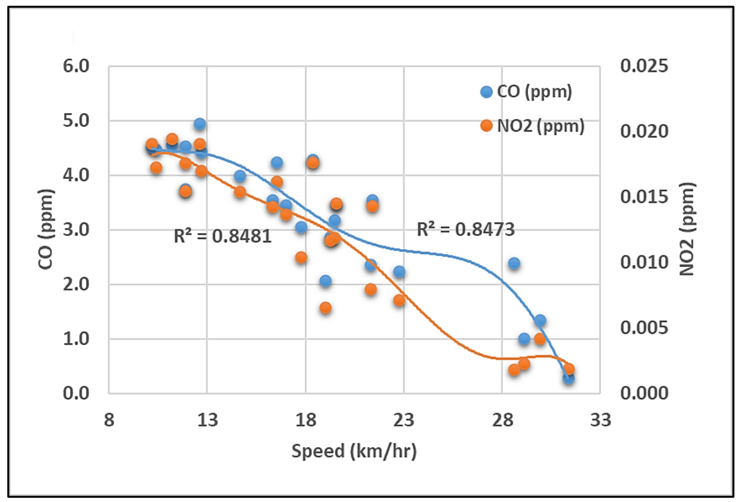

Figure (4.78): Relation of CO and NO_2 with speed on Al-Dhariba Street.

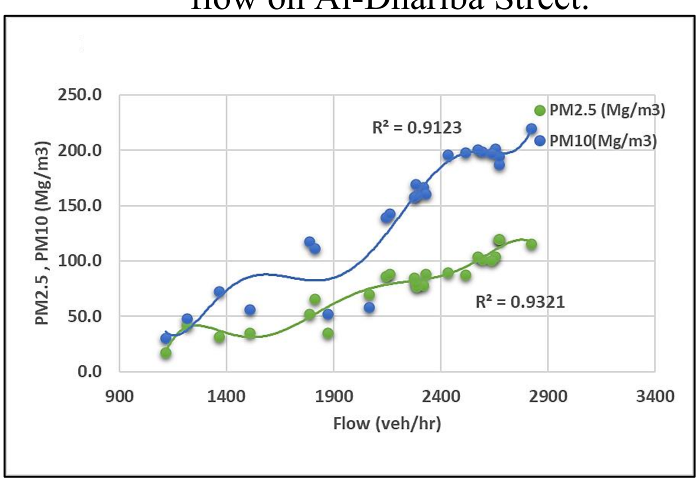

Figure (4.79): Relation of $PM_{2.5}$ and PM_{10} with flow on Al-Dhariba Street.

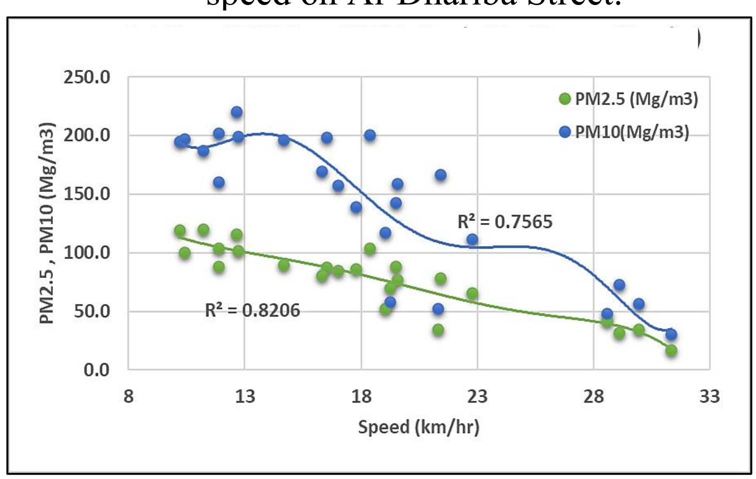

Figure (4.80): Relation of $PM_{2.5}$ and PM_{10} with speed on Al-Dhariba Street.

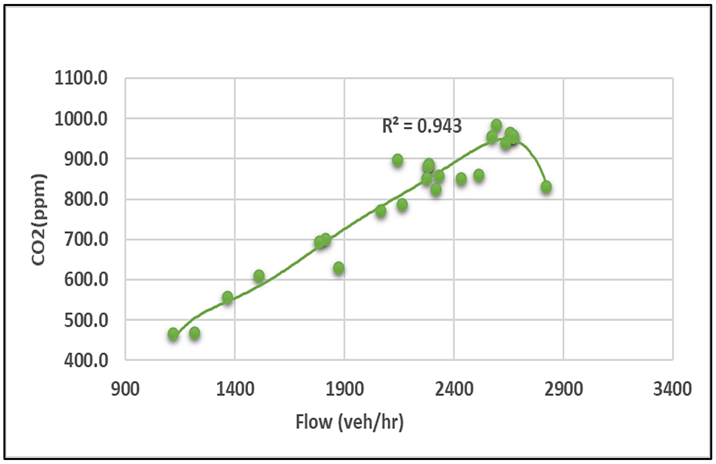

Figure (4.81): Relation of CO_2 with flow on Al-Dhariba Street.

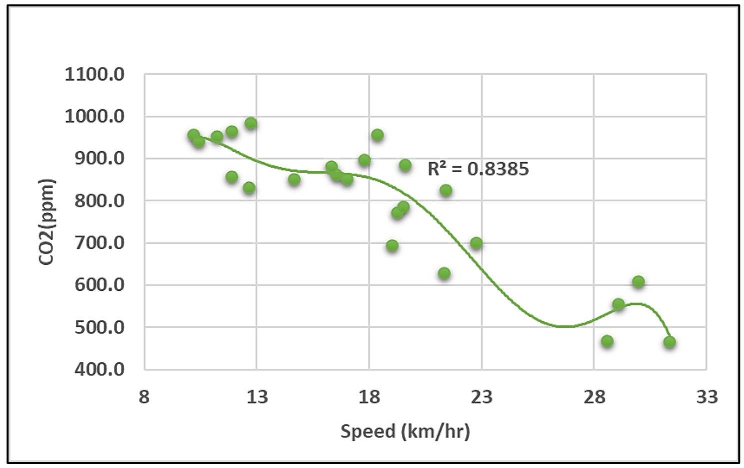

Figure (4.82): Relation of CO_2 with speed on Al-Dhariba Street.

Table (4.11): Regression equations and R^2 for Al-Tarbea Street.

Pollutant	Regression Equation	R^2
CO	$CO = 0.00004 \times V^{(1.553)} \times S^{(-0.017)}$	0.9171
NO_2	$NO_2 = 0.000006 \times V^{(3.256)} \times S^{(-0.333)}$	0.8648
CO_2	$CO_2 = 4.05038 \times V^{(0.722)} \times S^{(-0.107)}$	0.9048
$PM_{2.5}$	$PM_{2.5} = 0.00039 \times V^{(1.546)} \times S^{(-0.066)}$	0.7367
PM_{10}	$PM_{10} = 0.00339 \times V^{(1.296)} \times S^{(-0.021)}$	0.7663

Table (4.12): Regression equations and R^2 for Mostashfa Street.

Pollutant	Regression Equation	R^2
CO	$CO = 0.00004 \times V^{(1.587)} \times S^{(-0.043)}$	0.9560
NO_2	$NO_2 = 0.000006 \times V^{(4.407)} \times S^{(0.284)}$	0.8703
CO_2	$CO_2 = 58.97419 \times V^{(0.343)} \times S^{(-0.015)}$	0.8982
$PM_{2.5}$	$PM_{2.5} = 0.00005 \times V^{(2.211)} \times S^{(0.079)}$	0.8589
PM_{10}	$PM_{10} = 0.00009 \times V^{(1.780)} \times S^{(0.080)}$	0.8274

Table (4.13): Regression equations and R^2 for Al-Hur Street.

Pollutant	Regression Equation	R^2
CO	$CO = 0.01226 \times V^{(1.169)} \times S^{(-0.855)}$	0.8652
NO_2	$NO_2 = 0.00034 \times V^{(0.507)} \times S^{(0.012)}$	0.8943
CO_2	$CO_2 = 169.23984 \times V^{(0.195)} \times S^{(-0.040)}$	0.8987
$PM_{2.5}$	$PM_{2.5} = 0.09932 \times V^{(1.030)} \times S^{(-0.411)}$	0.8496
PM_{10}	$PM_{10} = 1.59675 \times V^{(0.606)} \times S^{(-0.204)}$	0.8795

Table (4.14): Regression equations and R^2 for Al-Mojammat Street.

Pollutant	Regression Equation	R^2
CO	$CO = 0.00003 \times V^{(2.174)} \times S^{(-1.226)}$	0.8929
NO_2	$NO_2 = 0.00026 \times V^{(0.594)} \times S^{(-0.072)}$	0.8975
CO_2	$CO_2 = 0.05819 \times V^{(1.173)} \times S^{(0.068)}$	0.9346
$PM_{2.5}$	$PM_{2.5} = 0.00072 \times V^{(1.663)} \times S^{(-0.697)}$	0.7792
PM_{10}	$PM_{10} = 0.00049 \times V^{(1.761)} \times S^{(-0.647)}$	0.8447

Table (4.15): Regression equations and R^2 for Hasan Al-Mujtaba Street.

Pollutant	Regression Equation	R^2
CO	$CO = 0.00006 \times V^{(2.299)} \times S^{(0.653)}$	0.9420
NO_2	$NO_2 = 0.00004 \times V^{(1.402)} \times S^{(0.327)}$	0.8007
CO_2	$CO_2 = 1.36548 \times V^{(0.765)} \times S^{(0.177)}$	0.8807
$PM_{2.5}$	$PM_{2.5} = 0.04422 \times V^{(1.051)} \times S^{(-0.210)}$	0.8642
PM_{10}	$PM_{10} = 3.69804 \times V^{(0.719)} \times S^{(-0.703)}$	0.7904

Table (4.16): Regression equations and R^2 for Maitham Al-Tammar2 Street.

Pollutant	Regression Equation	R^2
CO	$CO = 0.00033 \times V^{(1.324)} \times S^{(-0.086)}$	0.9504
NO_2	$NO_2 = 0.00008 \times V^{(3.238)} \times S^{(-0.200)}$	0.7952
CO_2	$CO_2 = 0.15178 \times V^{(1.143)} \times S^{(-0.048)}$	0.9602
$PM_{2.5}$	$PM_{2.5} = 0.01112 \times V^{(1.154)} \times S^{(-0.073)}$	0.9038
PM_{10}	$PM_{10} = 0.00793 \times V^{(1.123)} \times S^{(0.243)}$	0.7159

Table (4.17): Regression equations and R^2 for Sarie Ramadan Street.

Pollutant	Regression Equation	R^2
CO	$CO = 0.00008 \times V^{(1.424)} \times S^{(-0.099)}$	0.9819
NO_2	$NO_2 = 0.00003 \times V^{(5.768)} \times S^{(1.036)}$	0.7996
CO_2	$CO_2 = 2.03140 \times V^{(0.741)} \times S^{(0.015)}$	0.9458
$PM_{2.5}$	$PM_{2.5} = 0.00002 \times V^{(1.944)} \times S^{(0.340)}$	0.8256
PM_{10}	$PM_{10} = 0.00004 \times V^{(1.839)} \times S^{(0.043)}$	0.9285

The multivariate regression analysis conducted across multiple urban streets has demonstrated varying levels of association between traffic variables and pollutant concentrations. Among all pollutants studied, CO showed the strongest dependency on both traffic volume and speed. This high correlation reflects the pollutant's direct emission from vehicle exhaust, especially during acceleration and idling under congested conditions. NO_2 followed closely, with R^2 values generally falling between 0.92 and 0.98. Its emission pattern is strongly influenced by traffic flow and is typically exacerbated in low-speed scenarios, reflecting prolonged combustion phases and limited dispersion.

CO_2 also showed consistent and strong correlations, with R^2 values often in the range of 0.90 to 0.94. Its inverse relationship with speed suggests that stop-and-go traffic significantly contributes to its buildup, aligning with known inefficiencies in fuel combustion at low speeds. For $PM_{2.5}$ exhibited moderate to high association with traffic parameters, with R^2 values ranging from approximately 0.75 to 0.91. Its behavior was more variable across sites, indicating potential additional influences such as road surface conditions and atmospheric dispersion. PM_{10} showed the lowest overall R^2 values among the pollutants, typically ranging from 0.74 to 0.89. While still responsive to traffic volume, its correlation with speed was weaker and more inconsistent, likely due to contributions from non-exhaust sources such as road dust and mechanical abrasion. In summary, pollutants, especially CO and NO_2, are most strongly correlated with traffic activity and serve as reliable indicators of congestion-related air quality degradation. Particulate matter, though still influenced by traffic, appears more sensitive to localized environmental and infrastructural conditions, limiting its predictive consistency across all contexts.

4.7 Time Delay Analysis

As mentioned in Chapter three, the off-peak travel time computed from FFS, as well as the average travel time, has been obtained by the float method. Then the average travel delay is calculated by finding the difference between these two times. Figure (4.83) shows the value of the time delay for each street.

The analysis of average travel delays across the surveyed streets in Karbala reveals substantial variation in network performance, reflecting differences in traffic demand, roadway geometry, and operational conditions. The delays ranged from as low as 48 seconds on Al-Qebla Street to as high as 234 seconds on Maitham Al-Tammar 2 Street, indicating severe congestion. In contrast, streets like Al-Qebla Street (48 seconds), Al-Amel 2 Street (65 seconds), and Haidar Al-Karrar Street (70 seconds) experienced relatively low delays, implying smoother traffic flow and fewer interruptions. Such conditions could be due to lower traffic volume during peak hours.

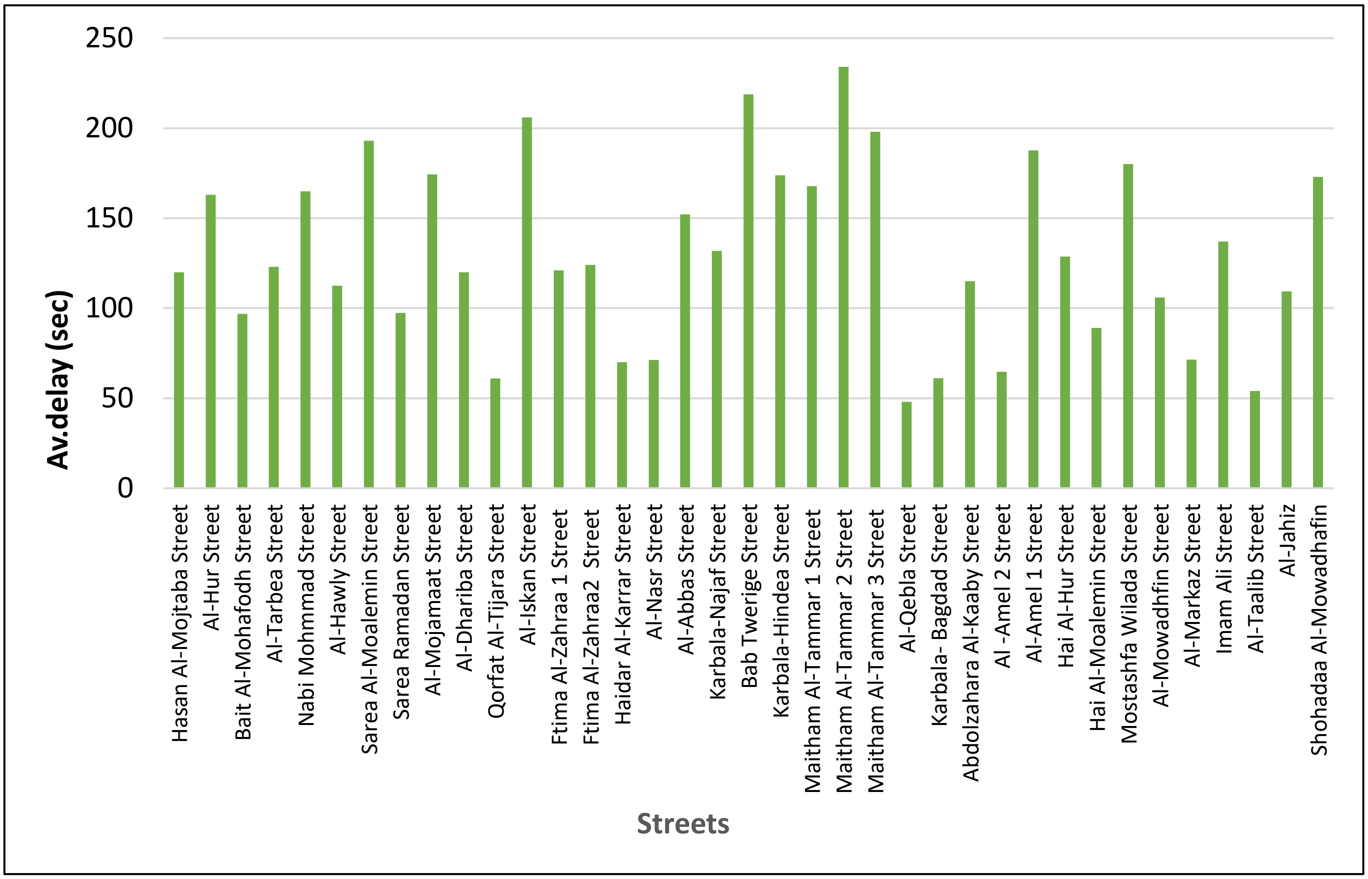

Figure (4.83): Delay time for each street.

4.8 Evaluating the Public Transport System

One of the leading causes of congestion problems in Karbala City is the absence of public transportation in the city. Private public vehicles such as minibuses, three-wheelers (MTRs), and shared taxis are used as a means of public transport in the city. Minibuses have a seating capacity of 11 passengers. Recently, the use of three-wheeler vehicles has spread widely, and their number has increased significantly, which has negatively affected congestion in the city. There is a small percentage of buses, but they are used to transport passengers to another country or another city and are not used for transportation in the town. For each street and each direction, Figure (4.84) represents the percentage of vehicle composition on the roads.

As shown in Figure 4.84, private cars have the highest percentage, at 42.7%, compared to buses and minibuses, which are significantly smaller, with percentages of 0.9 for buses and 10.7 for minibuses. It was also noticed that most of the buses are concentrated on the roads leading out of the city, such as Karbala-Najaf or Karbala-Baghdad, Haider Al-Karrar Street, and also the roads leading to the holy shrines, such as Bait Al-Mohafodh Street, Al-Dhariba, or Nabi Mohammad Street, etc. The highest percentage of buses was 2.81% at Haider Al-Karrar Street. For minibuses, the rate ranged from a minimum of 4.16 percent to a maximum of 18.3 percent, with an average equal to 10.4 percent. The second highest percentage was for MTR with an average of 17.4 percent, followed by motors and taxis with a rate of 11.4 and 10.4, respectively. Figures (4.85 to 4.90) show the ranges of vehicle types.

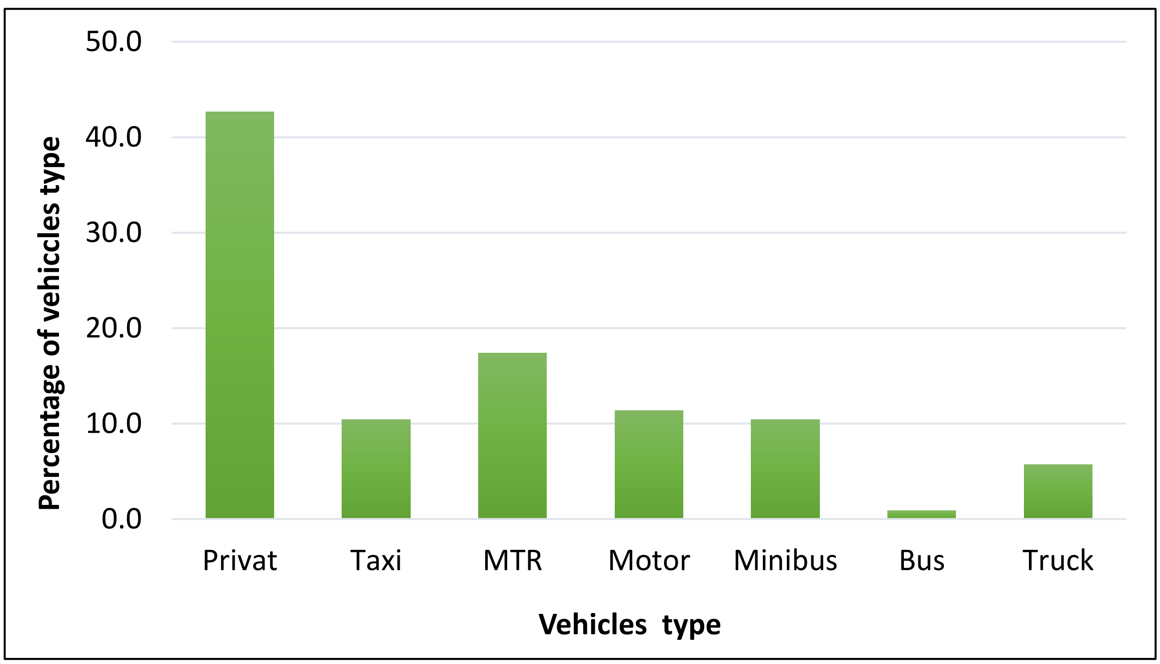

Figure (4.84): Percentage of vehicles type.

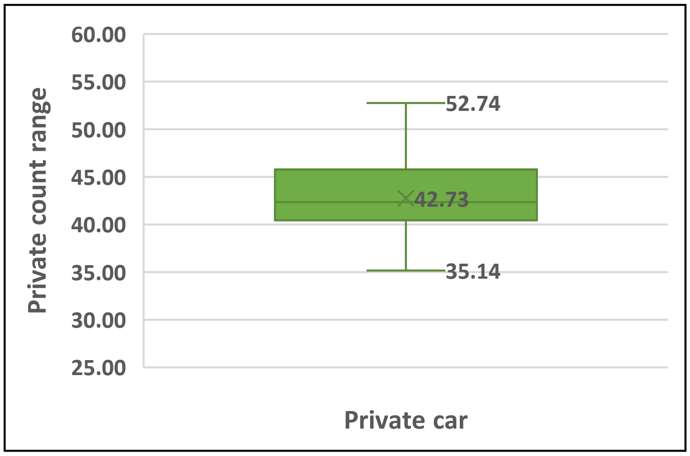

Figure (4.85): Private car ranges.

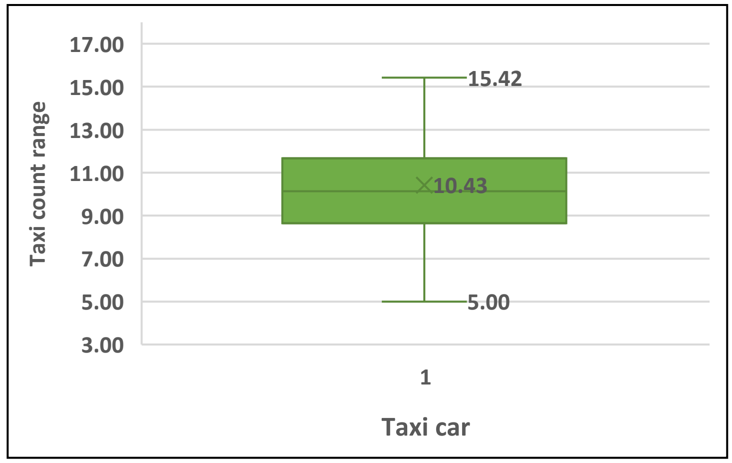

Figure (4.86): Taxi ranges.

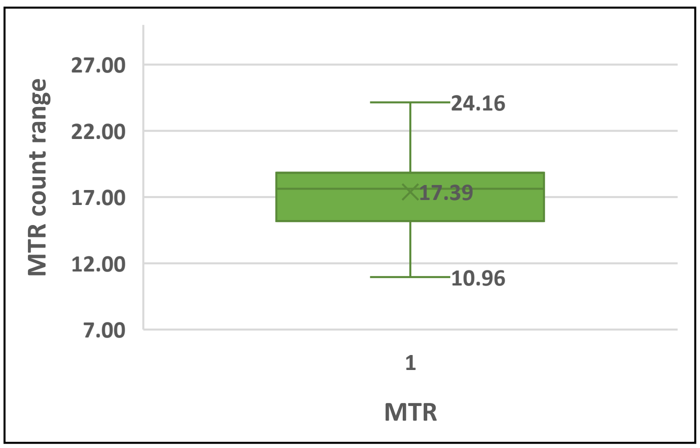

Figure (4.87): MTR ranges.

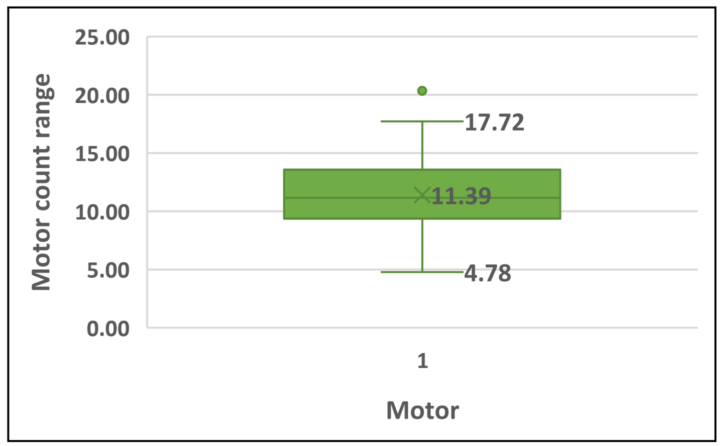

Figure (4.88): Motor ranges.

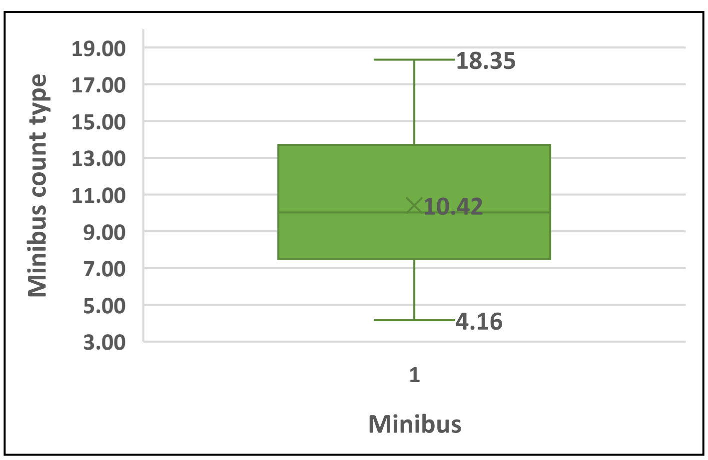

Figure (4.89): Minibus ranges.

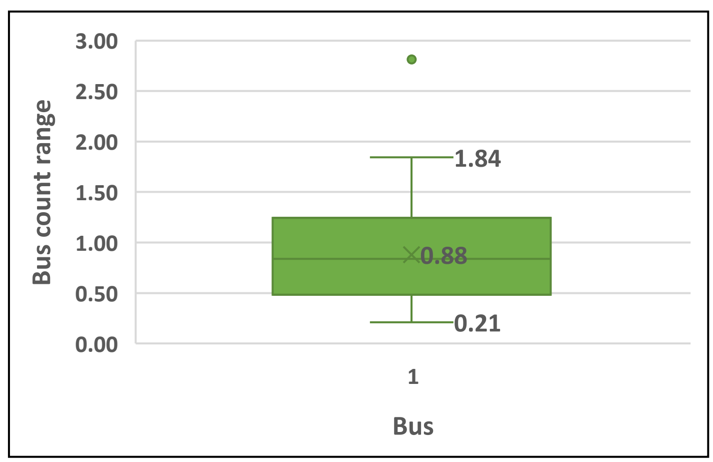

Figure (4.90): Bus ranges.

Chapter Five

Proposed Tram Networks

5.1 Introduction

This chapter discusses the main steps involved in selecting the optimal locations for a tram network based on predefined criteria. All criteria-related data have been used as a layer in the ArcGIS 10.8 application. Three separate models were created, for tram routes, intermediate stations, and end stations. Finally, the proposed routes were ranked based on the evaluation process using the CRITIC and EDAS methods.

5.2 Routes and Stations Site Selection Process

Choosing the best location for the routes and stations depends on several criteria as mentioned in Chapter Three. After criteria decoding, the data was gathered depending on these criteria, which are represented in GIS as the layers map. The layers are analyzed to find the best stations. The process of finding the best tram network location is divided into three steps and models. The first step involved determining the best locations for end stations, the second step entailed locating the best routes, and the third step involved finding the intermediate stations. Figures (5.1 to 5.8) represent all data layers needed to build a GIS model. The layers are land use, vital places, transportation networks, population, streets LOS, delay time, AQI, and noise level.

Figure (5.1) shows the distribution of land use types, such as residential, commercial, industrial, and governmental institutions. It forms the base for identifying demand and trip generation areas. For example, residential zones generate trips, while commercial and institutional zones attract them. This helps prioritize tram stations near high-demand zones, as well as select suitable areas for station placement, and avoid locations that are less appropriate for tram service.

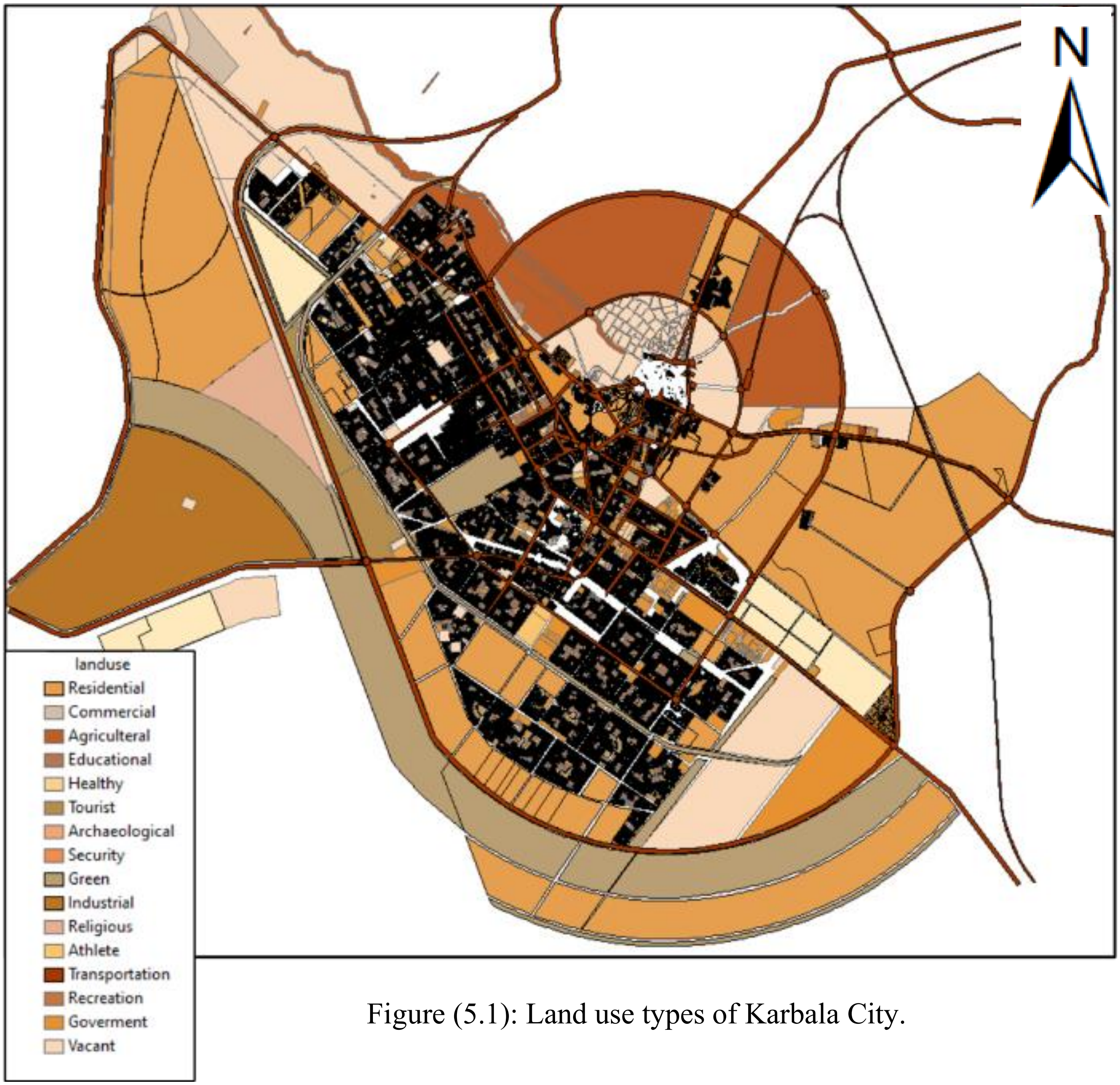

Figure (5.1): Land use types of Karbala City.

Figure (5.2) illustrates vital places layer which represents the essential facilities and landmarks, ensuring that tram lines serve high-demand public destinations (e.g., holy shrines, major hospitals, educational institutions, etc.) and that station locations are strategically situated near these key service areas.

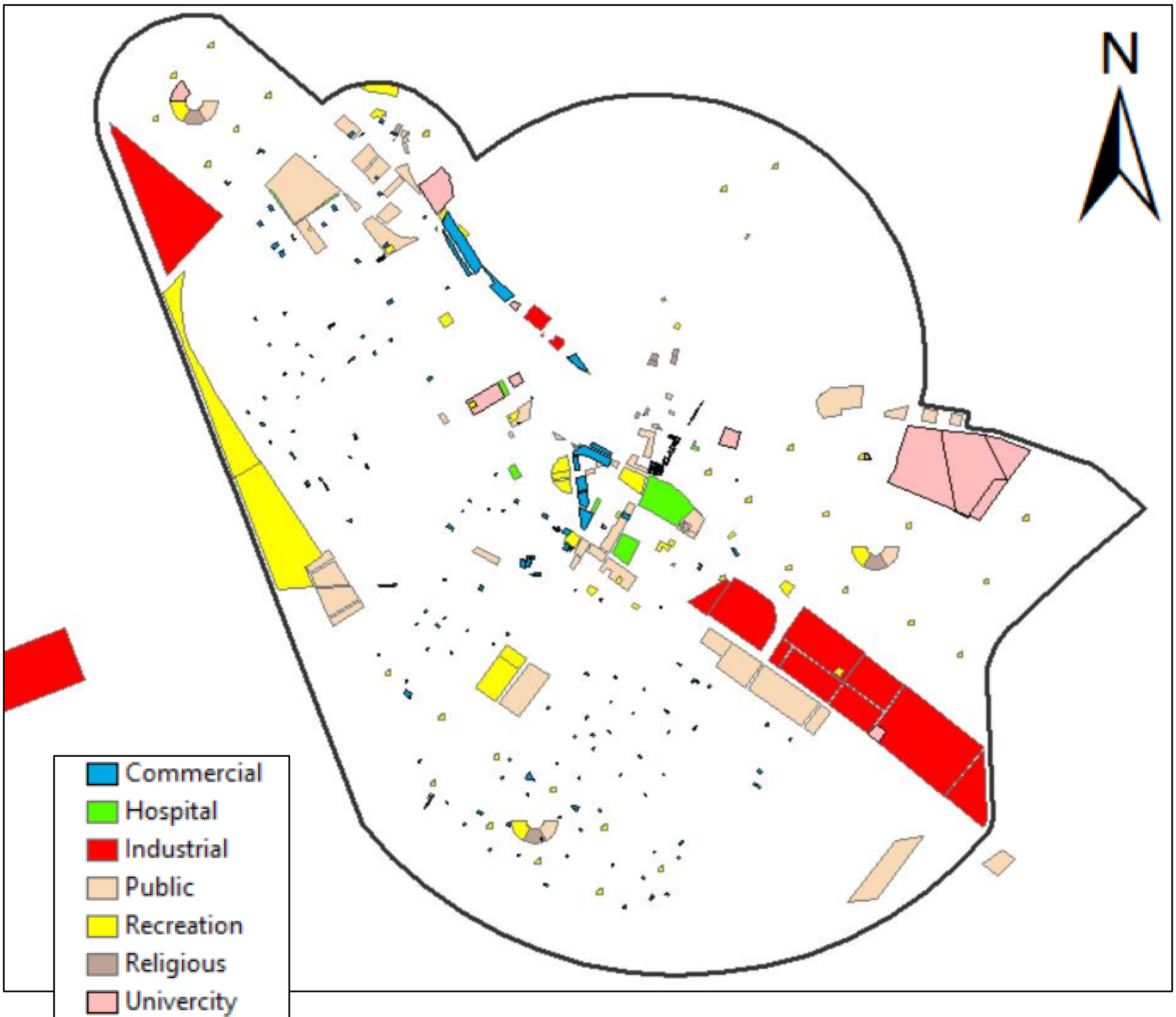

Figure (5.2): Vital places of Karbala City.

Figure (5.3) shows the primary arterial roads, main intersections, terminals, car parking, and connections to city gateways.

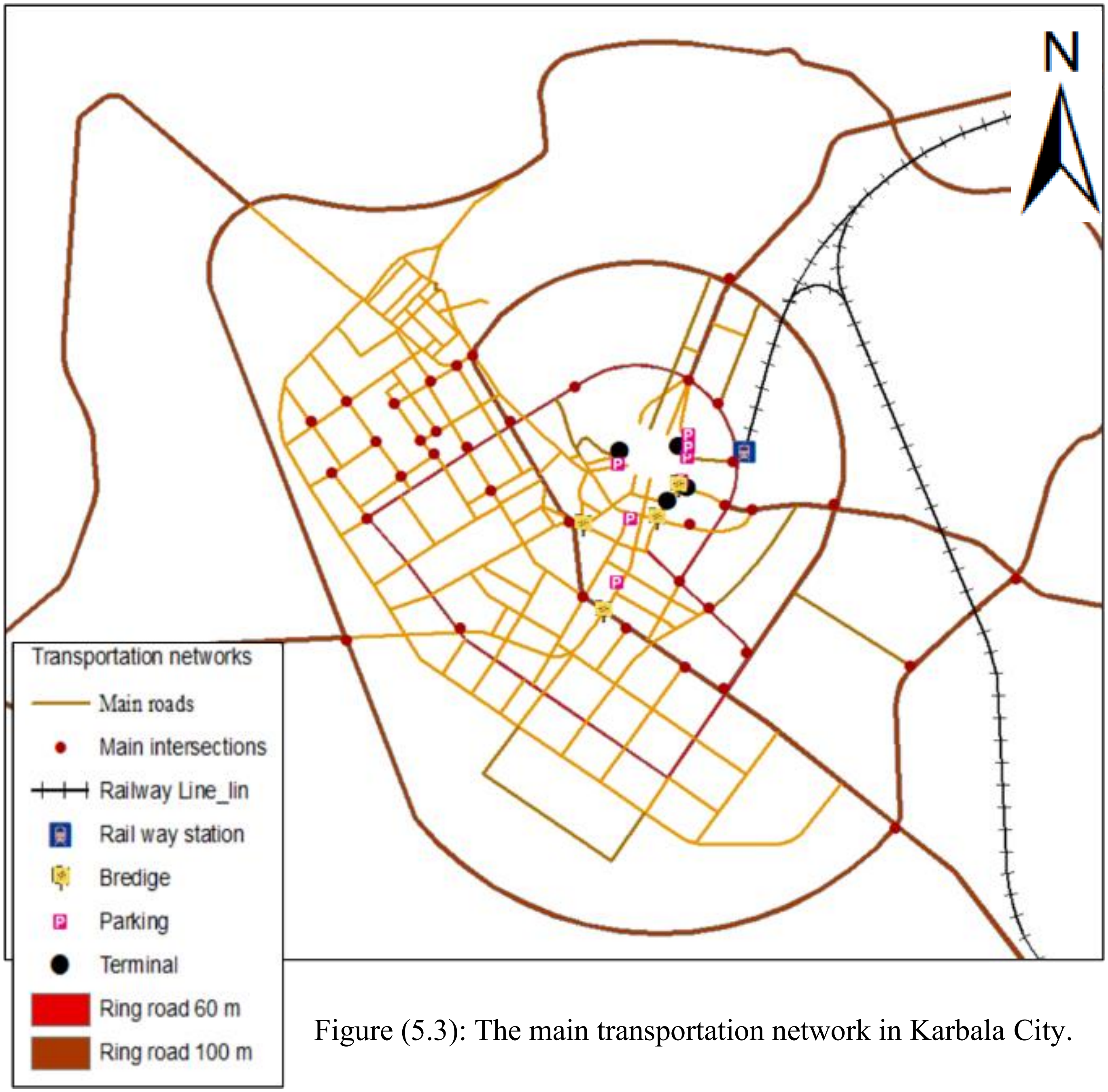

Figure (5.3): The main transportation network in Karbala City.

Figure (5.4) displays population layer across neighborhoods. This layer identifies areas with high trip generation potential. Tram lines should pass through or near high residential zones to maximize user benefit.

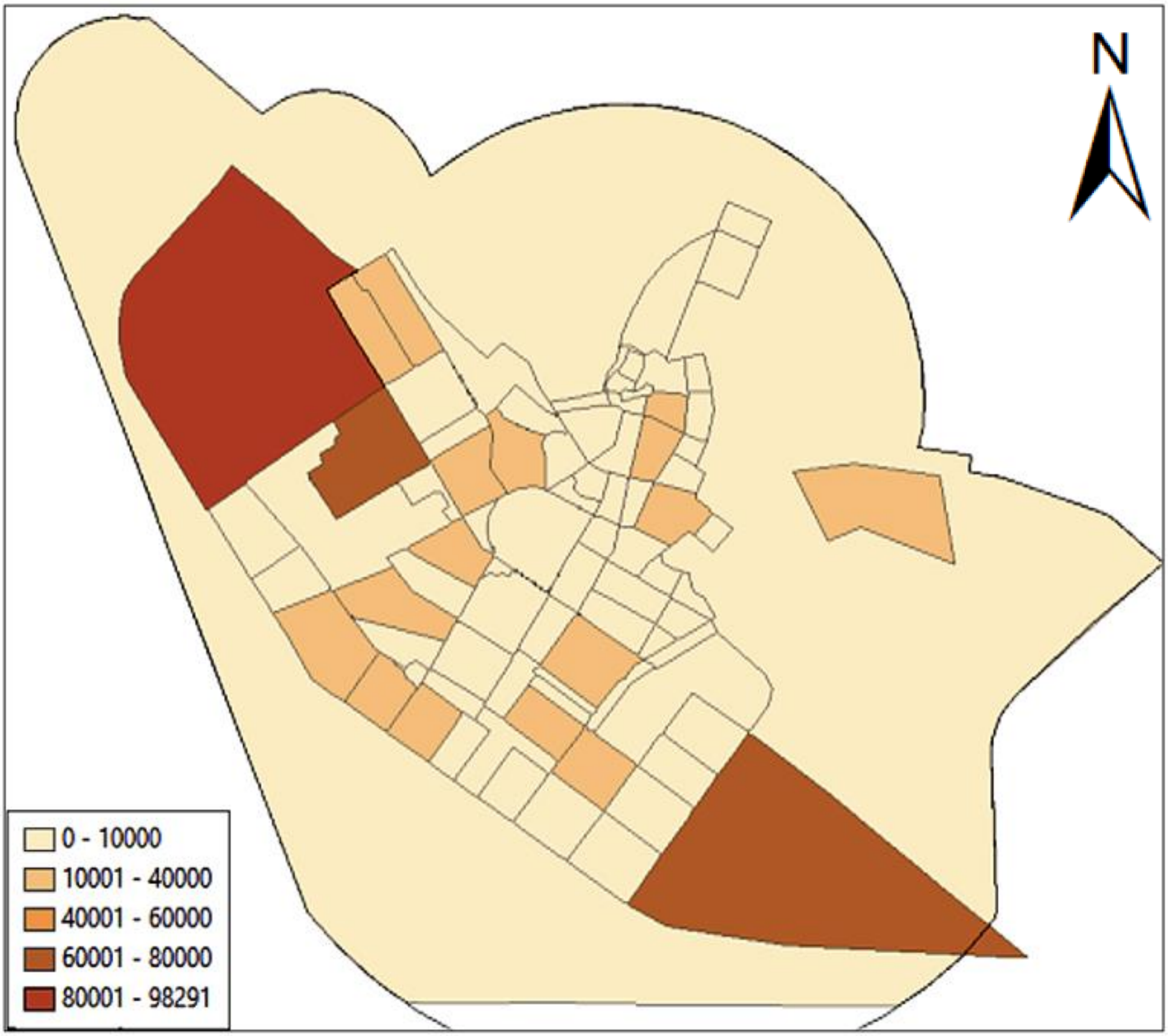

Figure (5.4): Karbala City's population layers.

LOS measures operational performance, graded from A (excellent) to F (severely congested) as indicated in Figure (5.5). This figure highlights congested areas that would benefit from a tram service as an alternative to private vehicle use.

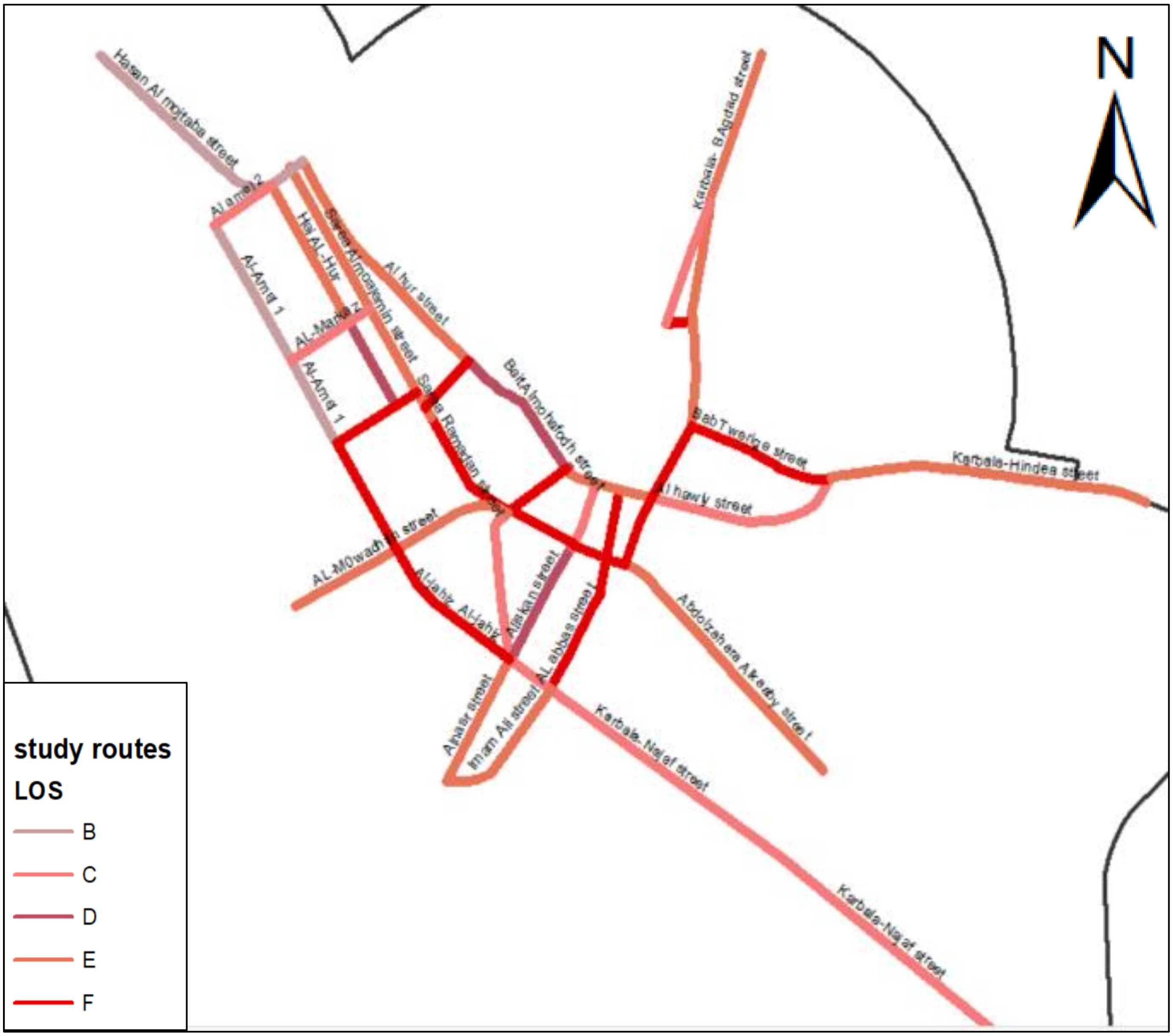

Figure (5.5): LOS map for streets.

Figure (5.6) illustrates the spatial distribution of AQI levels along the routes studied in Karbala City. The routes have been classified into two categories of air quality, ranging from acceptable to highly polluted conditions. Areas with poorer classifications are predominantly concentrated along major corridors with high traffic volumes.

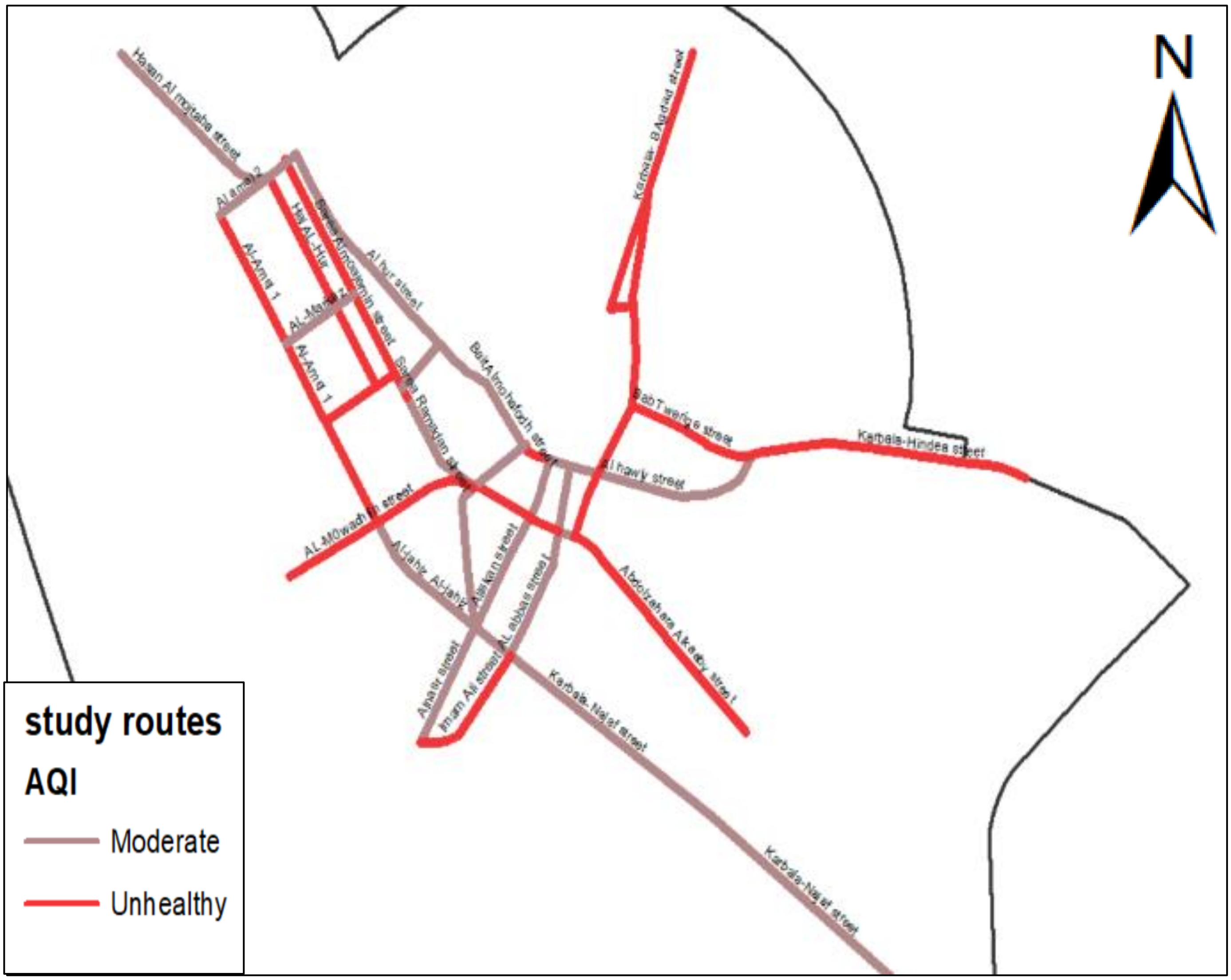

Figure (5.6): AQI map for streets.

Figure (5.7) shows the spatial distribution of travel delay times along the routes studied in Karbala City. The delays have been classified into four categories: 42–60 seconds, 61–120 seconds, 121–180 seconds, and 181–234 seconds per trip segment.

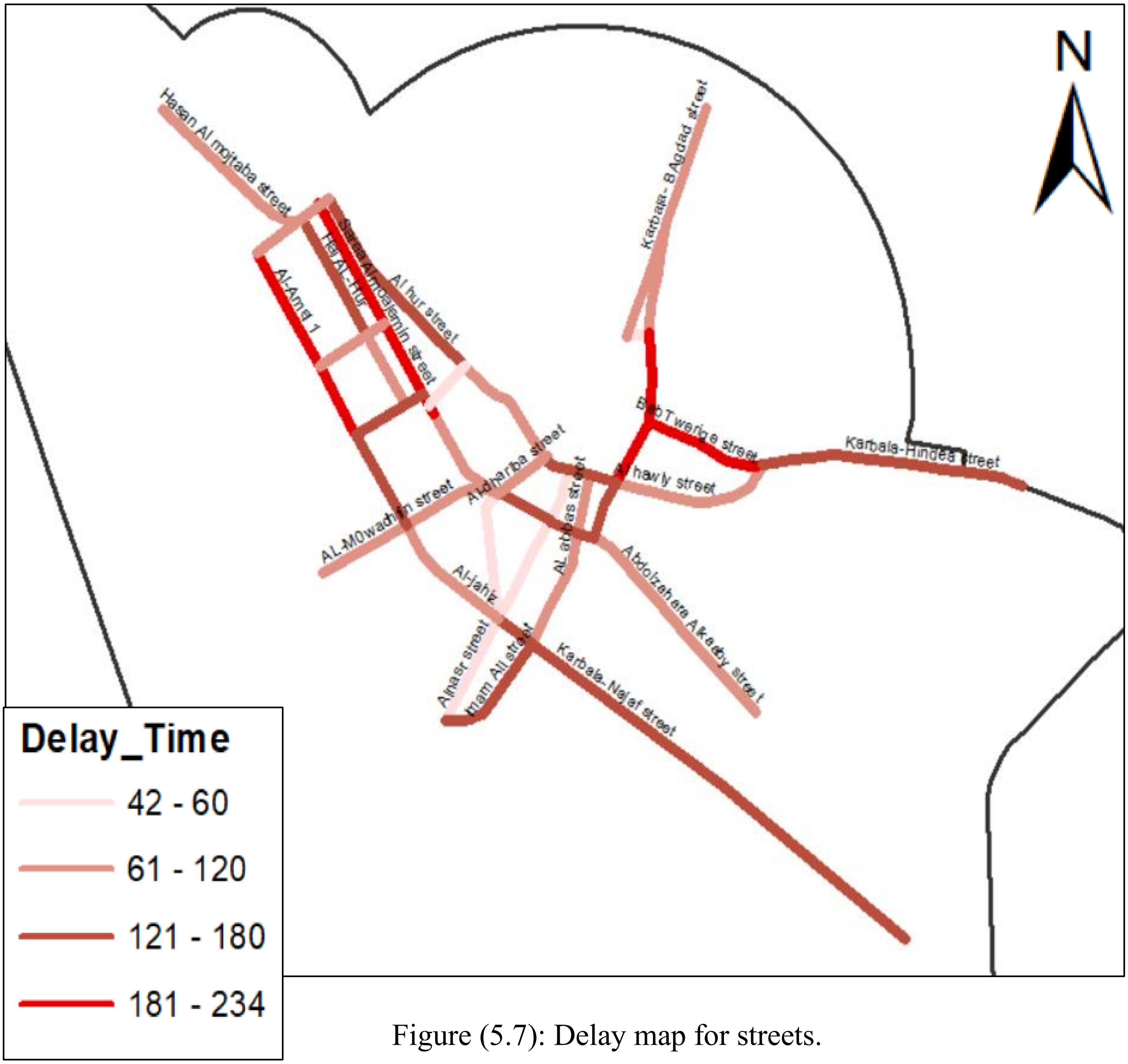

Figure (5.7): Delay map for streets.

Figure (5.8) displays the spatial distribution of noise levels along the study routes in Karbala City. Noise levels have been classified into three categories: 74–80 dB,81–85 dB, and 86–91dB. Trams, being quiet and electric, help reduce noise levels in affected zones. Hence, these areas are good candidates for tram line development.

Figure (5.8): Noise level map for streets.

5.3 Tram End Station's Locations

5.3.1 End Stations Limitations

1. The end station should be located on suitable land. Land uses such as natural reserves, built-up areas, water bodies, agricultural zones, and existing industrial sites should be avoided as much as possible. The land should be government-owned. Additionally, free-zone or unoccupied land is recommended. The area must be sufficiently large to accommodate train parking and maintenance facilities.
2. The end stations should be located at the main entrances to the city from the north and south parts (Baghdad-Karbala, Najaf-Karbala), as well as in the east (Hindiya-Karbala) and west part covering the city by the tram line.

5.3.2 GIS Model Builder to Create Alternatives

After clarifying the criteria and data necessary to assign locations of end stations which were the land use data, this data is entered in the form of the layers within the GIS and is processed by converting it into a raster layer, then using the weighted overlay tool to assign a weight for each sub criteria from 10, where the critical sub criterion was taken the number ten or nine and the less important criterion took a lower value, and so on. Because these stations were the end stations, they needed a large area. The high weights have been assigned to vacant areas, main streets, and intersections, whereas the low weights have been allocated to vital places. The output layer was the layer that represents suitable locations based on its values. The assigned weights were obtained through a survey conducted among experts in the fields of transportation and traffic engineering, ensuring that the results reflect practical and field-based insights.

The values (1-5) represent the poor area, the values (5-7) show moderate locations, and the values (7-10) represent the more suitable locations. Figure (5.9) shows the model builder, Table (5.1) shows the weighting process in GIS, and Figure (5.10) shows the resulting layer.

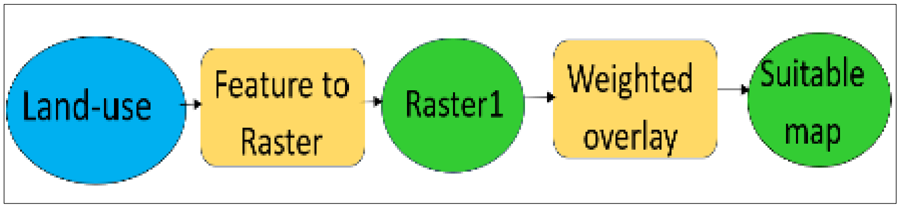

Fig. (5.9): End stations model builder.

Table (5.1): Weighting criteria in GIS program.

Layer	%Influence	Field	Scale value
Land use	%100	Commercial	3
		Industrial	5
		Religious	1
		Cemetery	7
		Green	7
		Recreation	8
		University	1
		School	1
		Public	1
		Hospital	1
		Healthy center	1
		Free zone	10
		Residential	7
		Ring road 60	10
		Ring road 100	10
		Railroad	1
		Intersections	9
		Parking	8
		Terminal	1
		Rail stations	1
		Main roads	10
		Secondary roads	8

Figure (5.10) illustrates the suitable areas proposed for establishing tram end stations within the urban area. The sites are classified into three categories: low suitability (Poor), moderate suitability (Moderate), and high suitability (More suitable). The most suitable zones reflect greater availability of space and better connectivity with major transportation corridors, whereas the less suitable zones should be avoided when selecting end station locations.

Fig. (5.10): Resulted in a suitable layer from end stations model.

5.4. Tram Routes Site Selection

5.4.1. Identify the Main Criteria

Based on previous studies and the nature of case studies, the main objectives and related criteria for determining optimal tram route's locations for Karbala City included:

Objectives: accessibility, traffic demand, and environmental.

Criteria: delay time, land use, traffic flow in terms of LOS, traffic pollution in terms of AQI, and traffic noise.

These criteria were chosen to make the tram system more efficient to meet the transportation needs, reducing the congestion, the resulting delay, environmental pollution, and noise pollution, in addition to accommodating the most significant number of passengers by placing the network within the areas generating trips such as residential areas and attracting trips such as commercial and educational areas, etc. Engineering, geotechnical, and cost-related criteria were excluded due to the characteristics of the study area. The topography of Karbala is generally flat, with no significant elevation changes that would require additional leveling work or increased construction costs. According to Karbala Directorate of wells and Groundwater, the groundwater is located at a shallow depth, approximately 7 meters below the surface, which does not pose a significant constraint. In terms of soil composition, the reports of soil investigation of Kerbala university illustrated that most of Karbala consists of sandy soil, except a small portion in the eastern area that contains clayey soil. Therefore, detailed cost analyses for construction and maintenance materials were deemed unnecessary. Additionally, the presence of median islands and sufficiently wide sidewalks allow for the potential installation of tram tracks and stations without major infrastructure modifications.

5.4.2 Criteria Weights

Since the criteria variables in each option have varying priorities based on the aims and objectives, a precise weight must be assigned to each of them. Specific weight must be given to each of the criteria components in each alternative since their priorities vary based on the goals and objectives. An effective way to determine weights is to compare each factor to its corresponding factor using the AHP approach, which is better than providing an absolute score with no comparison (Wahdan et al., 2019). The AHP assessment was developed in three phases. To compare the matrices, a matrix must be created first. A panel of 12 experts in the field of transportation and traffic engineering filled out a questionnaire based on the Saaty scale, which was used to assess the relative importance of the chosen criteria. The second step is to normalize the advanced pairing matrix from the previous comparisons; the eigenvectors of the comparison matrix are then determined using factor weight calculation.

5.4.3 Steps in the AHP Method

The weighting method can be calculated as follows: First, the factors are compared to each other; then, the weight of each attribute factor. This factor is the primary eigenvector of the resulting matrices obtained by multiplying the pairwise matrix itself. Following that, each row sum will be calculated and normalized by the sum of all rows, yielding the real factor weight for each attribute, and then each column is summed:

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$$

Then each cell was divided by the sum of the column.

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix}$$

$$X\ ij = \frac{C\ ij}{\sum_{i=1}^{n} C\ ij} \ldots\ldots\ldots\ldots\ldots (5.1).$$

Before applying the weights, the consistency of the decision maker's preferences must be examined. The evaluation matrix's eigenvector is calculated by multiplying the weights of each layer by the initial decision matrix, adding up the outcomes around the rows, and then dividing the sum of each row by the weight of the associated layer.

$$C.W= \begin{bmatrix} C11 & C12 & C13 \\ C21 & C22 & C23 \\ C31 & C32 & C33 \end{bmatrix} \begin{bmatrix} W11 \\ W21 \\ W31 \end{bmatrix} = \begin{bmatrix} Cv11 \\ Cv21 \\ Cv31 \end{bmatrix} \ldots\ldots\ldots\ldots (5.2)$$

where W is the criteria weight, and

$$Cv11 = \frac{C11W11 \quad + C12W21 + \quad C13W31}{W11}$$

$$Cv21 = \frac{C21W11 \quad + C22W21 + \quad C23W31}{W21} \qquad \ldots\ldots\ldots (5.3).$$

$$Cv31 = \frac{C31W11 \quad + C32W21 + \quad C33W31}{W31}$$

The consistency index (CI) is calculated by subtracting the number of criteria (n) and dividing the result by (n-1). The Consistency Ratio (CR) is calculated by dividing the Consistency Index (CI) by the Random Index (RI). The CR is less than 0.10. Table (5.2) shows the Random Index (RI) values.

$$\lambda = \frac{\sum_{i=1}^{n} C\ ij}{n} \ldots\ldots\ldots\ldots\ldots\ldots (5.4).$$

$$CI = \frac{\lambda - n}{n-1} \ldots\ldots\ldots\ldots\ldots\ldots (5.5).$$

Table (5.2): Random Index (RI) values depending on the number of the criteria (Sayl et al., 2020).

No. of criteria	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

CR= $\frac{CI}{RI}$……………… (5.6).

Five major criteria under the goal (choosing the most suitable tram routes) are adapted from the hierarchy created for this study. For each of these five groups, pair comparison matrices were produced. The produced pairwise comparison matrix is given in Table (5.3). The weight of each parameter is then determined using the AHP approach.

Table (5.3): Pairwise comparison matrix.

Criteria	LOS	Land use	Delay time	AQI	Traffic noise	Weight %
Traffic flow	1.00	2.00	3.00	4.00	4.00	37.83
Land use	1/2	1.00	3.00	4.00	5.00	29.43
Travel time	1/3	1/3	1.00	4.00	5.00	19.11
Traffic emission	1/4	1/4	1/4	1.00	2.00	7.97
Traffic noise	1/4	1/5	1/5	1/2	1.00	5.65
Sum						100%

So:

λ= 4.78

CI = 0.055

RI= 1.12 CR= 0.049 < 0.1 ok.

5.4.4 GIS Model Builder to Create Alternative Routes

5.4.4.1 Weighted Overlay Model

After clarifying the criteria weights and the related data necessary to assign locations of routes, then this data is entered in the form of the layers within the GIS and is processed by converting it into a raster layer. Using the weighted overlay tool to assign and enter the weights of each criterion and sub criteria from 10, where the critical sub criterion was taken the number ten or nine and the less important criterion took a lower value, and so on. The resulting layer from the weighted overlay model represents the cost surface.

5.4.4.2 Least Cost Path Analysis

This step involved a least cost path analysis to identify the most cost-effective routes that meet the city's and population's transportation needs in both the current and future scenarios. Before the analysis runs, the origins and destinations stations must be chosen from a set of the best stations that were selected in the stations site selection process. After that, a cost distance tool is employed to compute the least cumulative cost distance for each pixel from the origin to the destination. The cost layer (output layer from weighting the criteria) and origin point have been linked to this tool, then the output of the cost distance and destination point has been linked to the cost path tool, which calculates the least cost path from the origin to destination. Figure (5.11) shows the weighted overlay model, and Figure (5.12) shows the least cost path model.

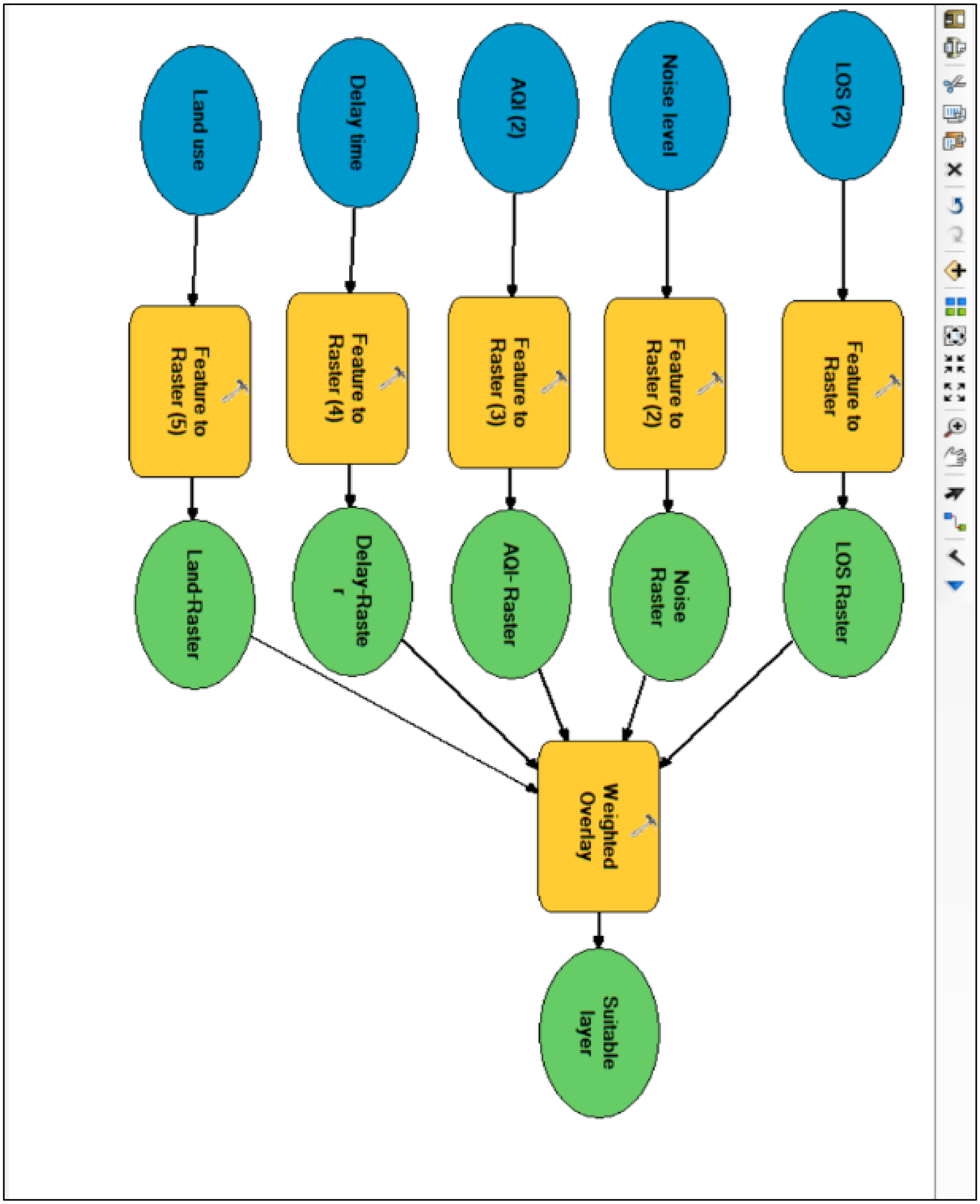

Figure (5.11): Weighted overlay model.

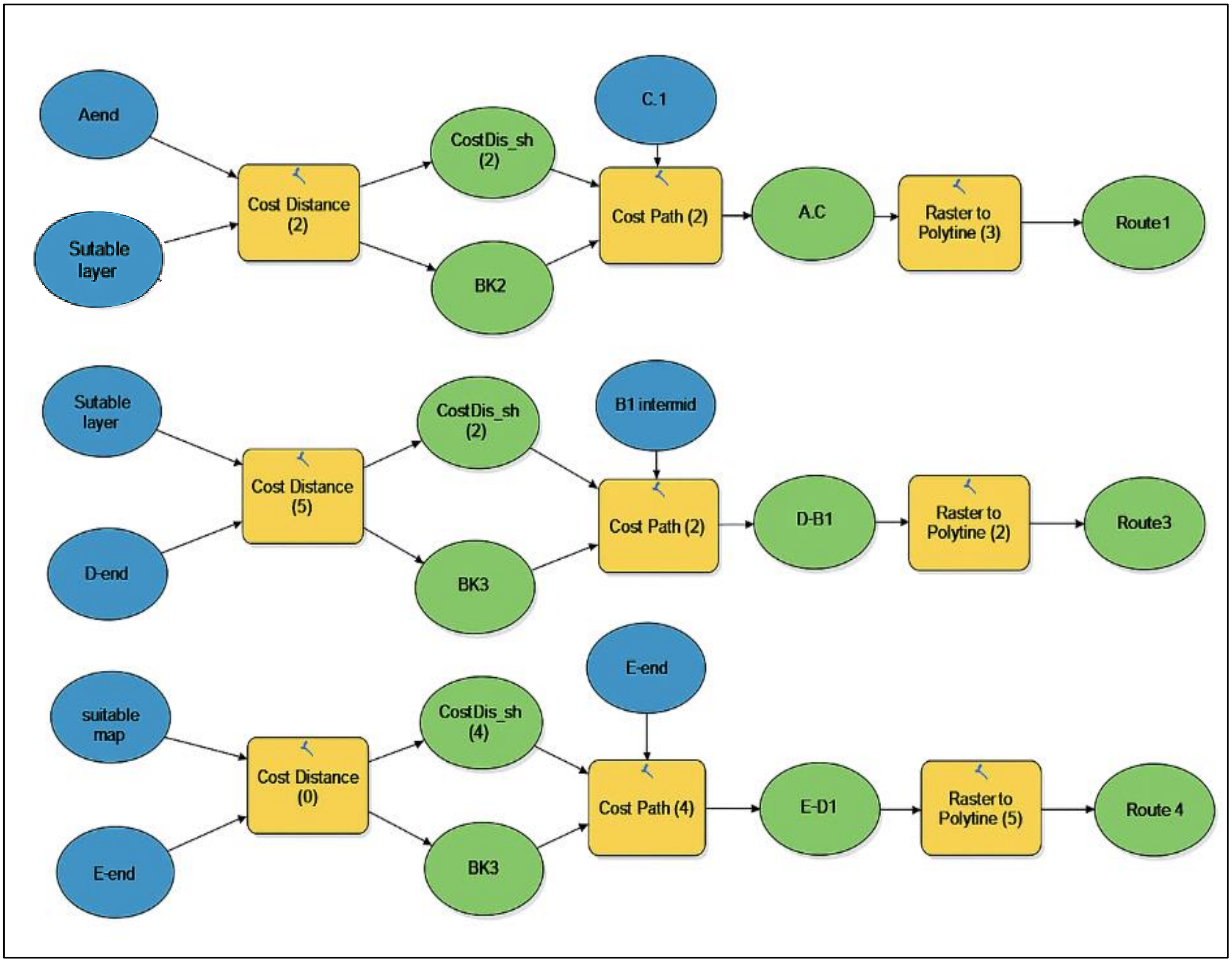

Figure (5.12): Least cost path model.

5.5 Intermediate Station's Locations

5.5.1. Intermediate Stations Limitations

1- Stop stations should be near trip generation zones, such as residential areas, and trip attraction zones, which are defined as vital places such as commercial, educational, health, public, recreation areas, and so on.

2- For high accessibility, the walking distance from vital places is preferred to be less than 300 m.

3- The stations' spaces should be not less than 300 m and no more than 1000 m.
4- The stations should be near the highly populated region to ensure the most significant number of passengers.

The primary data needed for stop stations were vital places, land use, and population layer. The following section outlines the process for selecting station locations.

5.5.2 GIS Model Builder for Intermediate Station

5.5.2.1 Walking Distance Buffers

As described in the preceding section, to ensure the highest accessibility to the stations, they must be close to the trip attraction zone, and the walking distance for the passengers to these places should be reduced. Therefore, buffers representing the walking distances to vital places were created around these areas, categorized into three distances: up to 150 meters, up to 300 meters, and up to 500 meters. A high weight was given to the areas of 150 and 300 meters. Figure (5.13) shows the buffers around vital places.

5.5.2.2 Processing of Layers

tool of features to raster was used. All layers (the land use, population, and buffer layers) were transformed into a raster layer with 20 cell sizes after the primary data have been gathered, represented as map layers, and created as a buffer layer. Following that, five classes were added to the population raster values, and each class took a new value. The class (0-10000) took a value of (1), the class (10000-40000) took a value of (2), and so on.

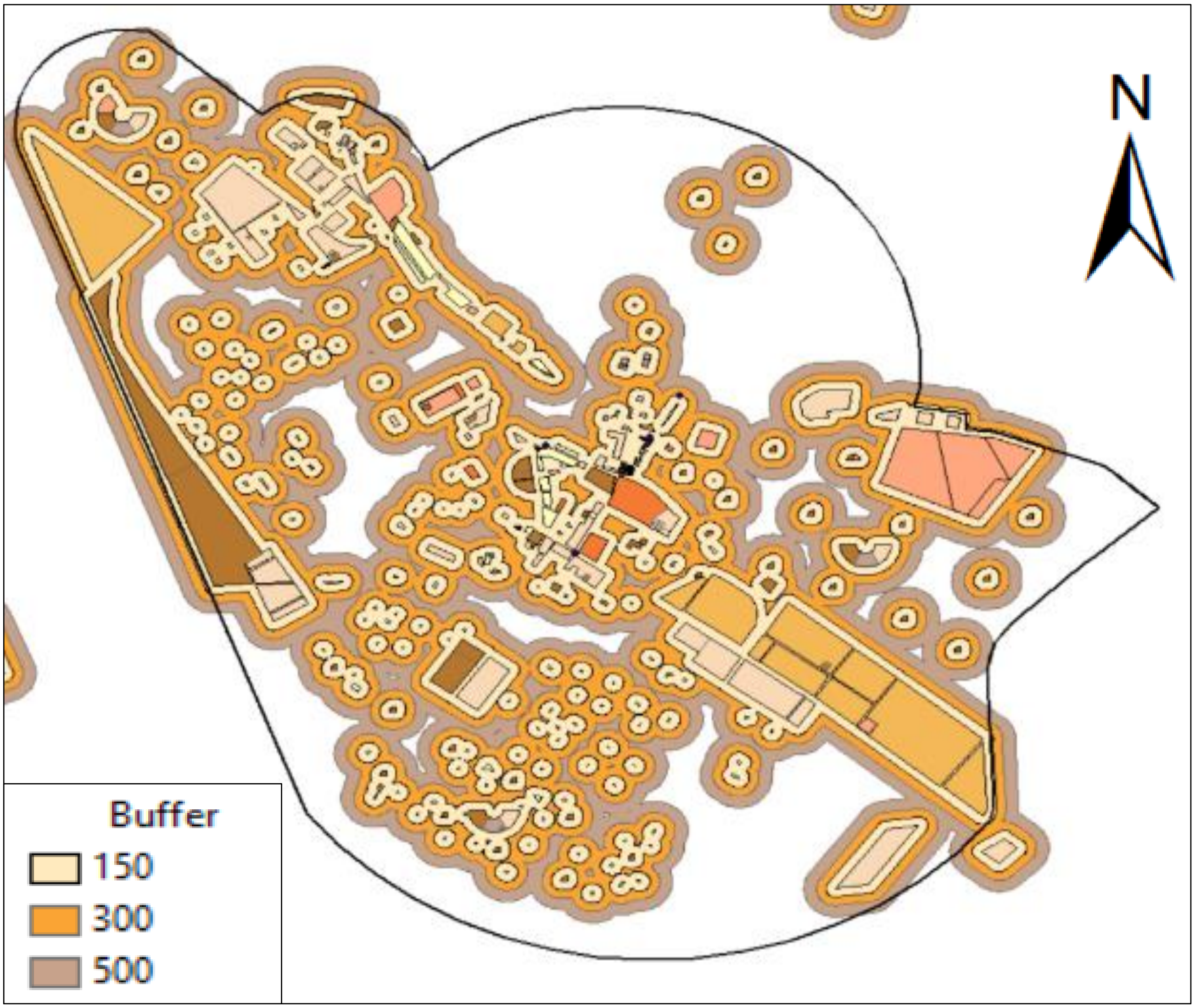

Figure (5.13): Buffer layer around vital places.

5.5.2.3 Weighting Process

After the weights of the criteria have been derived from the AHP method, which were %56 for walking distance, %32 for land user, and %12 for population, then these weights were entered into GIS within the weighted overlay tool from %100. A weight from 10 was given to the sub criteria according to their importance. To choose the best location for the intermediate stations, a high weight is given to areas that attract trips, main roads, intersections, and areas with high population density, so that essential locations are supplied with transportation. Table (5.4) shows the weighting process in the GIS program. Figure (5.14) represents the model builder for finding the stop stations.

The result of the best locations model was a suitable layer, which had values from 1 to 10. The values, which ranged from 1 to 5, represent the poor suitable locations, the lands with values from 5 to 7 were reclassified as moderate suitable lands, and the lands with values of 7-10 represented the most suitable lands, which preferred locating the stations as shown in Figure (5.15). The stop stations are strategically located on suitable lands, near intersections whenever possible, on main streets.

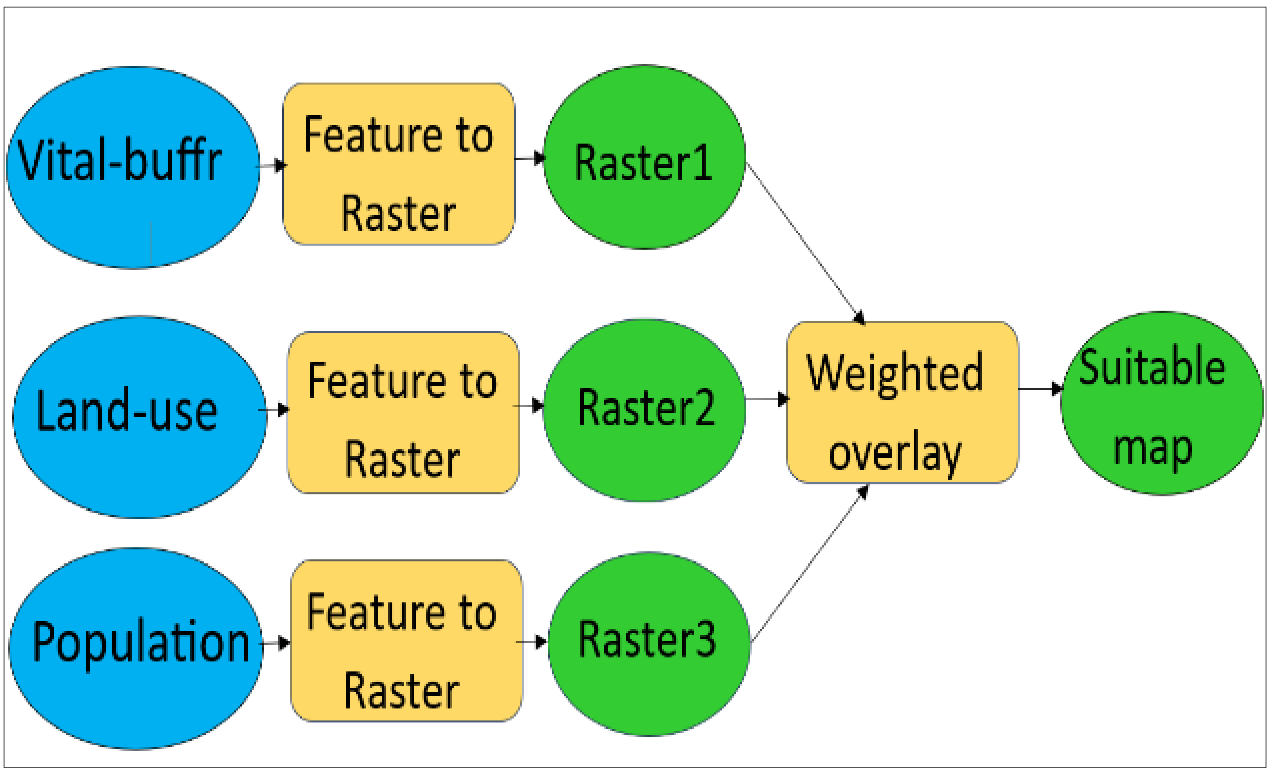

Figure (5.14): GIS model for intermediate stations.

Table (5.4): Weighting process in GIS program.

Layer	%Influence	Field	Scale value
Walking distance	56	150	10
		300	8
		500	5
Land use	32	Commercial	9
		Industrial	4
		Religious	8
		Cemetery	5
		Green	4
		Recreation	9
		University	10
		School	5
		Public	9
		Hospital	9
		Healthy center	3
		Free zone	4
		Residential	5
		Ring road 60	10
		Ring road 100	10
		Railroad	8
		Intersections	9
		Parking	8
		Terminal	8
		Rail stations	7
		Main roads	10
		Secondary roads	7
Population	12	Class 1	5
		Class 2	8
		Class 4	9
		Class 5	10

Fig. (5.15): Suitable layer resulting from the intermediate stations model.

5.6 Results and Discussion

Through the previous methodology approach and by conducting an operational analysis, the best locations for tram routes and stations were obtained by satisfying the main criteria. Figure (5.16) shows the best places of end stations, routes, and intermediate stations. The end stations were located in suitable positions at the city's entrances, specifically at the Karbala-Najaf, Karbala-Bagdad, and Karbala-Hindiya entrances on the west and south sides, as well as at the north and east sides. They are defined as Station A, which was located at the northwest side of the city, Station B, which was at Karbala- Bagdad entrance at north side, Station C at Karbala- Najaf entrance, Station D at Karbala- Hindiya entrance, and Station E was located at the west side of the city. Four routes were determined Route 1 with a total length of 20.18 km and with 32 stations. Route 2 has a total length of 14.17 km and 26 stations. The third route, with a total length of 14 km and 26 stations, and the fourth route has 22 stations with a length of 12.88 km. Four groups of intermediate stations were A, B, C, and D. There were 32 stations in Group A, 26 stations in Group B, 26 stations in Group C, and 22 stations in Group D.

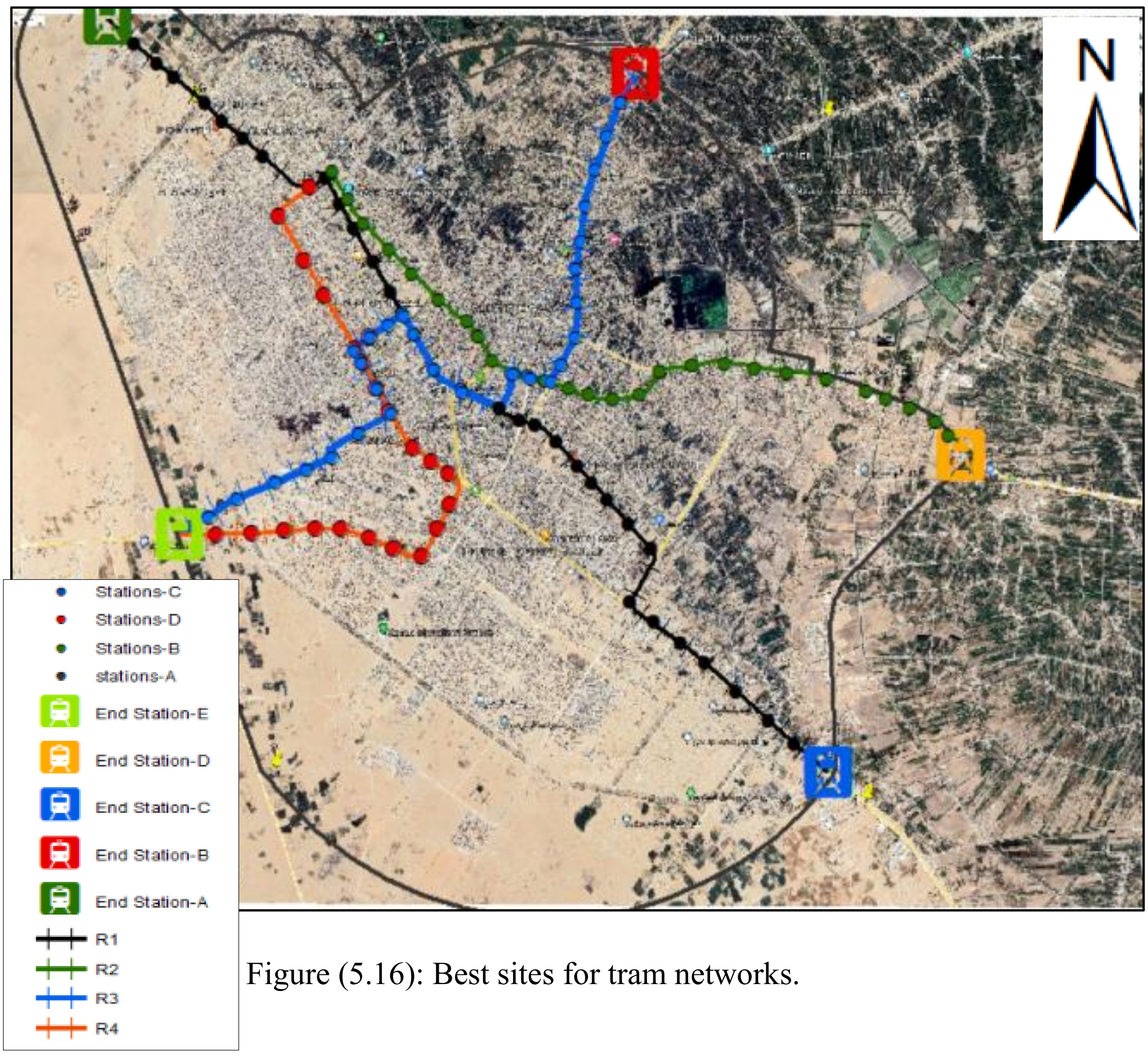

Figure (5.16): Best sites for tram networks.

These stations will service the city's most populated districts and be connected to major thoroughfares, crossroads, essential locations, and bustling zones. For checking the distance between each station and the nearest vital places, and the distance between each station, a tool of (Near distance) in GIS was used to compute the required distances. Table (5.5) shows the distances between each station and its vital places.

Table (5.5): Nearest distance to vital places and each station.

	Group A		Group B		Group C		Group D	
No.	Distance to nearest vital places (m)	Distance to nearest station(m)	Distance to nearest vital places (m)	Distance to nearest station (m)	Distance to nearest vital places (m)	Distance to nearest station (m)	Distance to nearest vital places (m)	Distance to nearest station (m)
1	9.5	446	20	551	574.3	620.2	24	744
2	37.5	477	16.6	512	778	493	47.3	520
3	84.2	498	39	510	466	492	198	464
4	13.6	331	22.7	597	532	584	355	468
5	25.8	332	53.4	590	190	524	382	713
6	79.8	512	55	633	21	348	76	216
7	92.5	512	10.3	349	76.3	347	292	218
8	373.5	635	348.6	340	31.8	317	7	369
9	498.4	429	316	415	35.7	316	346	482
10	82	391	57.3	317	47.3	672	75	480
11	143.12	390	28.1	317	26.6	638	216	422
12	153.6	636	31.5	339	13	637	58	371
13	19.2	637	96.4	361	42.8	716	30	370
14	21.1	321	37.8	360	221	647	63	483
15	47.5	320	226	461	261.2	507	291	475
16	98.3	381	163.3	504	571.6	630	593	555
17	43.7	491	359.6	558	519.8	623	504	477
18	37.8	409	35.5	602	88	621	37	475
19	61	586	231.3	568	27	510	98	471
20	270.4	600	43.5	565	386	534	312	589
21	113.2	570	52.2	617	253	612	37	602
22	35.4	572	51	747	341	533	15	669
23	20	575	62.6	378	73	642		
24	18	576	300.4	376	119	390		
25	23	399	785	480	153	352		
26	28.16	446	1313	341	632	570		
27	27	761						
28	17	613						
29	34	404						
30	363.8	406						
31	252.8	542						
32	170	613						

It can be recognized that the distance between each station was from 300 m to 800 m, which met with the tram station's limitation that the distances were not less than 300 m and not more than 1000 m.
Also, for the distances between Group A stations and nearest vital places, 75% of stations were located at distances less than 150 m from nearest vital places, 13% of them were located at distances less than 300 m, and 12% were more than 300 m up to 373 m. For Group B, 66% of stations were located at a distance less than 150 m from the nearest vital places, 15% of them were located at less than 300 m, and 19% located at distances more than 300 m. For Group C, 41% of stations were placed at a distance less than 150 m, 23% at less than 300 m, and 36% were at more than 300 m up to 778 m.
For Group D, 54% of stations were distributed at distances less than 150 m, 19% of stations were at distances less than 300 m, and 27% of stations were located at distances more than 300m up to 593 m.

5.7 Evaluation of the Routes Based on Evaluation Criteria

The purpose of route evaluation was to rank the routes based on evaluation criteria, as accessibility in terms of tram travel time, service area around the tram, residential areas close to the tram, and construction cost per kilometer of each line. For evaluation, the CRITIC and EDAS models have been used. The following steps outline the model's process.
evaluation criteria:
1- Travel time
Travel time can be expressed in the formula:
Travel time with tram = (In-vehicle travel time) + (Stopping time).
In-vehicle travel time = (Route length / Average speed).
Stopping time = (30 seconds) x (NO. of stations for each line).

The average running speed has been assumed to be 40 km/hr. Stop time represents the stopping times of the tramway at each stop platform. So, it can be calculated by multiplying the number of stop stations on each route by the stop time at each station. The stop time on the one platform has been assumed to be equal to 30 seconds. Table 5.6 shows the travel time of each route.

Table (5.6): Tram routes travel time.

Routes	R1	R2	R3	R4
Length (km)	20.18	14.17	14	12.88
In vehicle time (hr.)	0.5	0.36	0.35	0.32
Stop time (hr.)	0.26	0.21	0.21	0.18
Total travel time (hr.)	0.76	0.57	0.54	0.50

2- Service and residential area:

To determine the extent of service for each tram line, buffer sectors that represent the pedestrian walking distance of 300 meters around each station were made, and then the residential and service areas in each of these trams were calculated. The service area represented the universities, hospitals, industries, commerce, and public, the amusement area represented the recreation and religious land. Furthermore, the percentage of each sector within the buffer zone was calculated as depicted in Figure (5.17). Table (5.7) shows the number and percentage of service and residential areas for each route.

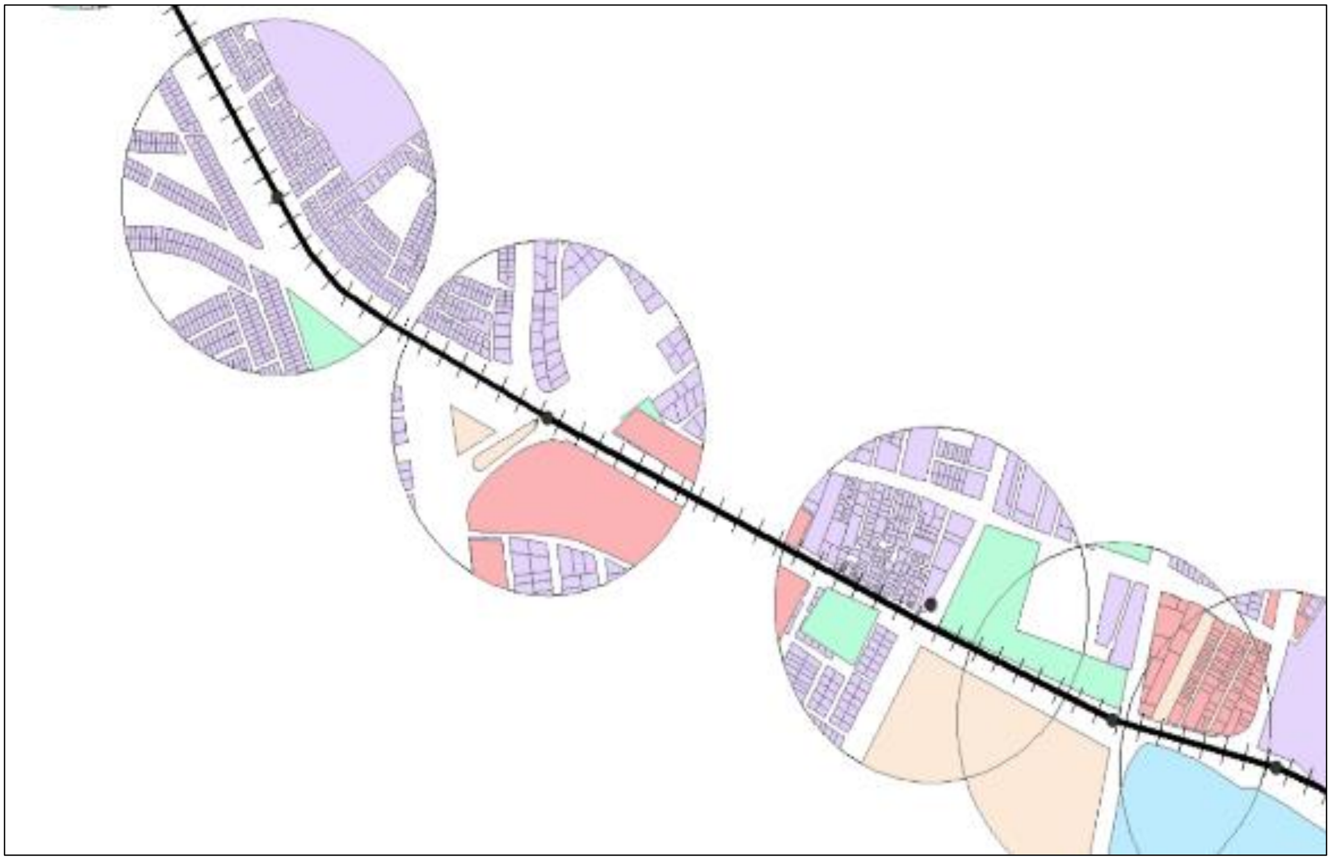

Figure (5.17): Land use calculation by sector around each station.

Table (5.7): Percentage of land use on each route.

	R1	R2	R3	R4
Residential%	52.84	65.58	46.20	70.83
Industrial%	8.82	2.16	0.00	0.00
Commercial%	1.91	6.10	0.66	2.38
Amusing%	10	8	6	4
Services%	28	13	9	12

3- Construction cost:

According to Guerrieri et al. (2019) the average cost of a tram ranges between 23 and 41.5 million dollars/km, so the average of this range was taken and multiplied by the length of the tracks. Table (5.8) shows the construction cost of each line in million dollars per kilometer.

Table (5.8): Construction cost for each route.

Construction cost (million dol)	R1	R2	R3	R4
	645.76	453.44	448	412.16

5.7.1. The CRITIC Method

It is a very helpful way to determine the importance of the selection criteria, as the description of this model in chapter two illustrates. This technique's primary focus is on the variations in values of all items on the same indices. As a result, this method looks at how two indices correlate and looks for conflicts between them. The CRITIC method has three implementation steps as follows:

Step1: Construct a decision matrix X:in this step, a decision matrix is constructed and xij represents performance of ith alternative for jth criterion.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.7).$$

Step-2: Normalization of decision matrix X: using Equations (5.8) and (5.9).

$$Xij^{*} = \frac{Xij}{\max Xij} \text{ .... (5.8).}$$

$$Xij^{*} = \frac{Xij}{\min Xij} \text{ ....(5.9).}$$

Step-3: Calculation of the weight values of criteria: Equations (5.10) are used to calculate the weights of the criteria; the following formula is used to calculate the indexes' correlation coefficient:

$$r_{ij} = \frac{\sum_{i=1}^{n}(di,k-\left(\frac{1}{n}\right)\sum_{i=1}^{n} di,k)\ (di,j-\left(\frac{1}{n}\right)\sum_{i=1}^{n} di,j)}{\sqrt{\sum_{i=1}^{n}(di,k-\left(\frac{1}{n}\right)\sum_{i=1}^{n} di,k)^{2}(di,j-\left(\frac{1}{n}\right)\sum_{i=1}^{n} di,k)^{2}}} \text{ .... (5.10)}$$

The conflict of the index Ci with other indexes can be expressed as follows:

$$Ci = \sigma \sum_{j=1}^{n}(1-rij) \text{ .... (5.11).}$$

The weight value of each criterion is calculated with the help of equation (5.12).

$$Wj = \frac{Ci}{\sum_{j=1}^{n} Ci} \text{ .... (5.12)}$$

Implementation of the CRITIC method: In the first step of the CRITIC method a decision matrix was constructed. Each element of this matrix (xij) represents numerical value of ith decision alternative for jth criterion. A constructed decision matrix X can be built in Table (5.9). In the second step of the CRITIC method, elements of the decision matrix X were normalized by using equations (5.8) and (5.9). While Equation (5.8) was used for the benefit criteria, Equation (5.9) was applied for cost criteria. Afterward, a normalized matrix was constructed, as can be seen in Table (5.10). Using the Equations

(5.10-5.12), the weights of the selection criteria were calculated and importance scores of the factors were determined at the end of the third implementation step of the CRITIC technique which showed in Table (5.11).

Table (5.9): Decision matrix X.

	Residential	Commer	Industrial	Amusing	Service	Time	Cost
R1	0.27	0.23	1.00	1.00	2.11	1.00	1.06
R2	0.79	1.00	0.25	0.67	0.44	0.18	0.18
R3	0.00	0.00	0.00	0.33	0.00	0.15	0.15
R4	1.00	0.32	0.00	0.00	0.33	0.00	0.00

Table (5.10): Normalized matrix X.

	Residential	Commer	Industrial	Amusing	Service	Time	Cost
Residential	1	0.623	-0.271	-0.394	-0.178	-0.44	-0.436
Commer	0.623	1	-0.009	0.222	-0.066	-0.183	-0.187
Industrial	-0.271	-0.009	1	0.884	0.983	0.980	0.980
Amusing	-0.394	0.222	0.884	1	0.789	0.863	0.858
Service	-0.178	-0.066	0.983	0.789	1	0.959	0.961
Time	-0.441	-0.183	0.980	0.863	0.959	1	0.999
Cost	-0.436	-0.187	0.980	0.858	0.961	0.999	1

Table (5.11): Evaluation criteria weights.

Options	Weights%
Residential	24.96686
Commer	18.44876
Industrial	8.870889
Amusing	9.129305
Service	18.43252
Time	9.749335
Cost	10.40234

5.7.2. The EDAS Method

The primary contention of the approach states that the distance from the average answer determines the optimal solution. It is possible to arrive at an ideal solution by following the seven implementation steps of the EDAS technique.

Step 1: Construction of the decision matrix: In the first step, a decision matrix, shown as follows, is constructed.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots (5.13).$$

Step2: Determination of the average solution: for each criterion, the average value is calculated by using Equation (5.14).

$$\mathrm{Xij}^* = \frac{Xij}{m} \ldots\ldots\ldots\ldots\ldots (5.14).$$

Step 3: Calculation of the positive and negative distances: considering the directions of criteria, the positive (PDA) and negative distances (NDA) of each criterion from the average are determined by using Equations (5.15) and (5.16).

$$\mathrm{dij}^+ = \begin{cases} \frac{\max\ (0,(xij-xij*))}{xij*} & ;\ \in \Omega max \\ \frac{\max\ (0,(xij*-xij))}{xij*} & ;\ \in \Omega min \end{cases} \ldots\ldots\ldots (5.15)$$

$$\mathrm{dij}^- = \begin{cases} \frac{\max\ (0,(xij*-xij))}{xij*} & ;\ \in \Omega min \\ \frac{\max\ (0,(xij-xij*))}{xij*} & ;\ \in \Omega max \end{cases} \ldots\ldots\ldots (5.16)$$

Step4: Determination of the weighted sum of PDA and NDA: by using Equations (5.17) and (5.18) values of weighted PDA and NDA are calculated.

Where Q^+ represents the weighted sum of PDA and Q^-symbolized the weighted sum of NDA.

$$Qi^+ = \sum_{j=1}^{n} wj.dij + \quad \text{.................. (5.17).}$$

$$Qi^- = \sum_{j=1}^{n} wj.dij - \quad \text{....................(5.18).}$$

wj is the non-negative weight value of the criterion j and it has been calculated with the help of the CRITIC technique.

Step 5: The normalization of the values of O^+ and Q^- the weighted sums of PDA and NDA are determined using Equations (5.19) and (5.20).

$$S^+ = \frac{Q+}{\max Qi+} \quad \text{............ (5.19).}$$

$$S^- = \frac{Q-}{\max Qi-} \quad \text{..............(5.20).}$$

Step: 6 Calculation of the appraisal score (AS) for all the alternatives: the appraisal scores are computed using Equation (5.21) as follows.

$$Si = \frac{1}{2}(Si^- + Si^+); 0 \leq Si \leq 1 \quad \text{........... (5.21).}$$

Step: 7 Ranking the decision alternatives: decision alternatives are ranked according to the descending appraisal values of options. The alternative that has the highest score is determined as the best and proper decision option. Tables (5.12–5.16) summarize the outcomes of the previously outlined steps.

Table (5.12): Positive distance matrix (PDA).

	Residential	Commer.	Industrial	Amusing	Service	Time	Cost
R1	0	0	0.196	0.0391	0.148	0	0
R2	0.0285	0.223	0	0.0130	0	0.006	0.0084
R3	0	0	0	0	0	0.008	0.0095
R4	0.050	0	0	0	0	0.0149	0.0171

Table (5.13): Negative distance matrix (NDA).

	Residential	Commer.	Industrial	Amusing	Service	Time	Cost
R1	0.0255	0.0567	0	0	0	0.0301	0.035
R2	0	0	0.0186	0	0.0297	0	0
R3	0.053	0.140	0.0887	0.0130	0.0772	0	0
R4	0	0.025	0.0887	0.0391	0.0416	0	0

Table (5.14): The weighted positive distance matrix (Q^{+}).

	Residential	Commer.	Industrial	Amusing	Service	Time	Cost
R1	0	0	2.217	0.428	0.806	0	0
R2	0.114	1.211	0	0.1428	0	0.0715	0.0809
R3	0	0	0	0	0	0.0822	0.0920
R4	0.203	0	0	0	0	0.153	0.164

Table (5.15): The weighted negative distance matrix (Q^{-}).

	Residential	Commer.	Industrial	Amusing	Service	Time	Cost
R1	0.102	0.307	0	0	0	0.308	0.337
R2	0	0	0.210	0	0.161	0	0
R3	0.215	0.761	1	0.142	0.419	0	0
R4	0	0.138	1	0.428	0.225	0	0

Table (5.16): Routes rank results.

	Q+	Q-	Si+	Si-	AS	Rank
R1	0.384	0.147	0.999	0.604	0.802	1
R2	0.280	0.048	0.729	0.870	0.799	2
R3	0.017	0.373	0.045	1.1E-07	0.022	4
R4	0.082	0.195	0.215	0.477	0.346	3

As illustrated in Table (5.15), Route 1 has a higher rank, it can decide that Route 1 is the best route which meets criteria, followed by Route 2, and Route 4, on contrast the Path 3 which took the lowest rank.

Chapter Six

Simulation of the Impact of Tram Performances

6.1 Introduction

This chapter presents a simulation-based assessment of proposed tramway scenarios in Karbala City center streets, aiming to evaluate their impact on traffic performance and environmental quality. Two alignment options were examined: a shared alignment operating within mixed traffic lanes and a segregated alignment running along a dedicated central median. Key performance indicators such as LOS, traffic delay, pollutant emissions, and noise levels were analyzed. The results highlight the benefits of a segregated tram system in enhancing urban mobility, reducing delays, and minimizing environmental impacts, particularly when combined with grade-separated pedestrian access.

6.2 Simulation Process

This scope aims to assess the feasibility of implementing an urban tram network in Kerbala City through a scientific methodology based on precise simulation using VISSIM software, with a focus on analyzing interactions between tram routes and existing traffic flow. The simulation was conducted in three main stages:

1. Accurately modeling the current traffic network.
2. Calibrating the model by comparing simulation outputs with real-world data to ensure credibility.
3. Integrating tram routes into two distinct designs (shared with cars vs. isolated in median lanes) and comparing the performance of each scenario. The main objective for this process is to measure the impact of trams on

traffic performance indicators (e.g., travel time, average speed, LOS, emissions, delay, and noise).

6.3. Simulation Modelling

The VISSIM program is advanced software for modeling traffic and pedestrian movement, where the movement of each vehicle, tram, or passenger is simulated individually on a dynamic basis. The following explains the main modeling steps used in the VISSIM program:

6.3.1. The Utilized Data

To create the model necessary for simulation in PTV VISSIM, the following data have been inserted:

- Existing roads.
- Proposed tram routes and stations.
- Proposed tram stations.
- Traffic volume on each road.
- Tram route decisions.
- Average travel speed.
- Traffic composition (passenger car, taxi, three-wheel motor, heavy vehicle, minibus, and bus).
- The percentages of each type of traffic composition.

Figures (6.1- 6.8) show the type of traffic composition used in software.

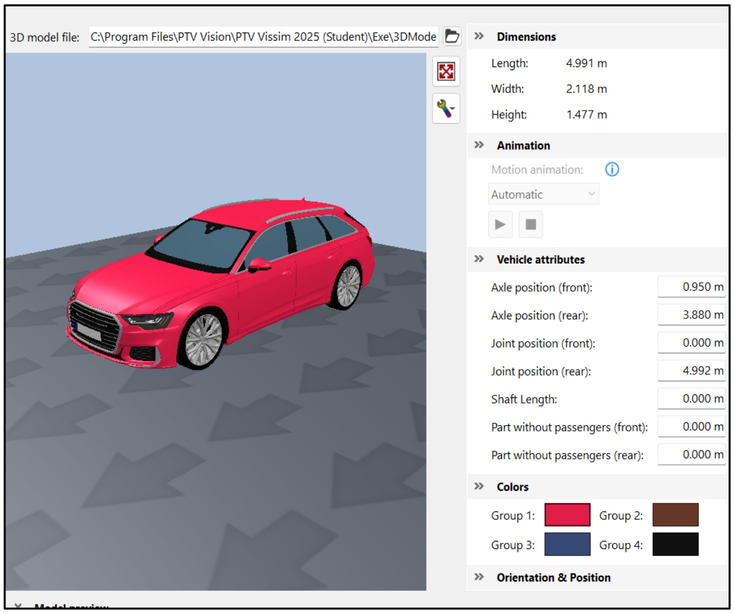

Figure (6.1): Passenger car modeling.

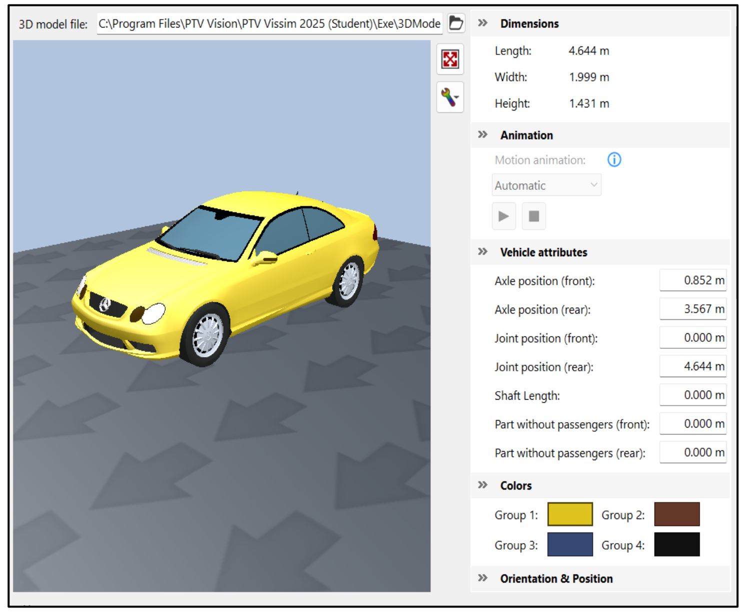

Figure (6.2): Taxi car modeling.

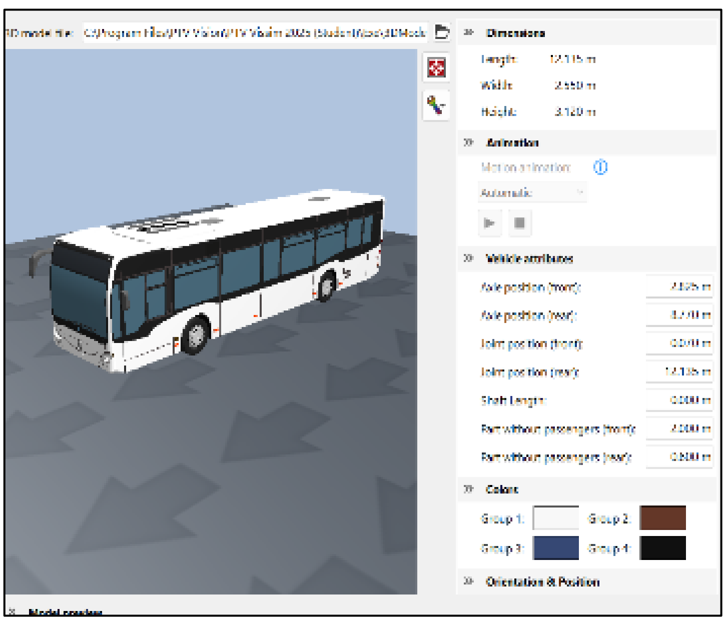

Figure (6.3): Bus modeling.

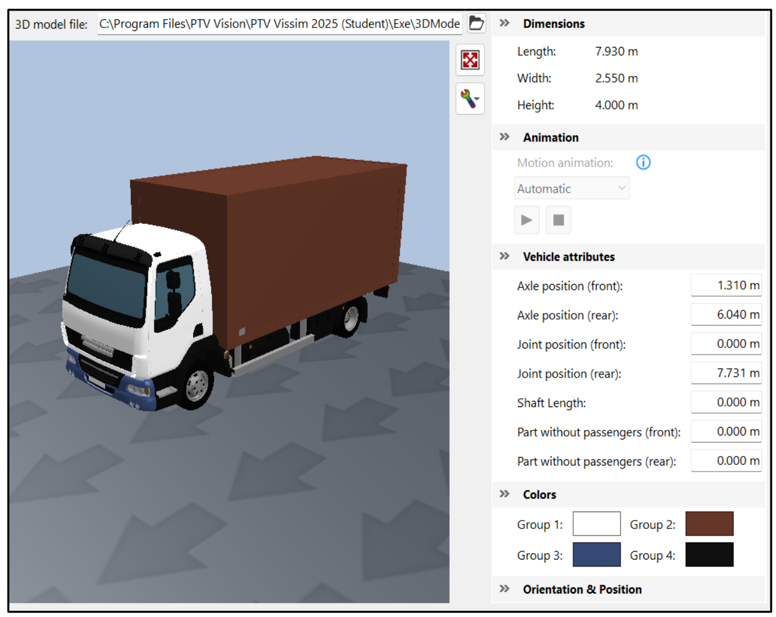

Figure (6.4): Heavy vehicle modeling.

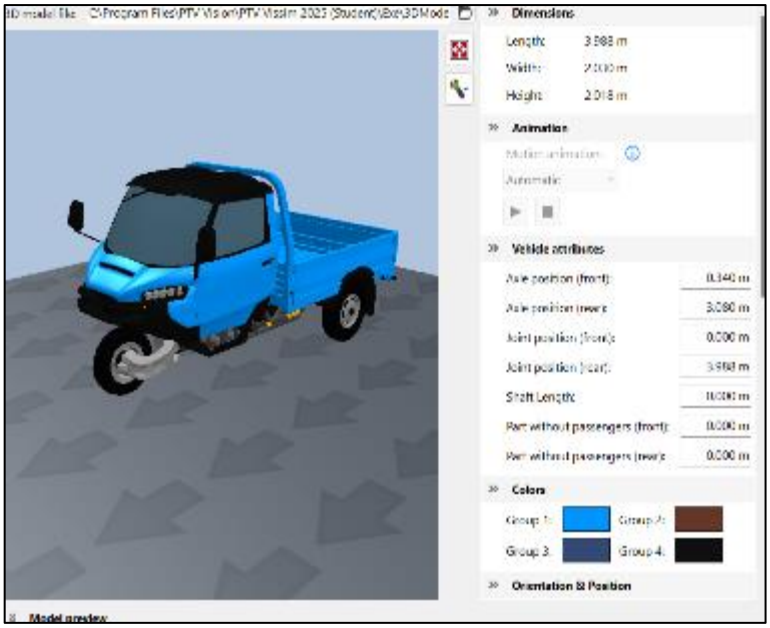

Figure (6.5): MTR (type1) modeling.

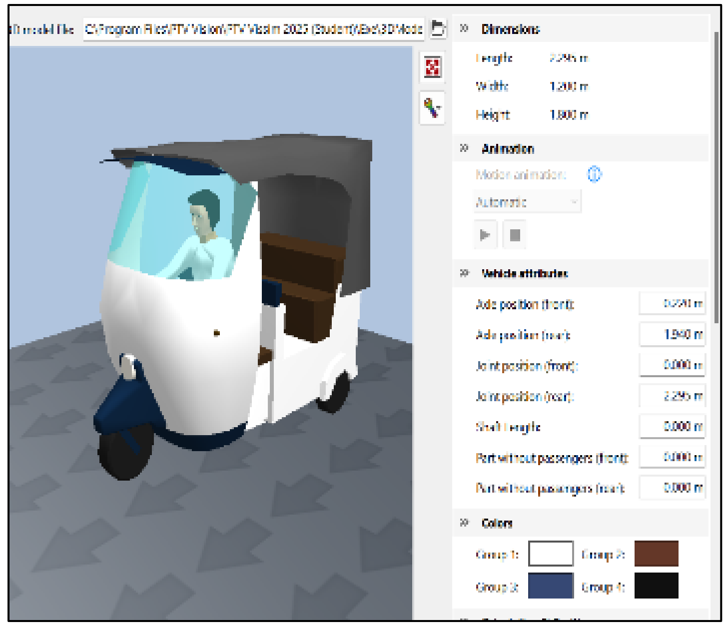

Figure (6.6): MTR (type2) modeling.

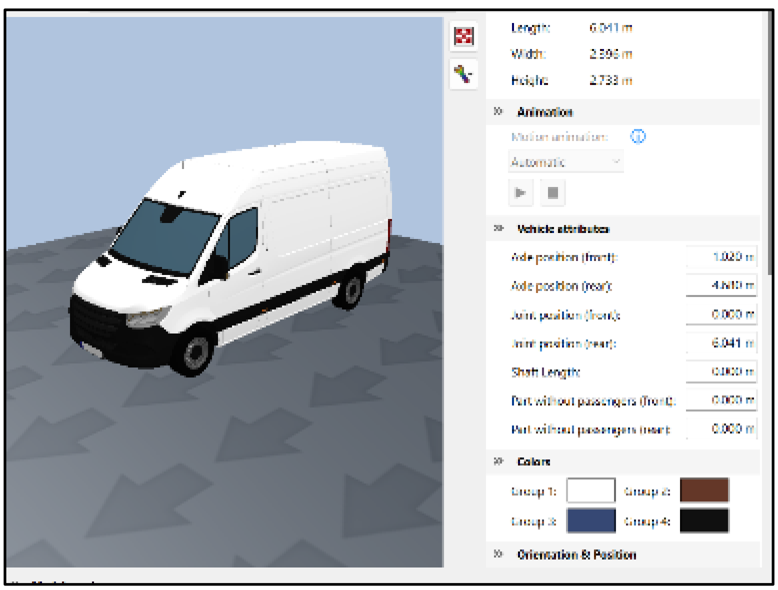

Figure (6.7): Minibus modeling.

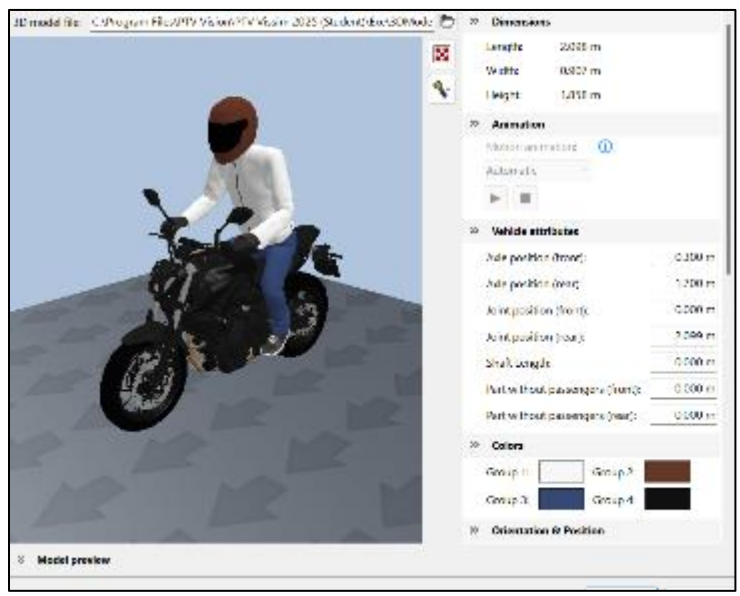

Figure (6.8): Motor modeling.

6.3.2.The Setting Up of Existing Roadways

Based on an aerial view of the program, the Linke command was used to draw the street network. Peak traffic volumes for each side of the street were entered using the Input Vehicles command. The vehicle composition for each road was defined, and the percentage of each vehicle type was inserted according to its distribution on that street for each direction of the roads. Moreover, pedestrian crossings, footbridges, and parking zones were integrated into the street layouts within the software environment.

Figures (6.9) and (6.10) illustrate the road setup process using Ramadan Street as an example.

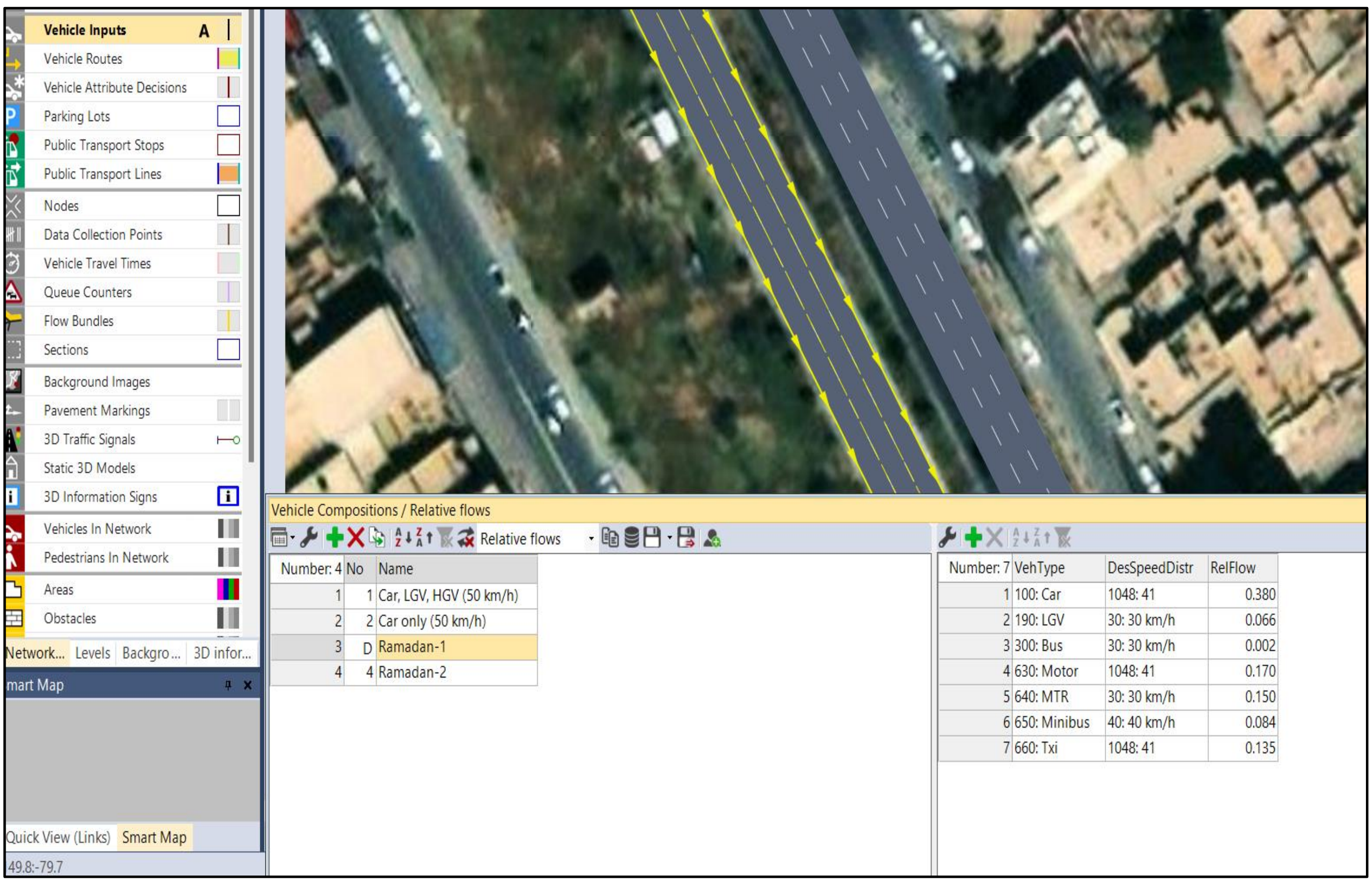

Figure (6.9.a): Setting roadway direction 1 for Ramadan Street.

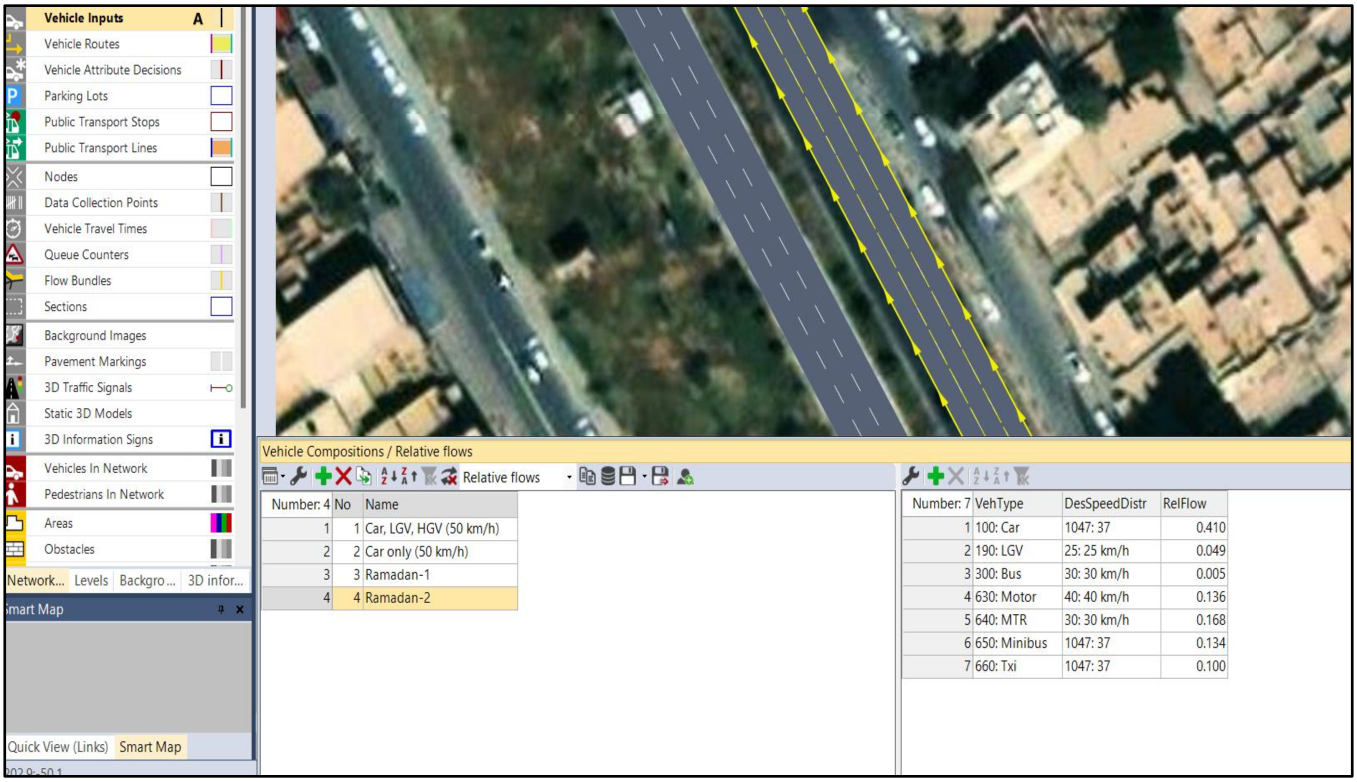

Figure (6.9.b): Setting roadway direction 2 for Ramadan Street.

Figure (6.10): Simulation of Ramadan Street.

6.3.3.Model Calibration and Validation

Calibration is the process in which the various parameters of the simulation model are adjusted till the model accurately represents field conditions (Basuki et al., 2024). To ensure the accuracy of the simulation model towards the input traffic volume data in existing conditions, validation was done with Geoffrey E. Havers (GEH) formula (Basuki et al., 2024). The GEH equation model is a modified statistical formula of Chi-square by combining the difference between relative and absolute values (Haryanti et al., 2015). The GEH equation is shown in Equation (6.1), and the meaning of the GEH criteria and results are shown in Table (6.1) and Table (6.2).

GHE= $\sqrt{\frac{2(qsimulated - qobserved)2}{(qsimulated+qobserved)}}$……………... (6.1).

Where:

$qsimulated$= Output traffic volume from the simulation model (vph).

$qobserved$= Input traffic volume (vph).

Table (6.1): GEH value criteria.

GEH < 5,0	Good model, accepted
5,0 ≤ GEH ≤ 10,0	Bad model, possible errors
GEH > 10,0	Models have to be rejected

Table (6.2): GEH value results.

Street	GEH value (dir.1)	GEH value (dir.2)
Al-Mojamaat	0.692	1.928
Al-Moalemin	1.113	0.658
Al-Wilada	0.418	3.620
Shohada Al-Mmowadhafin	2.721	0.864
Al-Dhariba	0.602	2.496
Al-Tarbia	2.129	1.562
Karbala-Hindea	4.052	3.248
Ramadan	1.515	1.527

Table (6.2): Continued.

Street	GEH value (dir.1)	GEH value (dir.2)
Al-Naser	3.459	2.062
Maitham Al-Tammar	4.591	0.794
Al-Hur	3.326	0.751

The results of GEH value were less than 5, the simulation is fit.

6.4 Tram Modelling

A 3D tram model was developed using PTV VISSIM software with a two-car configuration and a 3500 mm road clearance, suitable for the conditions in Karbala. Figure (6.11) presents the key parameters of the simulated tram model.

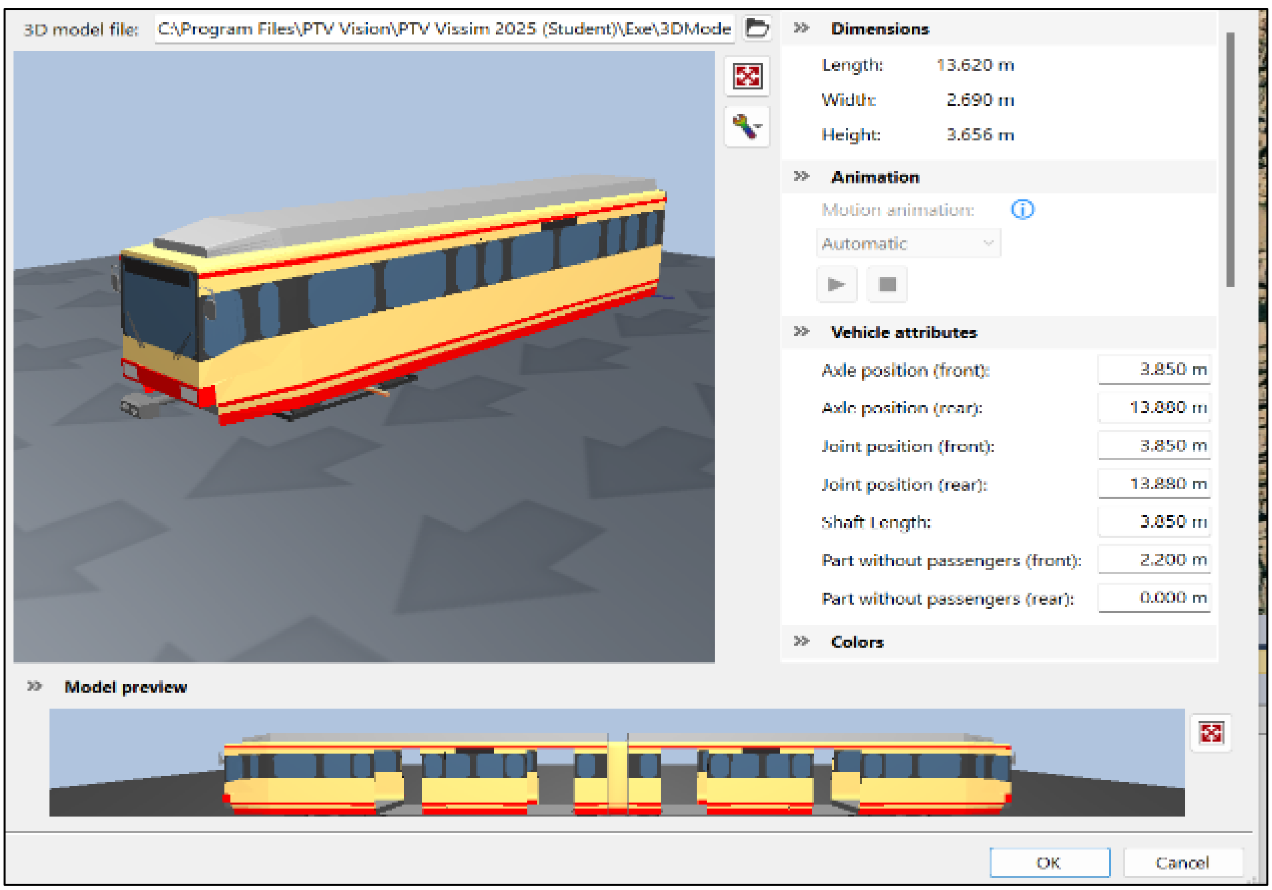

Figure (6.11): Tram model input.

6.5 Right-of-Way Considerations

As illustrated in Chapter Two, tram systems can be designed with different types of track alignments depending on the urban context, street geometry, and traffic conditions. The main types of tram track configurations include mixed traffic lanes, where the tram shares the same lane as general vehicles. This is the most efficient but can lead to delays, dedicated Lane (semi-exclusive) when the tram operates in a separate lane, often physically separated by markings or curbs but still within the street, and exclusive right-of-way when the tram runs on a completely separated track, either in the central median or in a segregated corridor. In this study, to simulate realistic tram operations in Karbala City, two primary right-of-way scenarios were considered in PTV VISSIM:

1. Mixed traffic alignment, where the tram shares the lane with general vehicular traffic.

2. Exclusive alignment, where the tram is separated from traffic using either the central median (island) or a designated track on the far right.

As stated in Chapter two, the recommended spatial requirements for tram tracks and platforms were:

- For single track width: (3.5 - 4) meters, include clearance on both sides.
- For double track width: (7-8.5) meters, including spacing between tracks and lateral clearance.
- For side platform width: (2.5-3.0) meters, and (3.0-4.0) meters for central platforms. The platform length is typically (30-45) meters, depending on tram length and capacity.

In this study, track width was modeled as 3.5 meters, with a stop platform width of 2.5 meters for the single-track configuration.

A sample of 11 streets was selected to simulate the proposed tram networks' effect in Karbala City, which were (Hasan Al-Mujtaba, Al-Hur, Sarie Al-Moalemin, Sarie Ramadan, Al-Mojamaat, Fatima Al-Zahra1, Al-Tarbea, Nabi Mohammad, Al-Dhariba, Maitham Al-Tammar2, and Al-Wilada Street).

Accordingly, six streets (Sarie Ramadan, Al-Tarbea, Al-Mojamaat, Al-Dhariba, Maitham Al-Tammar 2, and Mustashfa Wilada Street) were simulated, where the tram track and stop platforms are located within the central median. In this case, pedestrian access to the tram platforms was provided through pedestrian overpasses. The number of pedestrians crossing these streets during the peak hour was recorded to simulate the impact of installing pedestrian overpasses near tram stop locations, and to evaluate their effect on the level of service and delay. Figure (6.12) shows the number of pedestrian crossings at selected streets. The Passengers could descend from either the center or side of the bridge directly onto the platforms. This design separated pedestrians from vehicle traffic, which improved safety, reduced traffic conflicts, and minimized travel delays. In sections where the tram operates on a physically segregated track, priority was granted to trams at signalized intersections, ensuring minimal delays and maintaining travel time reliability. This prioritization was integral to improving tram efficiency, especially in dense urban areas with high traffic demand.

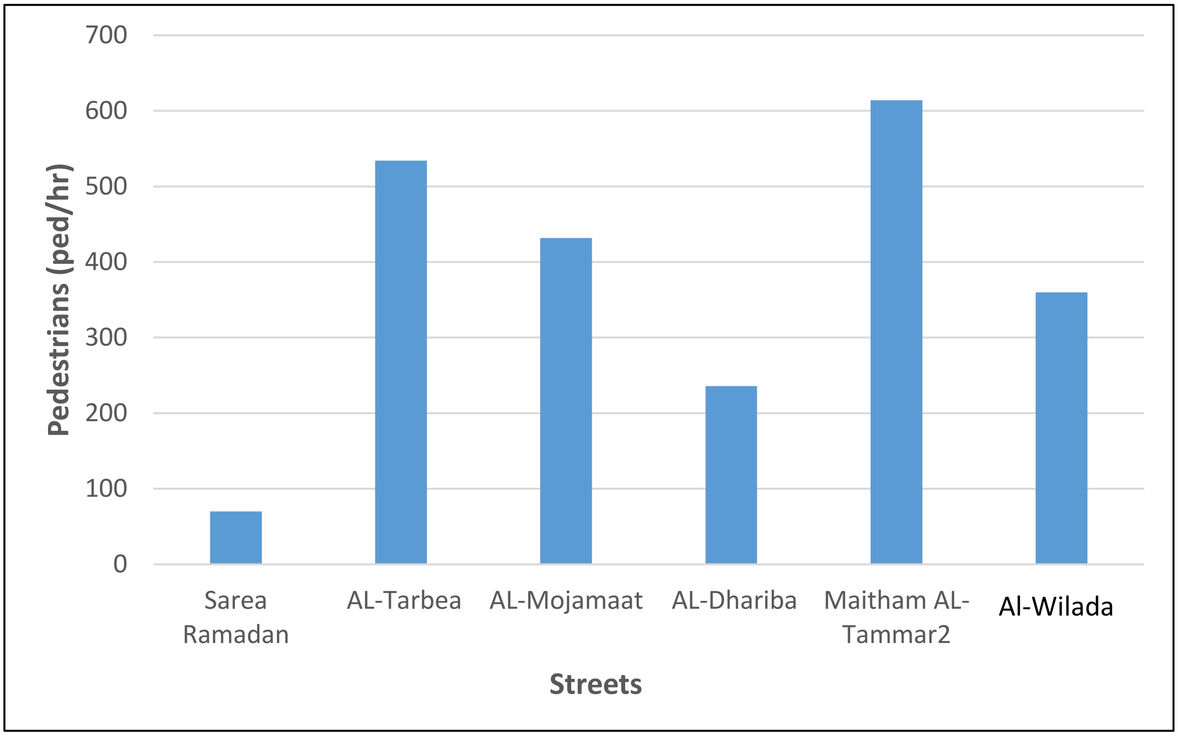

Figure (6.12): Pedestrian crossings at selected streets.

For the remaining streets (Hasan Al-Mujtaba, Al-Hur Street, Sarie Al-Moalemin, Fatima Al-Zahra, and Nabi Mohammad Street), a shared right-of-way design was adopted. In these segments, the tram operates in mixed traffic lanes to ensure compatibility and avoid extensive urban modifications.

Figure (6.13) illustrates the proposed location of a tram station and its shared alignment with the roadway along Al-Hurr Street. The tram line operates within the existing traffic lanes, indicating a mixed-traffic configuration, where the tram shares the right-of-way with general vehicles. The station platform is positioned laterally, adjacent to the traffic stream, enabling easy access while maintaining continuity with the urban street network.

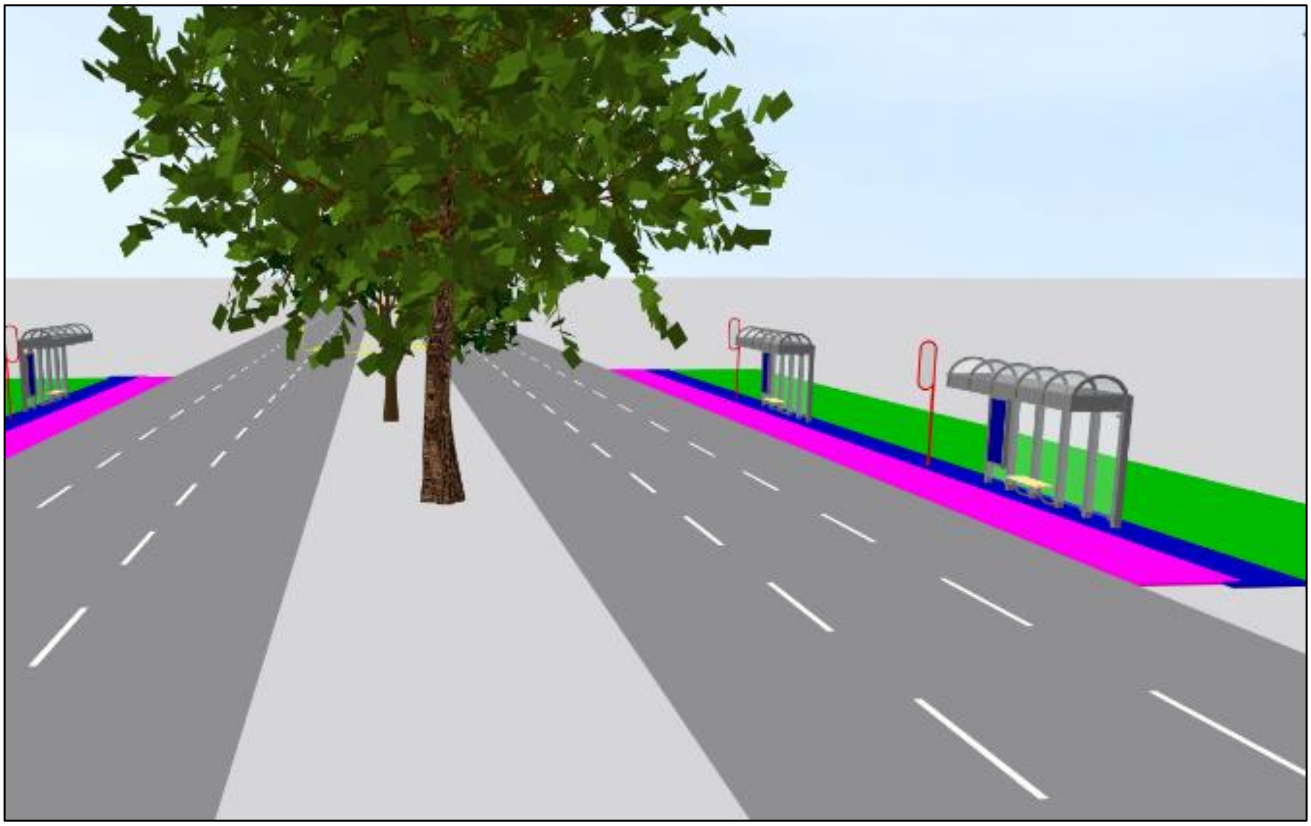

Figure (6.13.a): Simulated tram stops and shared lane alignment at Al-Hur Street.

Figure (6.13.b): Simulated tram stops and shared lane alignment at Al-Hur Street.

Figures (6.14) and (6.15) illustrate dedicated tram corridors positioned within the central median and side island of a significant urban roadway. This design represents a segregated tram alignment, where the tram tracks are entirely separated from mixed vehicular traffic, enhancing operational efficiency, minimizing delays caused by traffic congestion, and reducing the risk of accidents. To ensure safe and direct pedestrian access to the median-based tram station, a pedestrian overpass has been constructed, enabling passengers to cross above the traffic lanes and access the platform without interfering with road traffic. This configuration significantly improves passenger safety, reduces conflict points, and supports smooth boarding and alighting processes, particularly during peak hours or in high-density urban environments.

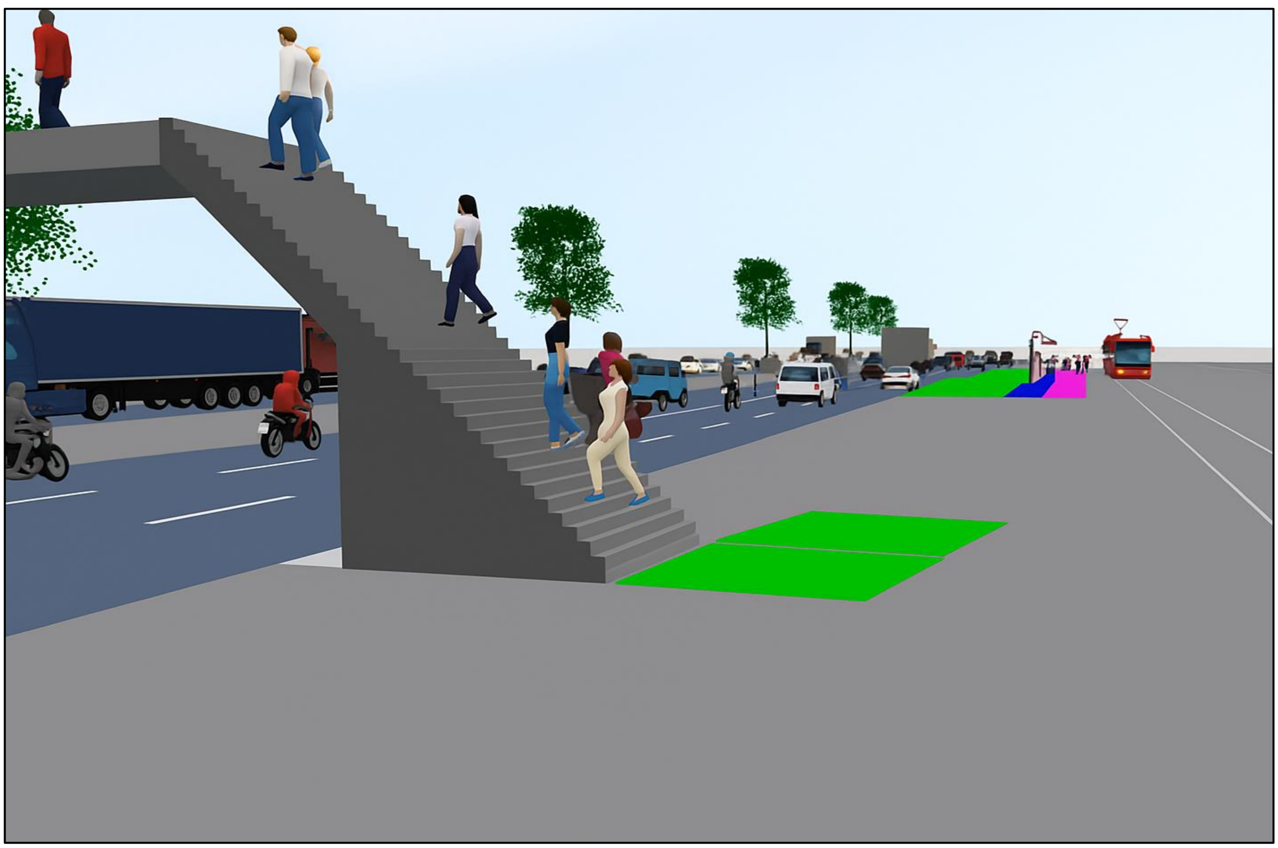

Figure (6.14.a): Simulated tram stops and isolated lane alignment.

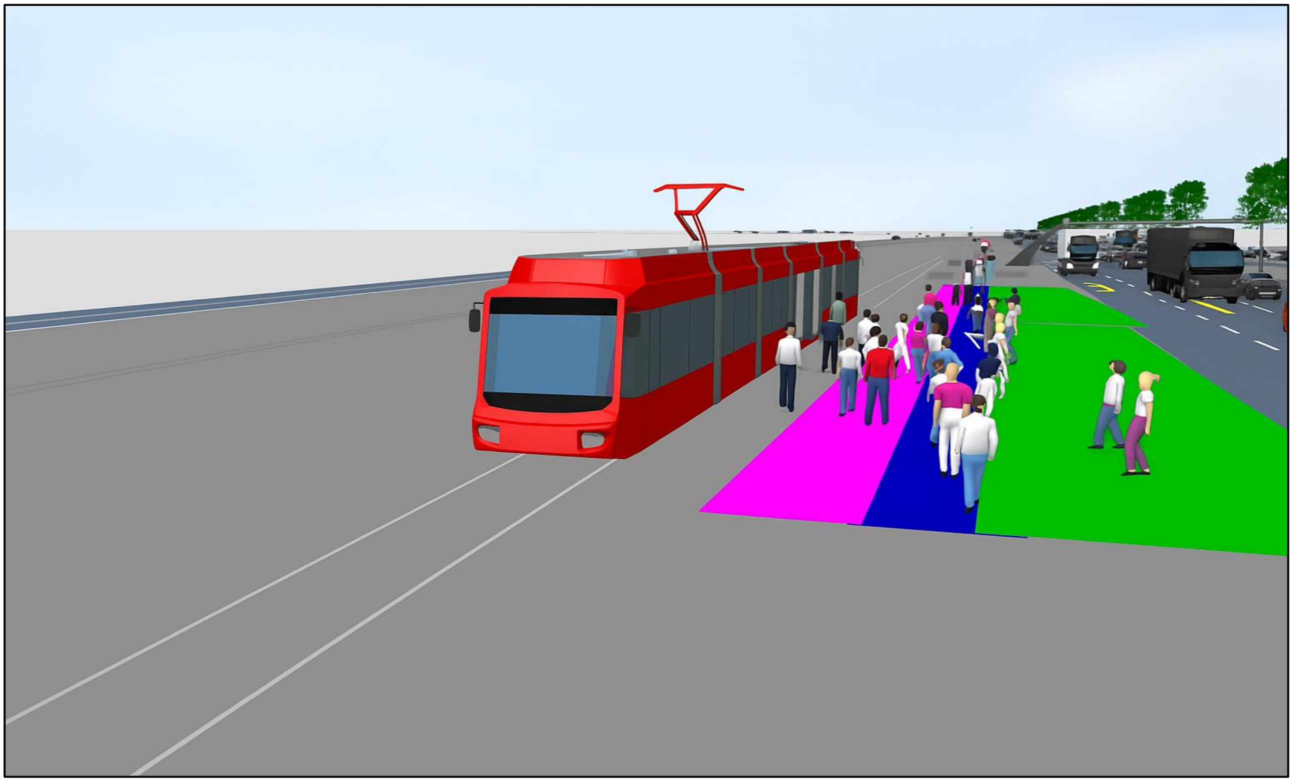

Figure (6.14.b): Simulated tram stops and isolated lane alignment at side island.

Figure (6.15.a): Simulated tram stops and isolated lane alignment at central median.

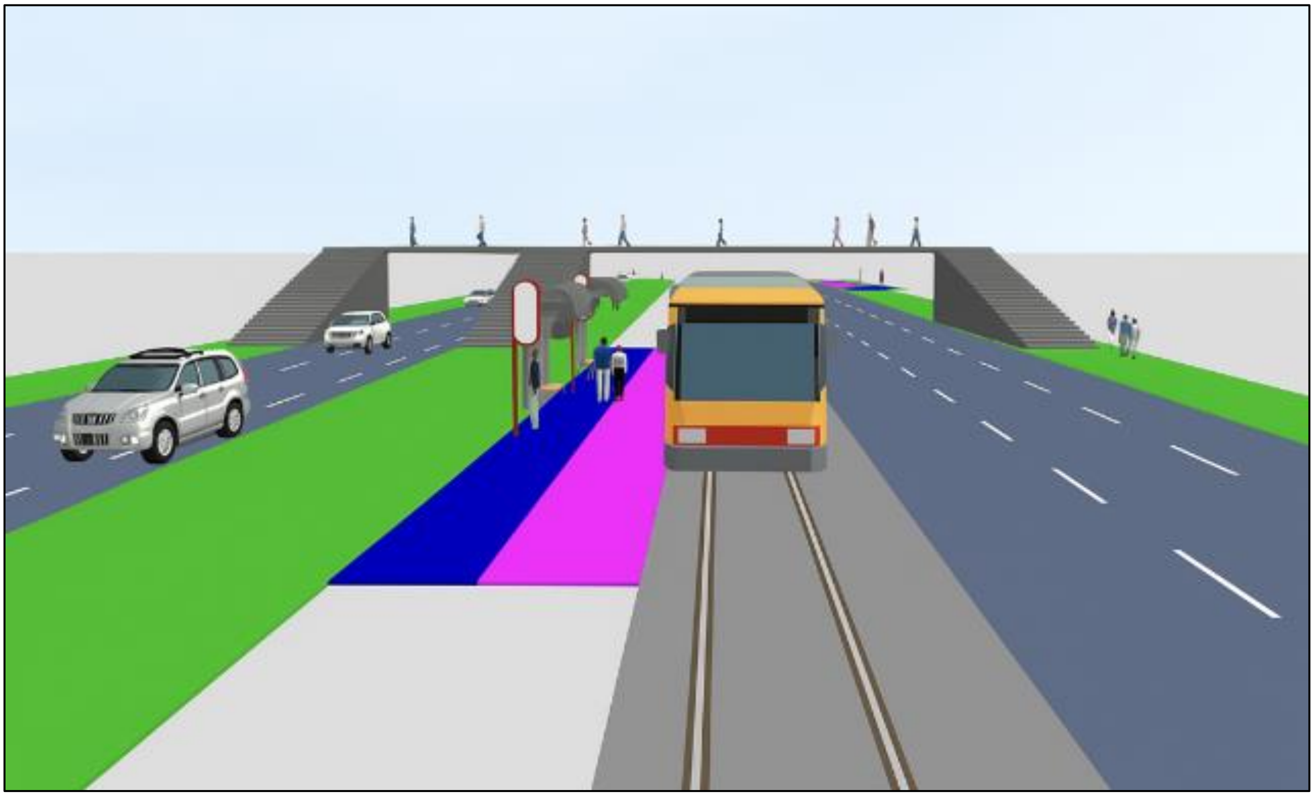

Figure (6.15.b): Simulated tram stops and isolated lane alignment at central median.

6.6 Assessment of Potential Mode Shift to Tram System

To assess the feasibility of implementing a tram system in Karbala City, which currently lacks organized public transportation and experiences severe traffic congestion, a stated preference survey was carried out. The survey targeted two main groups: private car owners and users of informal or shared transport modes such as taxis, MTR, and minibuses.

The survey revealed that 22% of private vehicle owners expressed a willingness to shift to the tram if it was available and operated efficiently. Moreover, a significantly higher proportion 76% of shared/public transport users indicated their preference for using the tram instead of their current modes.

These percentages were applied to the observed vehicle volumes across city streets, specifically targeting private vehicles and informal transport categories, while maintaining the volumes of freight vehicles, buses and motorcycles constant. This allowed for the recalculation of traffic volumes under a hypothetical tram scenario. The results of this demand adjustment were then used to re-estimate traffic indicators such as volume-to-capacity ratio (v/c), delay, LOS, traffic noise, and air pollutant emissions, enabling a comparative analysis before and after the implementation of the tram system.

6.6.1 Impact of Tram Implementation on LOS

Table (6.3) illustrates the LOS comparison before and after tram implementation. The comparison between traffic LOS before and after the hypothetical implementation of a tram system in Karbala reveals a significant improvement in operational conditions across the network. Prior to introducing the tram, the dominant LOS levels were F (40%) and E (30%), indicating severe congestion and poor service across the majority of the studied streets. These high proportions of low LOS levels reflect the inefficiency of the existing traffic system, characterized by overcrowding, delays, and poor flow conditions.

After implementing the tram scenario, the distribution shifted dramatically:

- LOS F and E completely disappeared from the network, dropping to 0.0%.
- LOS C became the most dominant category, representing 64.3% of the streets, followed by LOS B with 19.0%, and LOS D at 16.7%.

This transformation demonstrates the positive impact of reducing private and informal public vehicle volumes through tram integration. The tram system, by absorbing a significant portion of travel demand, effectively relieved roadway pressure, allowing for smoother traffic operations and enhanced service levels.

Table (6.3): LOS comparison before and after tram implementation.

Street	Dir.	LOS-before	Max.flow(vph)	Capacity	v/c	LOS-after
Ftima Al-Zahraa 2	1	F	1901	2370	0.80	C
	2	E	1224	2370	0.52	C
Haidar Al-Karrar	1	D	2454	4060	0.60	C
	2	C	1920	4060	0.47	C
Al-Nasr	1	E	1932	3190	0.61	C
	2	D	1674	3190	0.52	C
AL-Abbas	1	F	1583	2370	0.67	C
	2	F	1653	2370	0.70	C
Karbala-Najaf	1	C	1448	3040	0.48	B
	2	D	1517	3040	0.50	B
Bab Twerige	1	F	1410	2180	0.65	C
	2	F	1402	2180	0.64	C
Karbala-Hindea	1	E	2181	3040	0.72	B
	2	E	1602	3040	0.53	B
Maitham Al-Tammar1	1	F	1671	2310	0.72	D
	2	F	1567	2310	0.68	D
Maitham Al-Tammar2	1	E	1461	2370	0.62	C
	2	F	1456	2370	0.61	C
Maitham Al-Tammar3	1	E	1488	2310	0.64	D
	2	E	1385	2310	0.60	C
Al-Qebla	1	F	1229	1650	0.74	C
Karbala- Bagdad	1	C	1359	2370	0.57	C
	2	E	1827	2370	0.77	C
Abdolzahara Al-Kaaby	1	E	1820	3040	0.60	B
	2	E	1690	3040	0.56	B
Al-Amel2	1	C	943	2370	0.40	C
	2	C	957	2370	0.40	C

Table (6.3): Continued.

Street	Dir.	LOS-before	Max. flow (vph)	Capacity	v/c	LOS-after
Al-Amel 1	1	B	1249	2310	0.54	C
	2	B	1138	2310	0.49	C
Hai Al-Hur	1	E	1318	2310	0.57	C
	2	E	1219	2310	0.53	C
Hai Al-Moalemin	1	D	1059	2370	0.45	C
	2	C	1089	2370	0.46	C
Al-Wilada	1	F	1647	2370	0.69	C
	2	E	1491	2370	0.63	C
AL-Mowadhfin	1	E	1240	2310	0.54	C
	2	E	1259	2310	0.55	C
Al-Markaz	1	C	2055	2180	0.94	D
	2	C	1130	2180	0.52	C
Imam Ali	1	F	1449	2180	0.66	C
	2	E	1405	2180	0.64	C
Al-Taalib	1	F	1228	2310	0.53	C
	2	F	1302	2310	0.56	C
Al-Jahiz	1	F	1457	2370	0.61	C
	2	F	1362	2370	0.57	C
Shohadaa Al-Mowadhafin	1	F	1704	2370	0.72	D
	2	F	1517	2370	0.64	D

6.6.2 Average Speed Changes After Tram Implementation

The analysis of average vehicular speeds before and after the implementation of the tram system indicates a notable improvement across most studied streets. Figure (6.16) shows that almost all streets experienced an increase in traffic flow efficiency, with speed gains ranging from 13.9% to over 130%.

For instance, Al-Hur and Sarie Al-Moalemin streets witnessed moderate increases (27.9% and 43.6% respectively). In comparison, streets such as Al-Mojamaat and Al-Tarbea experienced unusually high improvements in average speed (131.4% and 92.9%). Substantial infrastructure upgrades along those corridors can explain this sharp increase. Specifically, the installation of pedestrian overpasses effectively separated pedestrian movements from vehicular flow, eliminating delays caused by pedestrian crossings. Additionally, the tramway was allocated within the central median (the central island), which reorganized the street layout and contributed to clearer, unobstructed vehicle paths. These upgrades collectively resulted in smoother, faster traffic operations. The findings reinforce the impact of integrated planning that combines public transport enhancements with infrastructure modifications, leading to measurable improvements in urban mobility.

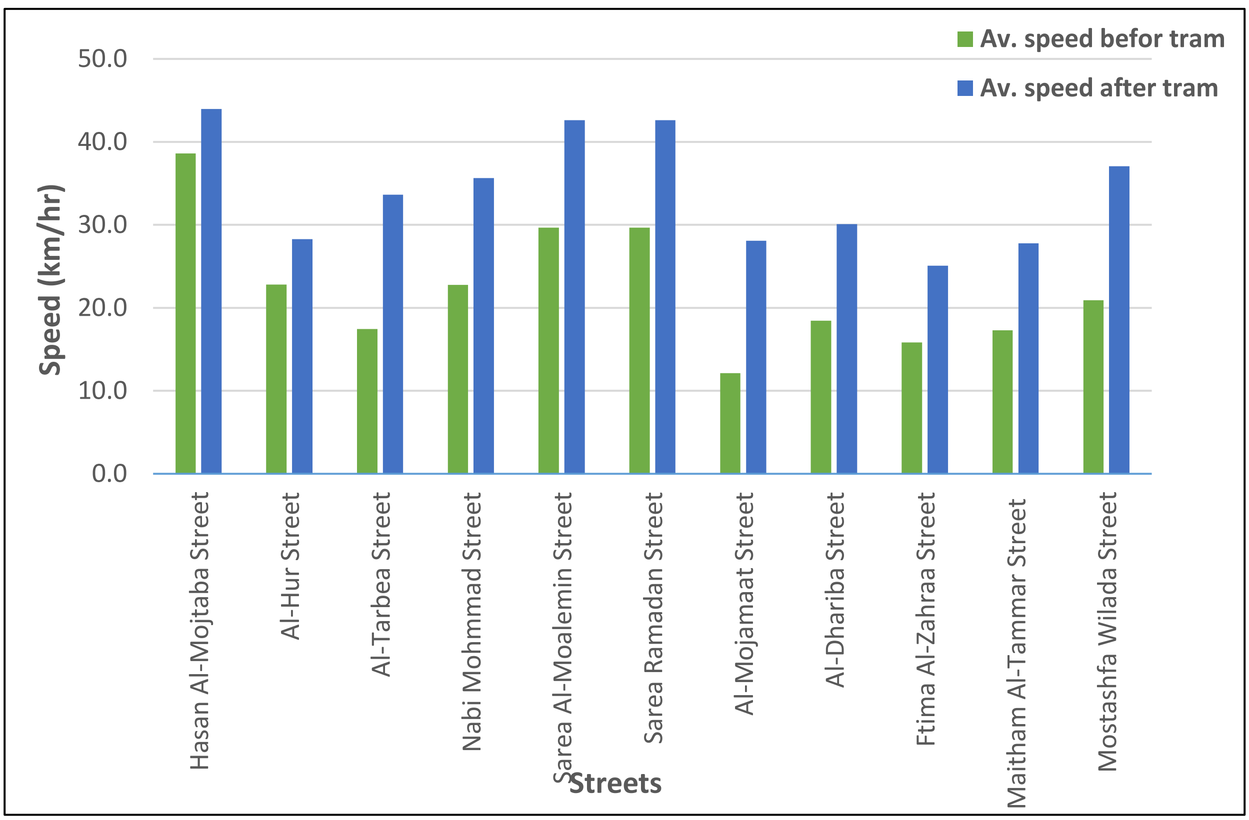

Figure (6.16): Comparison of average speeds before and after tram implementation

6.6.3 Delay Reductions After Tram Implementation

The analysis of delay reduction across the studied urban streets in Karbala after the implementation of the tram system shows significant variation in the percentage decrease, ranging from 11.0% on Hasan Al-Mojtaba Street to 65.0% on Al-Wilada Street. Streets such as Al-Tarbea Street with a reduction of 63.6%, Al-Mojaamat Street with 64.8%, Maitham Al-Tammar Street with 59.1%, and Al-Dhariba Street with 50.1% showed notably high decreases in travel time. These improvements were mainly due to the simulation scenario in which the tram was operated on an exclusive alignment within the central median and pedestrian movements were separated through overpasses, eliminating pedestrian interference with traffic and allowing smoother tram operation. Streets such as Hasan Al-Mojtaba Street, with a reduction of 11.0% and Al-Hur Street, with 25.0%, experienced relatively lower decreases in travel time, according to the simulation of tram line mixing with traffic. Figure (6.17) shows the comparison of the time delay before and after tram implementation.

6.6.4 Noise Level Reductions After Tram Implementation

The analysis of average noise levels before and after tram implementation reveals generally moderate but noteworthy reductions in traffic-related noise across the evaluated streets. As shown in the accompanying chart, several streets experienced a clear improvement in urban acoustic conditions. Hasan Almojtaba Street recorded the highest reduction in average noise, with a decrease of 21.32%, followed by Al-Tarbea Street and Al-Wilada Street, with reductions of 9.97% and 10.51% respectively. These outcomes are most likely attributed to decreased congestion, improved vehicle flow, and fewer stop-and-go situations due to reduced conflicts with informal transit modes. However, certain streets such as Sarie Al-Moalemin, Sarie Ramadan, and

Maitham Al-Tammar 2 showed minimal noise reductions, with percentages below 4%.

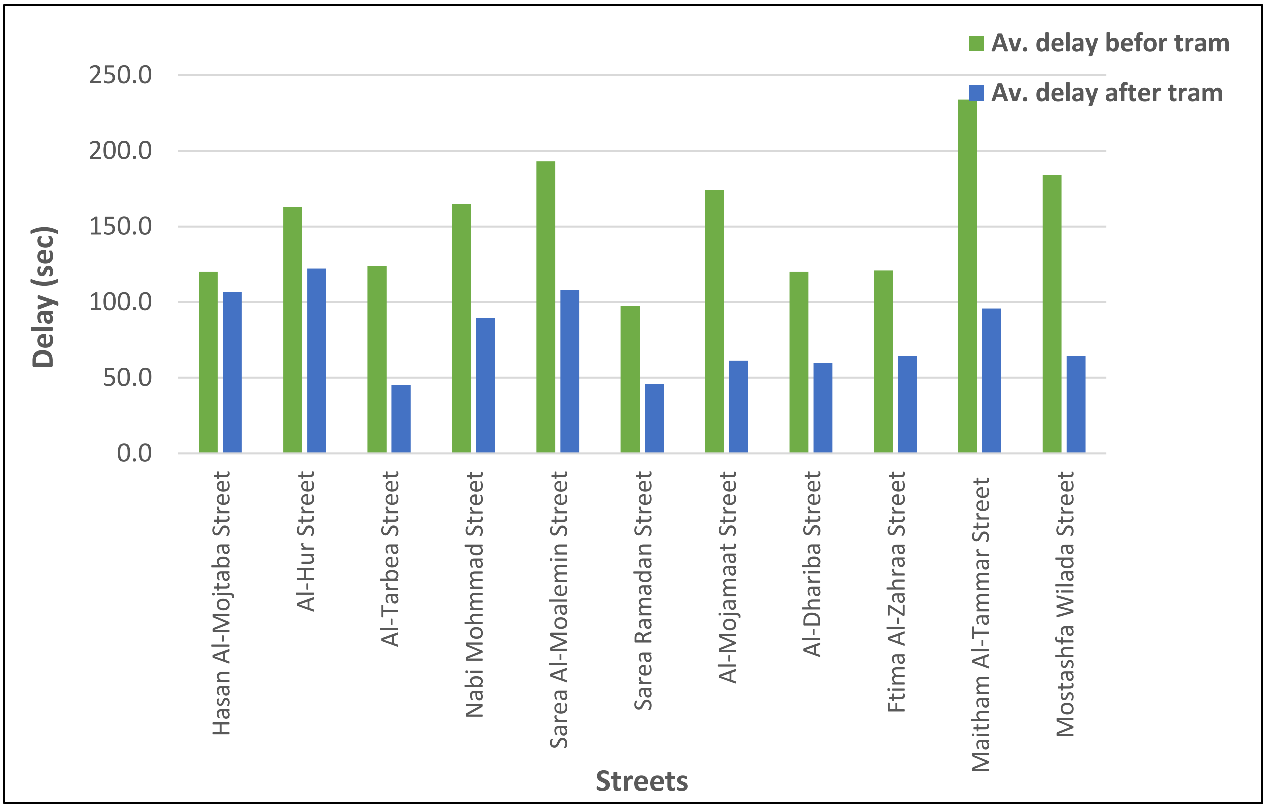

Figure (6.17): Comparison of average delay before and after tram implementation.

This limited decline may not be directly related to traffic flow improvements alone. Instead, residual noise levels may have been influenced by other contributing factors such as road surface texture, vehicle type distribution, driver behavior (aggressive acceleration or excessive horn use), and non-traffic noise sources in the surrounding environment. The comparison in the case before and after tram implementation is presented in Figure (6.18).

6.6.5 Air Pollutant Reductions After Tram Implementation

The implementation of the tram system has led to a measurable decrease in the concentration of multiple air pollutants, including CO, CO_2, NO_2, $PM_{2.5}$, and PM_{10}, across various streets in the study area. Figures (6.19 to 6.23) offer a comparison of traffic pollutants.

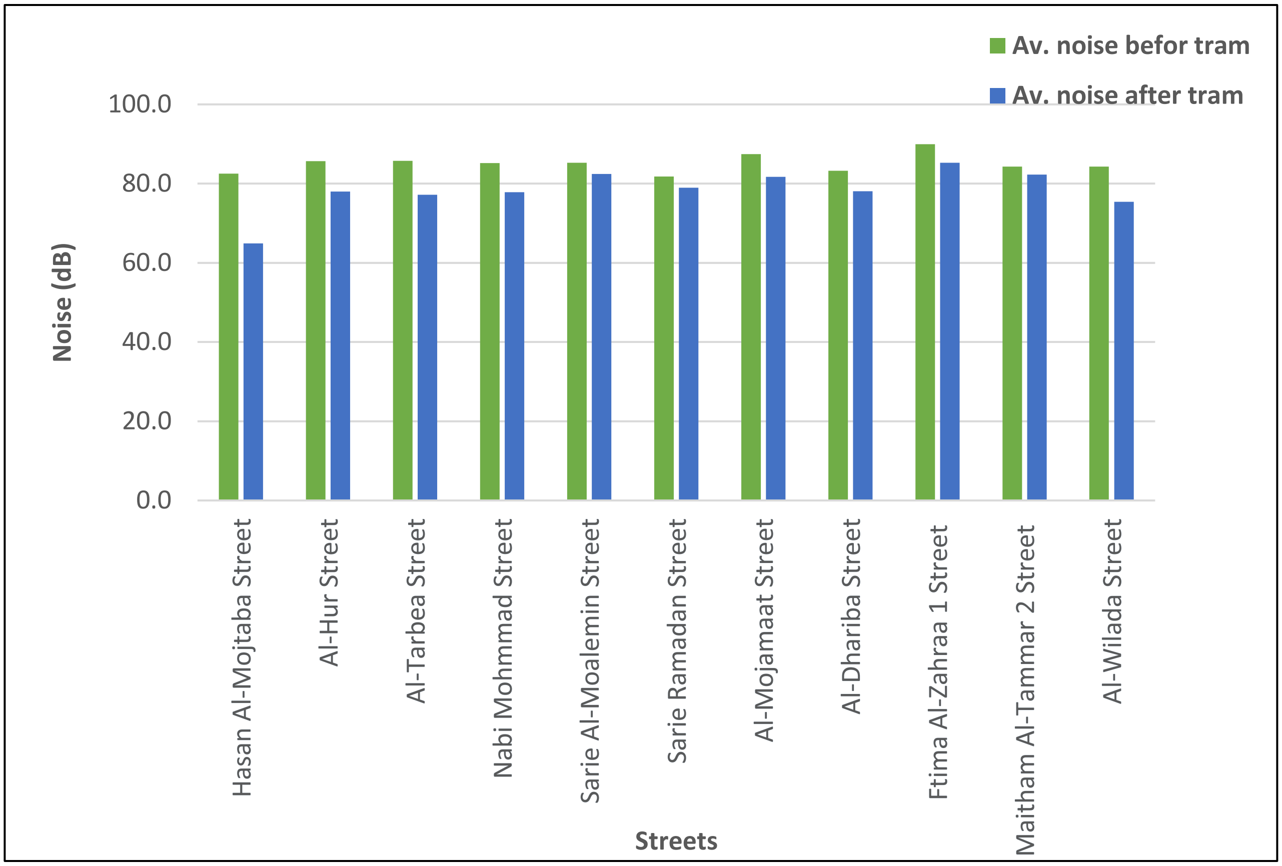

Figure (6.18): Comparison of average noise levels before and after tram implementation.

CO concentrations had a significant drop in most locations, with reductions ranging from approximately 13% to over 35%. This can be directly attributed to the modal shift from private and informal public transport to the tram, resulting in fewer internal combustion vehicles.

CO_2 emissions followed a similar pattern, though reductions were generally moderate (6-47%), reflecting both traffic volume reductions and potentially improved vehicle operating conditions (less idling and stop-and-go behavior).

Nitrogen dioxide (NO_2), a key traffic-related pollutant, experienced notable reductions, particularly in denser urban corridors. Some streets recorded decreases exceeding 60%, demonstrating the direct correlation between heavy traffic removal and NO_2 emission control.

The reductions in particulate matter $PM_{2.5}$ and PM_{10} were also substantial. Streets with high pre-tram congestion, such as Al-Mojamaat and Al-Tarbea Street, showed the highest improvements, with some cases exceeding 50%. These particles are known to originate from tire and brake wear, resuspension of dust, and diesel exhaust; thus, their decline is indicative of reduced vehicular stress and better air quality. However, it should be noted that variations exist among the streets. Differences in percentage reduction may be influenced by factors such as street width, the degree of tram segregation, pedestrian crossings, traffic calming features, and background pollution sources.

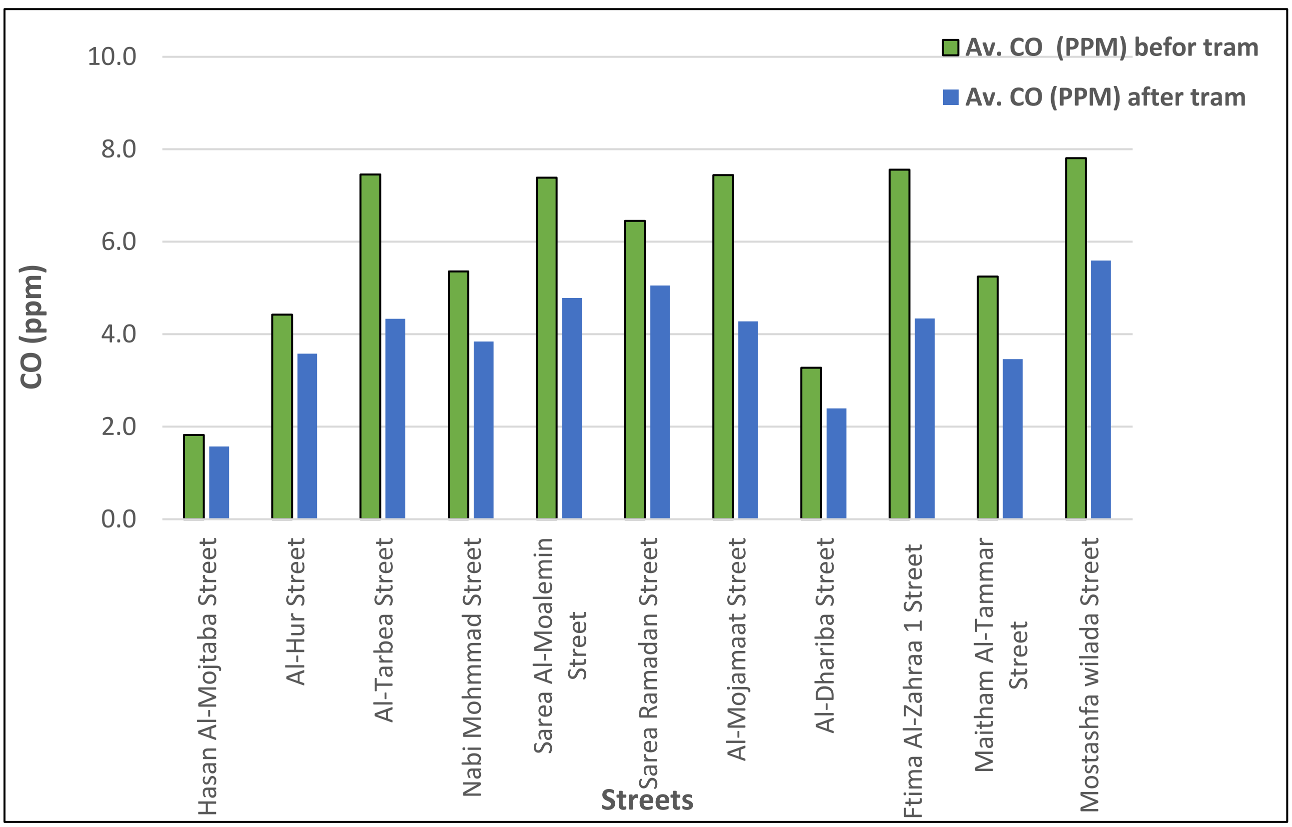

Figure (6.19): Comparison of average CO before and after tram implementation.

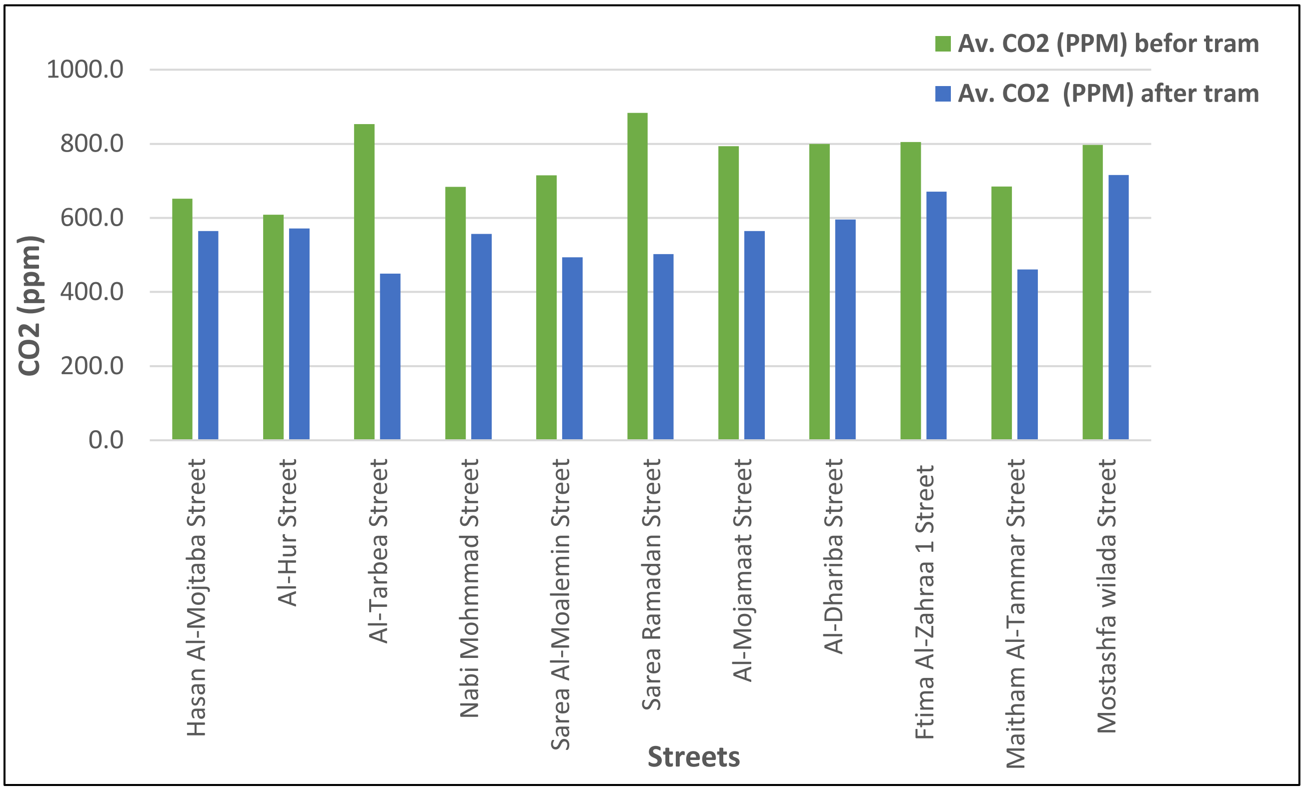

Figure (6.20): Comparison of CO_2 before and after tram implementation.

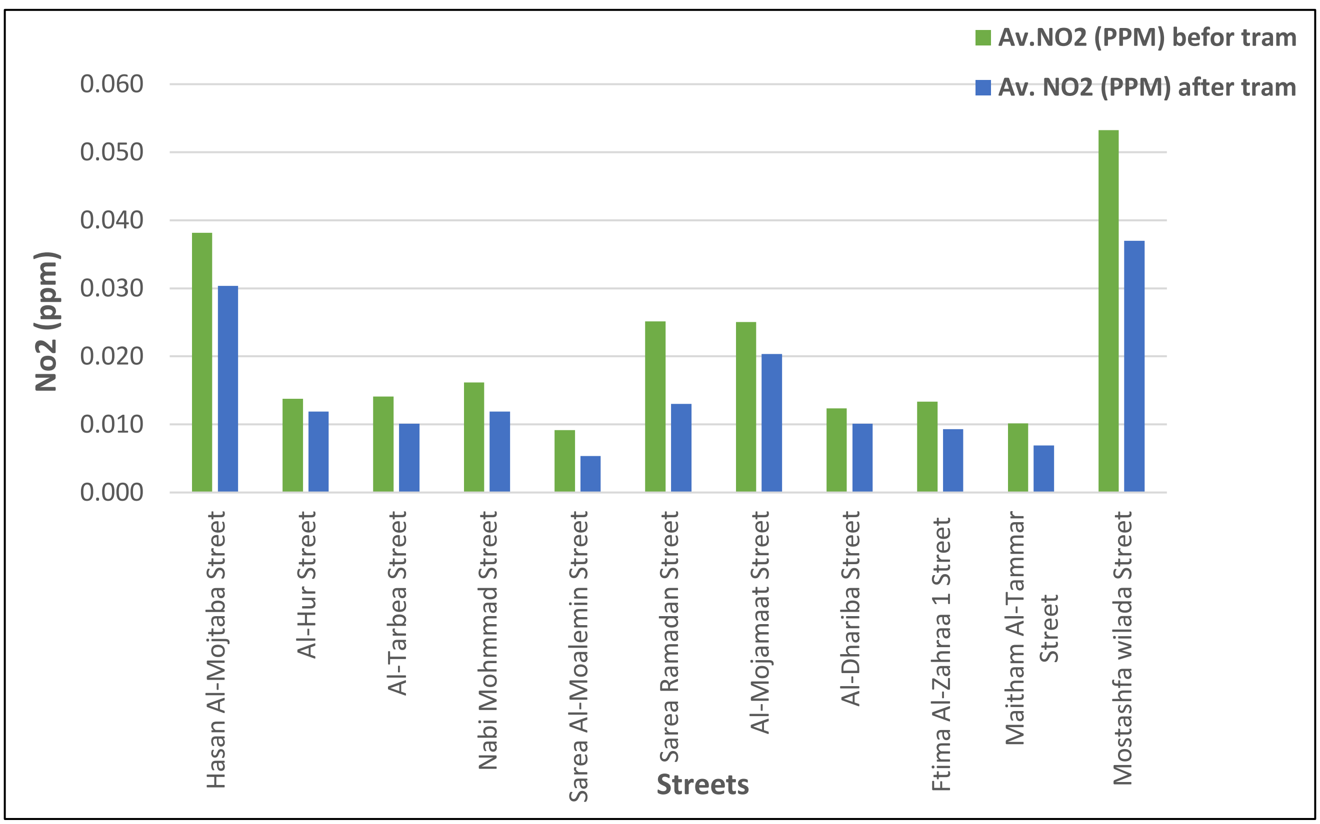

Figure (6.21): Comparison NO_2 before and after tram implementation.

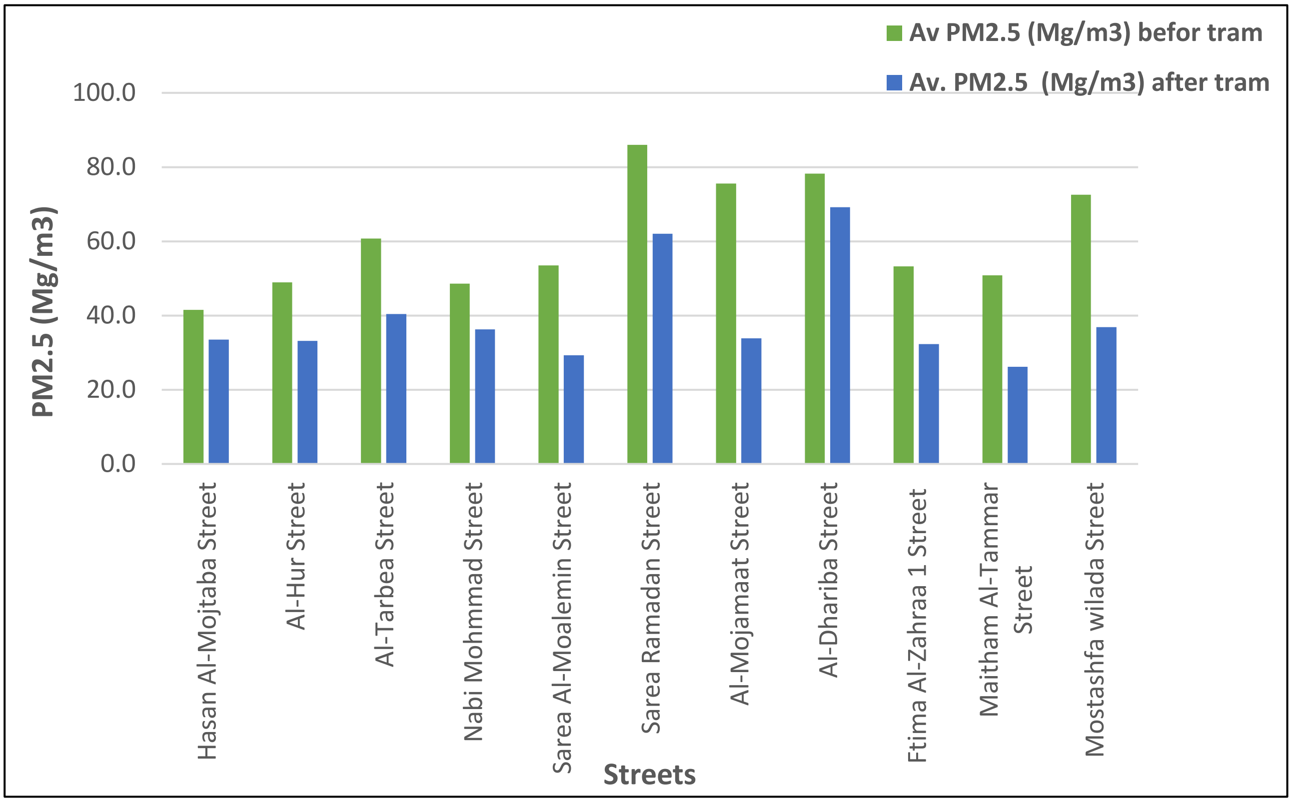

Figure (6.22): Comparison $PM_{2.5}$ before and after tram implementation.

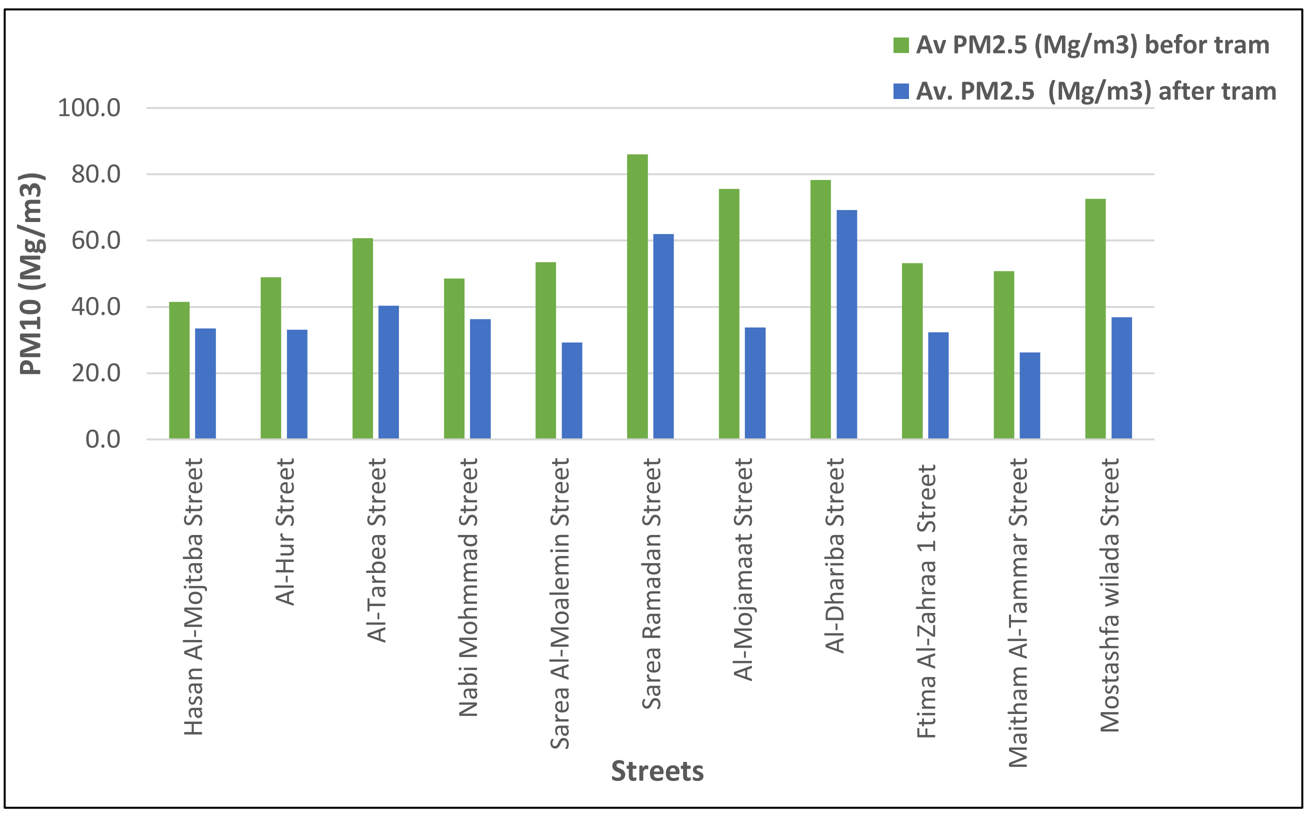

Figure (6.23): Comparison of PM_{10} before and after tram

Chapter Seven

Conclusions and Recommendations

7.1 Conclusions

Based on data surveyed and the results in the current study, the study concluded the following:

7.1.1.Traffic Data Analysis Results

1- According to the collected data on peak-hour traffic volumes, the highest recorded traffic flow was on Sarie Ramadan Street direction 1, with a maximum volume of 4144 veh/hr. This indicates that the street experiences severe congestion and serves as a major urban arterial in the network.

2- In contrast, the lowest traffic flow was observed on Hasan Al-Mojtaba Street direction 2, with only 1606 veh/hr, reflecting relatively low traffic demand or higher operational efficiency in that direction.

3- Regarding average travel speeds, Karbala–Najaf Street reported the highest speed of 44 km/hr, which suggests a relatively uncongested route with smooth flow conditions during the observation period.

4- The lowest average travel speed was recorded on Fatima Al-Zahraa 1 Street, at just 16 km/hr, indicating severe congestion and possibly inefficient signal coordination or high pedestrian activity.

5- According to the free flow speed classification, approximately 55% of the studied streets were designated as Class II (55–70 km/h), reflecting moderate operational conditions commonly seen in urban corridors with balanced traffic and access functions. Conversely, only 16% were qualified as Class I (≥70 km/h), indicative of arterial routes with high mobility and limited conflict points.

6- The LOS evaluation indicated that around 80% of all street directions fall within the critical thresholds of LOS D, E, and F. Specifically, 40% of directions were rated at LOS F (severely congested), while 30 % operated under LOS E, suggesting saturated flow and limited maneuverability. Only 4% of directions achieved LOS B, and none reached LOS A conditions.

7- Generally, a consistent nonlinear inverse relationship between traffic flow and travel speed was observed across all evaluated corridors. As traffic volumes surpassed 2500–3000 veh/hr, average speeds declined below 20 km/h, reflecting the onset of unstable flow conditions. The correlation coefficients (R^2 values) ranging between 0.765 and 0.896 reinforce the statistical reliability of these findings.

8- Environmental noise levels exceeded permissible thresholds outlined by the WHO (70 dB) and CPCB (65 dB) across all study streets. Notably, Ftima Al-Zahraa 2 and Sarie Ramadan streets recorded peak values of 91.55 dB and 90.33 dB, respectively. Regression analyses demonstrated strong relationships between noise and heavy vehicle percentage, with R^2 exceeding 0.9 in multiple cases, confirming the dominance of truck activity in noise generation.

9- In terms of air pollution, the emission of major pollutants, including CO, CO_2, NO_2, PM2.5, and PM10, showed strong dependency on traffic flow and speed. Nonlinear regression models applied to key streets revealed high R^2 values for CO (up to 0.98), CO_2 (up to 0.96), and NO_2 (up to 0.95), suggesting a robust predictive capability based on traffic indicators. Emission intensity was particularly elevated under low-speed, high-volume scenarios, emphasizing the role of stop-and-go conditions in exacerbating urban air quality degradation.

10- Regarding the AQI, approximately 51.35% of the study streets were classified under unhealthy categories either 'Unhealthy' or 'Unhealthy for Sensitive Groups'. The most alarming cases were Fatima1 Street with an AQI of 188 and Maitham Al-Tammar1 Street with an AQI of 198, both far exceeding EPA-recommended thresholds. Only 48.65% of streets maintained 'Moderate' air quality levels. This distribution highlights the chronic nature of pollutant exposure in the urban fabric of Karbala, with implications for public health, especially among children, the elderly, and individuals with respiratory conditions.

11- Delay time analysis revealed severe congestion on streets such as Maitham Al-Tammar 2 Street with 234 sec, Bab Twerige Street with 219 sec, and Al-Iskan Street with 206 sec. Compared to lower-delay corridors like Al-Qebla Street with 48 sec, Al-Amel 2 Street with 65 sec, and Haidar Al-Karrar Street with a delay of 70 sec.

12- In terms of modal composition, private vehicles dominated the urban traffic mix with an average of 42.7%, while public transport modes remained significantly underrepresented. Buses comprised only 0.9% of the total fleet, and minibuses contributed around 10.4%. The lack of organized public transit systems aggravates congestion and pollution, underscoring the urgent need for integrated solutions such as tram networks to enhance urban mobility and environmental sustainability.

7.1.2.Tram Networks Results

1. Based on the nature of the case study and previous studies, five criteria were identified for the best Karbala tramway route’s locations: (traffic flow, land use, travel time, traffic pollution, and traffic noise), and they achieved the objectives, which were accessibility, environmental, and

traffic flow objectives. The cost, engineering, and geotechnical criteria have been neglected due to the nature of the Karbala earth surface which does not need for leveling process or rehabilitation of the soil therefore there will not be additional construction and rehabilitation cost.

2. The main criterion which has been decided for the locations of tram end stations was the land use, the land use as natural reserve, built up, water, agricultural, and existing industrial have been avoided. In contrast, the free zone land use, main roads and so on have been preferred as well as their locations should be near the city entrances.
3. The criteria for intermediate stations were land use, trip generation and attraction zones, social in terms of population, and accessibility within 300-500 meters of walking distance.
4. The AHP method was used for weighing the main criteria based on Saaty's nine-point comparison scale.
5. The result of the AHP weighting process showed that the traffic flow has the highest influence equal to 37.83% followed by land use which is equal to 29.43%, travel time of 19.11%, traffic emission, and traffic noise equal to 7.97% and 5.65% respectively.
6. The result of AHP for station criteria showed that the walking distance took a higher weight of 56%, land use took 12%, and population density weighed 12%.
7. Four routes were selected as the best alternatives, Route 1 with a total length of 20.18 km and with 32 stations. Route 2 has a total length of 14.17 km and 26 stations. The third Route, with a total length of 14 km and 26 stations, and the fourth route has 22 stations with a length of 12.88 km.

8. The results were five end stations, which were located at suitable locations on the north, south, west, and east sides of the city at entrances. The intermediate stations were divided into four groups: A, B, C, and D. Group A contained 32 stations, Group B contained 26 stations, Group C had 26 stations, and Group D had 22 stations. These locations of stations will provide service to the most populated districts of the city while integrating with major thoroughfares, crossroads, hubs, and bustling zones.
9. The distance between each station was from 300 m to 800 m.
10. The distances between Group A stations and nearest vital places were that 75% of stations were located at distances less than 150 m from nearest vital places, 13% of them located at distance less than 300 m, and 12% were more than 300 m up to 373 m. For Group B, 66% of stations were located at a distance of less than 150 m from the nearest vital places, 15% of them were located at less than 300 m, and 19% located at a distance of more than 300 m. For Group C, 41% of stations were placed at a distance less than 150 m, 23% at less than 300 m, and 36% were at more than 300 m up to 778 m. For Group D, 54% of stations were distributed at distances less than 150 m, 19% of stations were at distances less than 300 m, and 27% of stations were located at distances more than 300m up to 593 m.
11. The alternatives have been evaluated for ranking them based on evaluation criteria, which were accessibility in terms of tram travel time, service area around tram, residential areas close to stations, and construction cost per kilometer of each line. The CRITIC and EDAS models have been used.
12. The results of alternatives evaluation showed that Route 1 has a higher rank, and it can be decided that Route 1 is the best route that meets the

evaluated criteria, followed by Route 2, and Route 4; on the contrary, Path 3, which took the lowest rank.

7.1.3 Results of the Impact of Tram Simulation on Urban Transport

1. According to the stated preference survey, 22% of private vehicle users and 76% of informal/shared transport users expressed willingness to shift to tram usage. This mode shift assumption was pivotal in estimating future traffic volumes, supporting the credibility of improved LOS, speed, and emissions in the post-tram scenario.
2. Based on the simulation analysis conducted using VISSIM, the implementation of an urban tram network in Karbala resulted in a substantial enhancement of traffic operational conditions. The proportion of streets experiencing critical congestion (LOS F and E) declined from 70% to 0%, while LOS C became the dominant condition (64.3%) following tram integration.
3. According to the simulation outputs, average vehicular speeds increased significantly across the network. Streets such as Al-Mojamaat and Al-Tarbea exhibited speed improvements of 131.4% and 92.9%, respectively. These enhancements were linked to infrastructure modifications, including the introduction of median tram corridors and pedestrian overpasses, which minimized traffic interference and pedestrian conflicts.
4. Generally, time delay experienced notables' reductions in post-tram implementation. For example, Al-Wilada Street observed a 65.0% drop in average delay, while Al-Mojamaat and Al-Tarbea followed closely with reductions of 64.8% and 63.6%, respectively. Such outcomes underscore the tram system's role in alleviating congestion hotspots.

5. With respect to acoustic performance, average noise levels decreased moderately in most streets. Hasan Al-Mojtaba showed the highest reduction at 21.32%, followed by Al-Tarbea with a percentage of 9.97% and Al-Wilada with a rate of 10.51%. Noise mitigation was mainly achieved through reduced vehicular volumes and smoother flow patterns.
6. The air pollution assessment revealed substantial environmental benefits. CO levels dropped by 13%–35%, CO_2 emissions by 6%–47%, and NO_2 levels by up to 60%. Particulate matter ($PM_{2.5}$ and PM_{10}) saw reductions exceeding 50% in highly congested streets. These results confirm the positive environmental impact of the modal shift from combustion vehicles to electric tram systems.

In general, the combined effect of reduced traffic volumes, exclusive tram rights-of-way, and priority signaling for trams resulted in improved urban mobility, decreased emissions, and enhanced quality of life indicators. These findings highlight the viability of tram systems as sustainable transport solutions in medium-density cities like Karbala.

7.2 Recommendations

1. The study recommends expanding the study area to include Karbala governorate, not just the city center.

2. Study models can be applied in other study areas, considering the criteria related to each study area, such as the existence of rivers, airports, and other facilities.

3- When applying a GIS model to a new study area, the criteria for Digital Elevation Model (DEM) should be taken into account, as it has a significant impact on the cost of constructing the tram. In this study, this criterion was neglected because the DEM of all parts of the city is almost the same.

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Appendices

Appendix- A

Traffic Volume Data

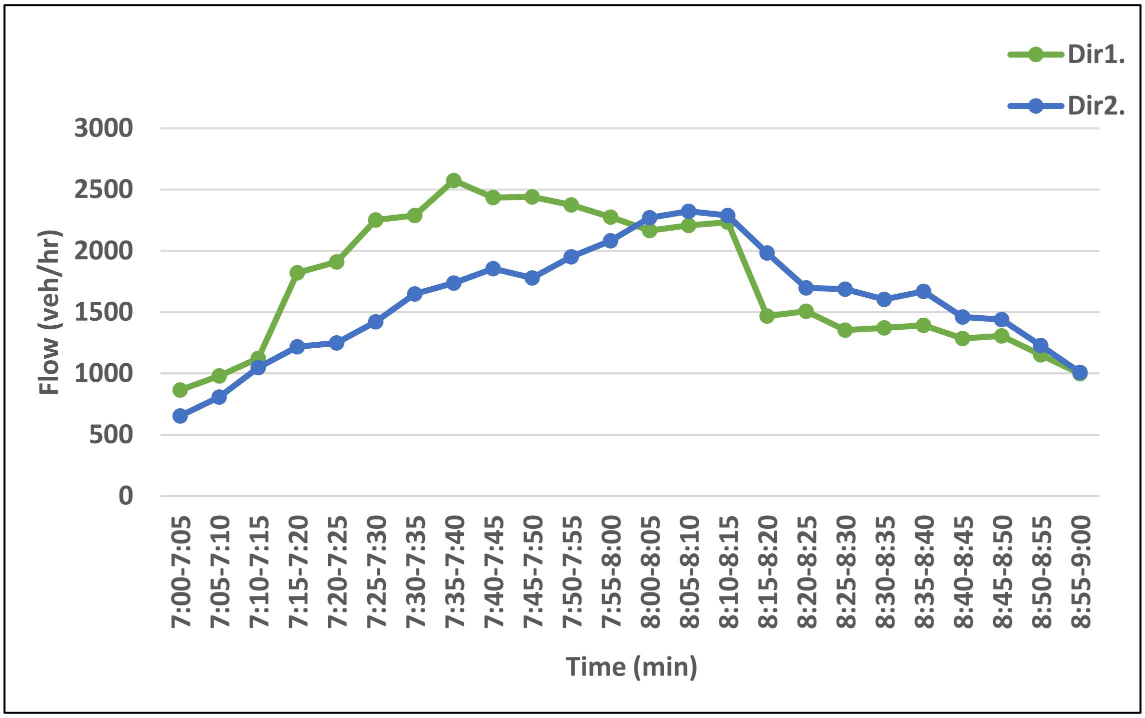

Figure (A-1): Al-Hur Street traffic flow.

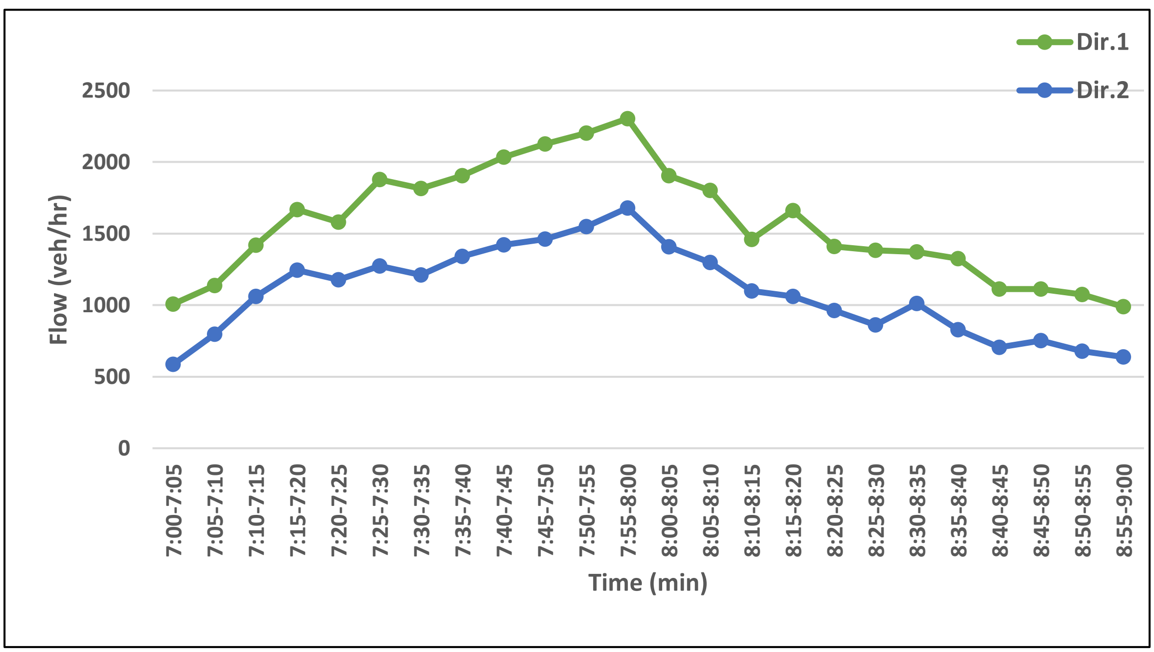

Figure (A-2): Bait Al-Mohafodh Street traffic flow.

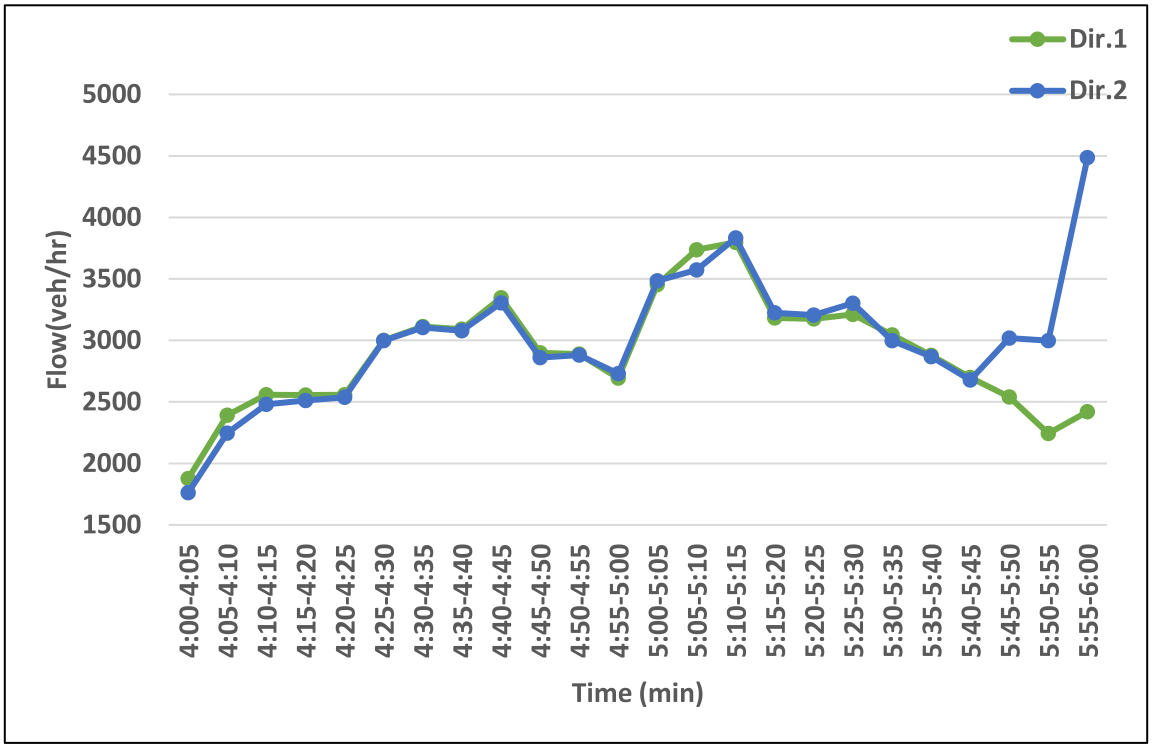

Figure (A-3): Al-Mojamaat Street traffic flow.

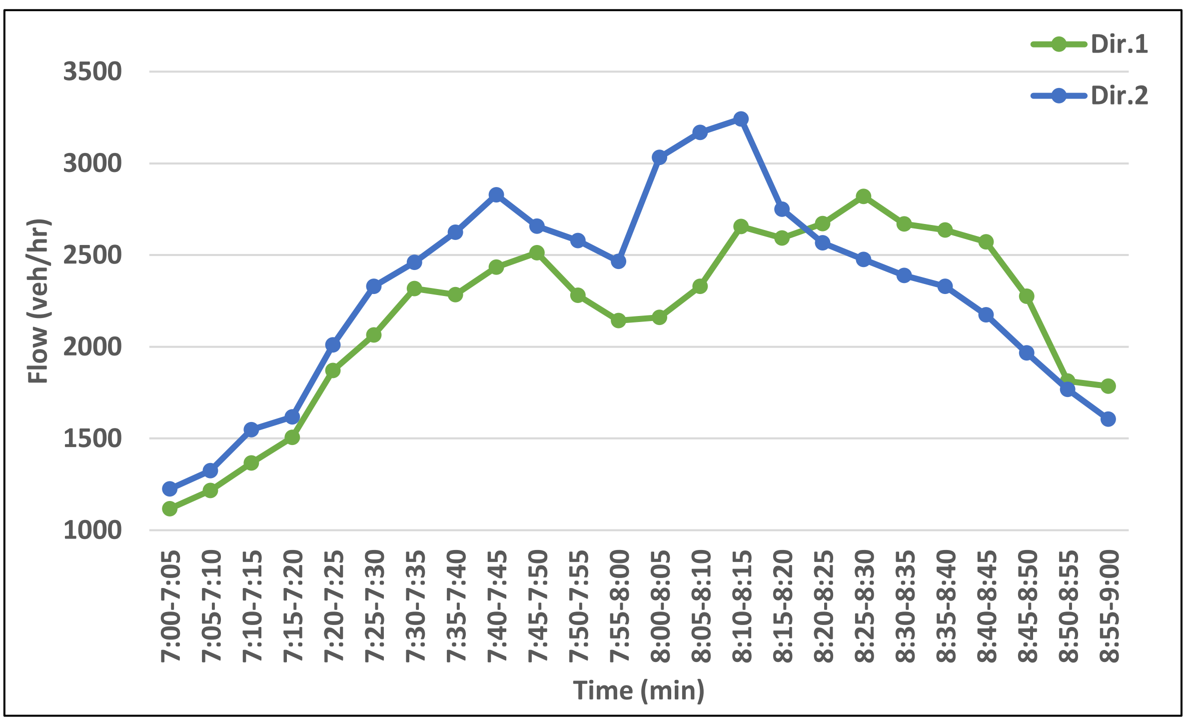

Figure (A-4): Al-Dhariba Street traffic flow.

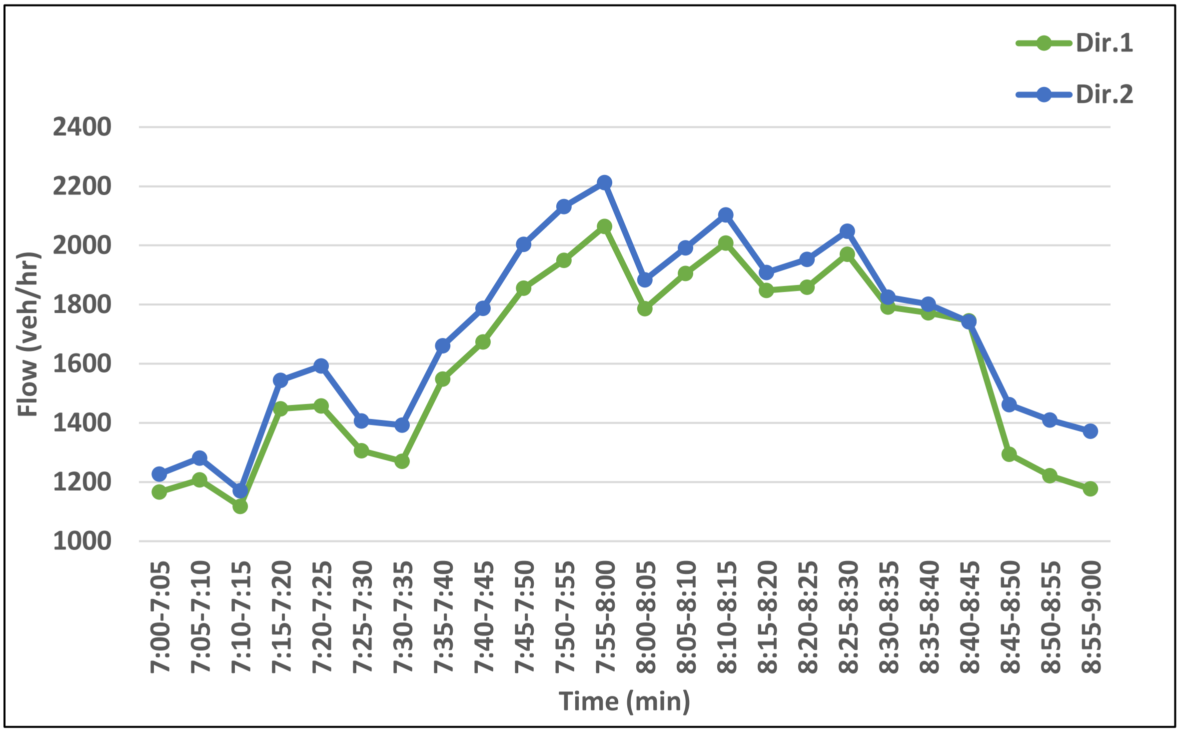

Figure (A-5): Qorfat Al-Tijara Street traffic flow.

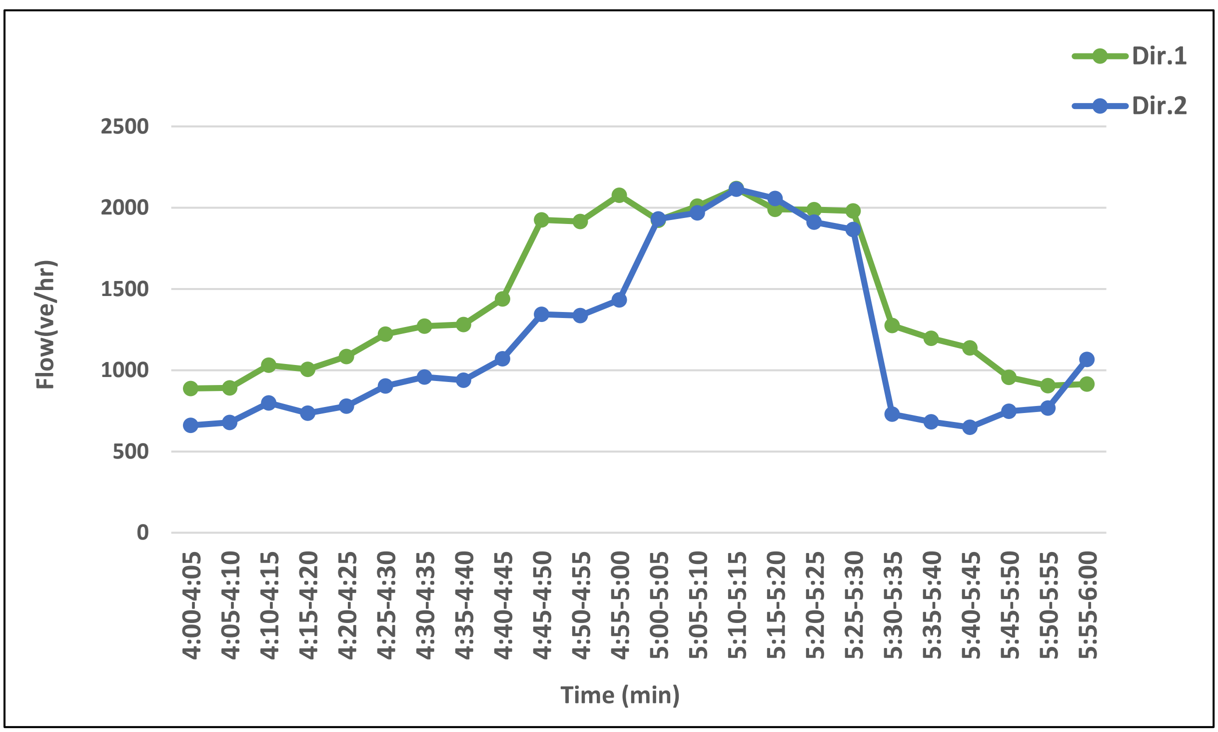

Figure (A-6): Al-Iskan Street traffic volume.

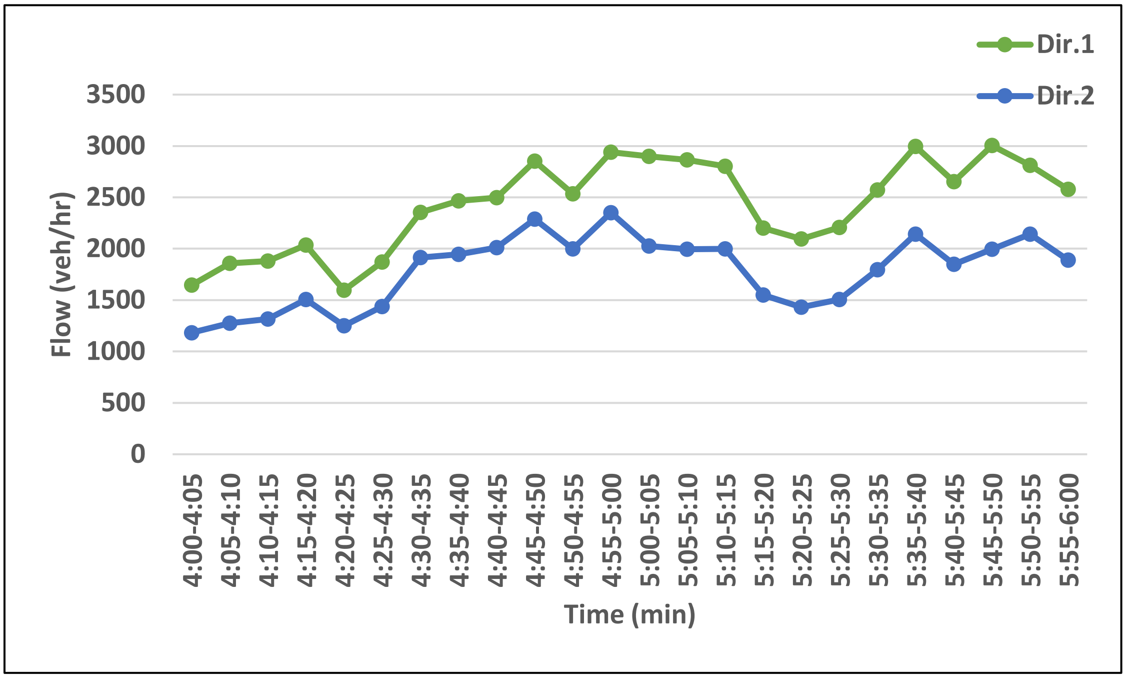

Figure (A-7): Fatima Al-Zahraa 1 Street traffic flow.

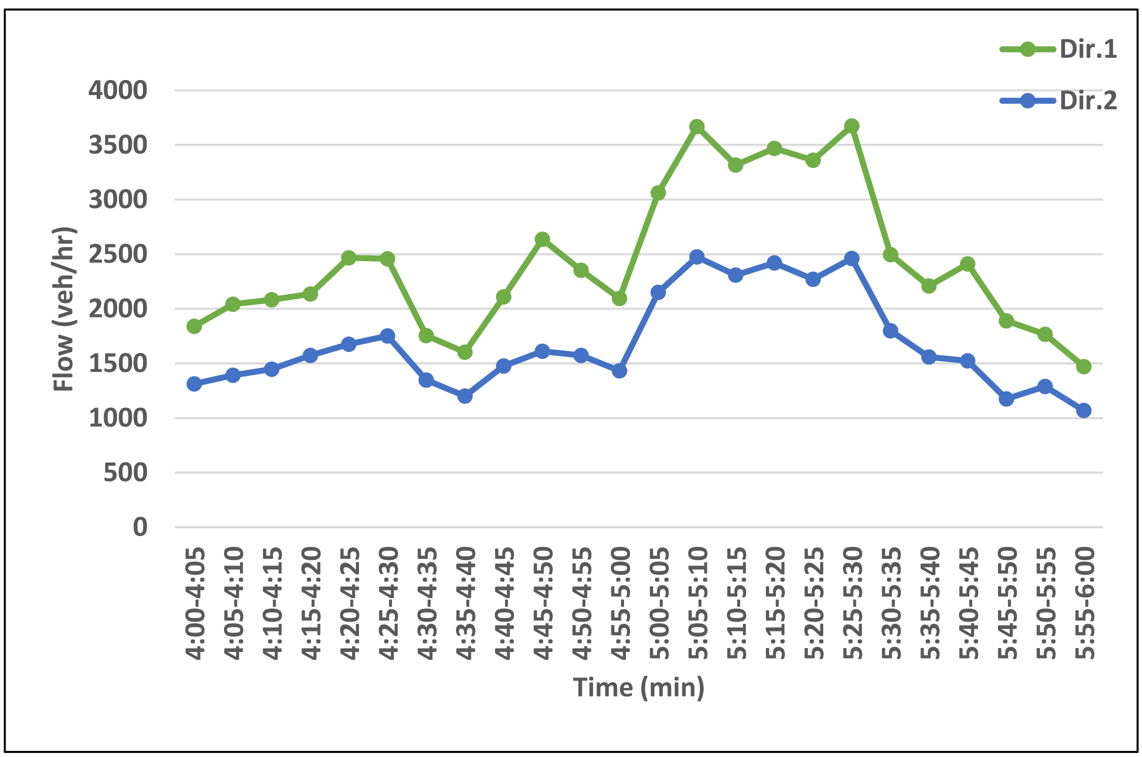

Figure (A-8): Fatima Al-Zahraa 2 Street traffic flow.

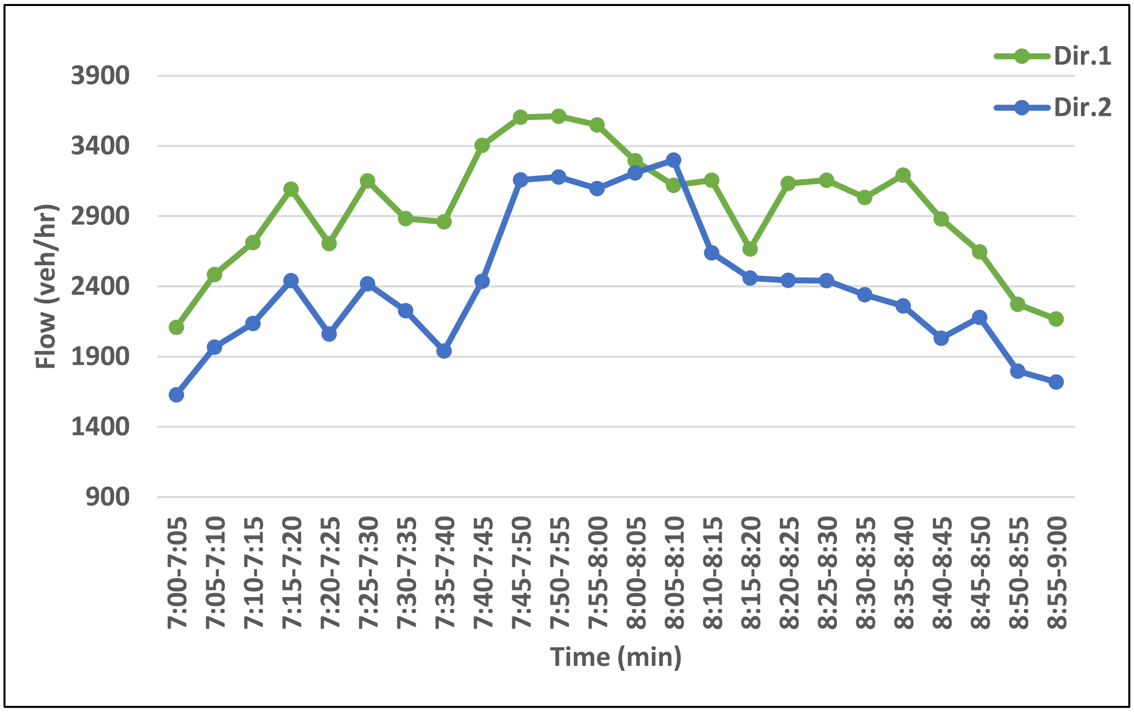

Figure (A-9): Haider Al-Karrar Street traffic flow.

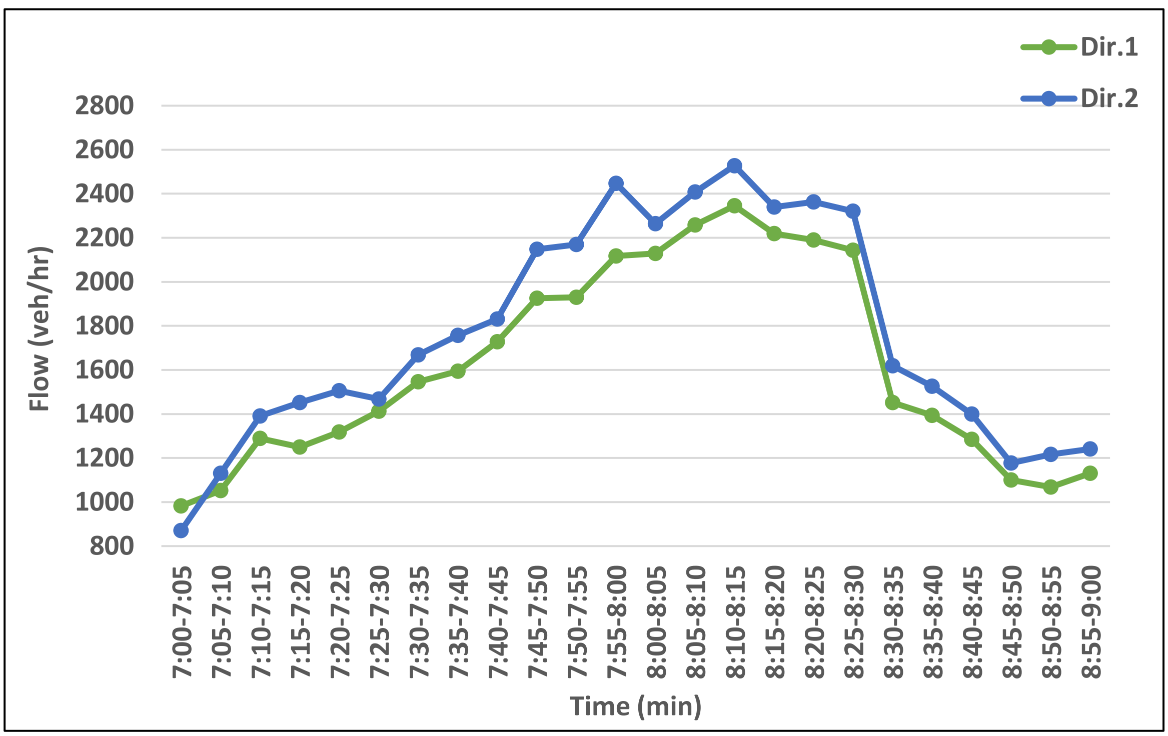

Figure (A-10): Al-Nasr Street traffic flow.

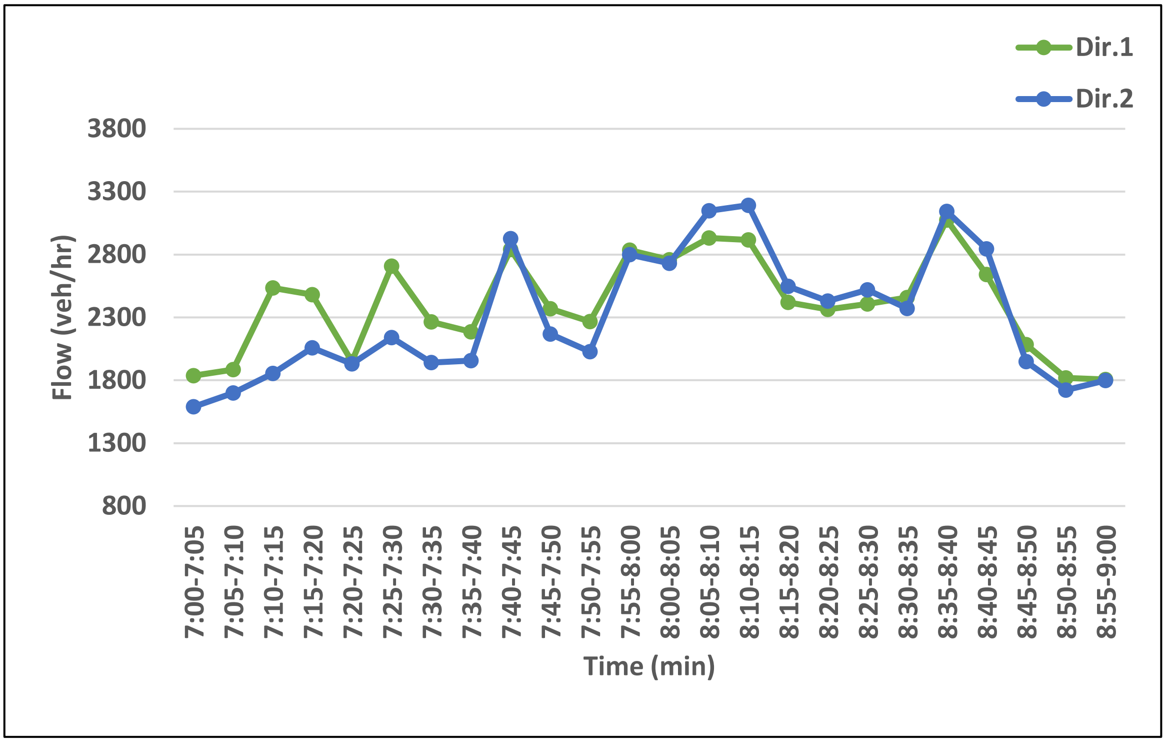

Figure (A-11): Abdolzahraa Al-Kaaby Street traffic flow.

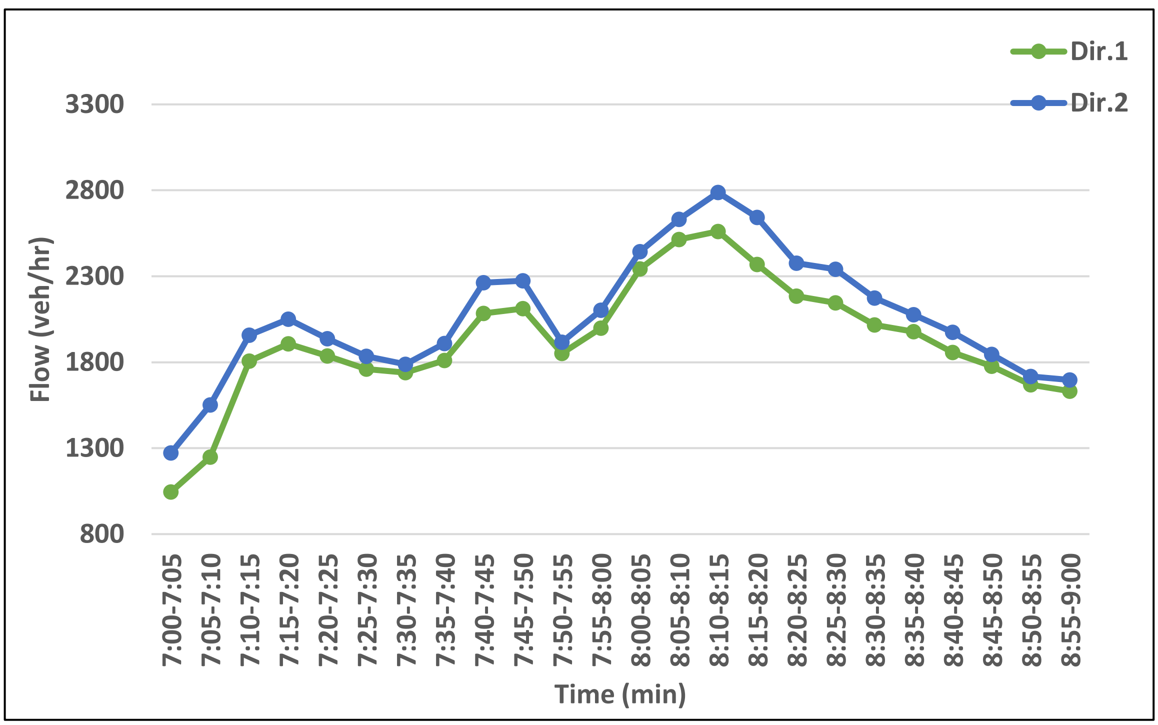

Figure (A-12): Karbala-Najaf Street traffic flow.

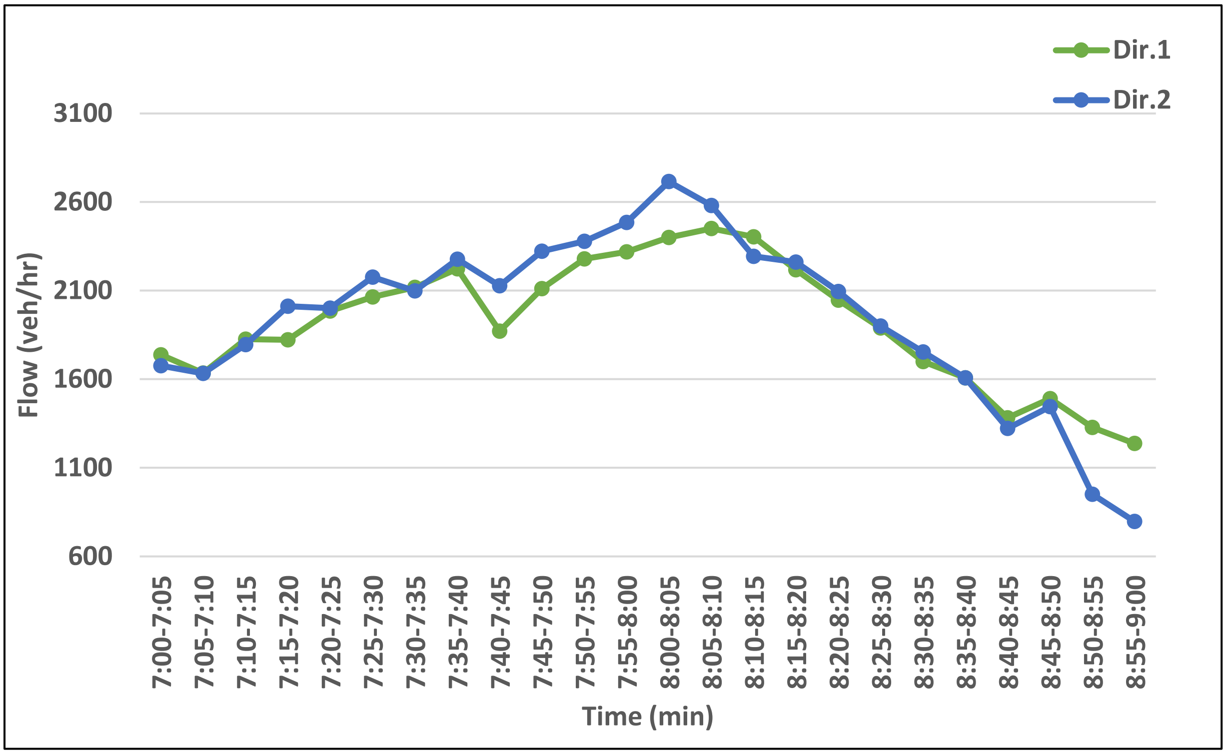

Figure (A-13): Bab Twerige Street traffic flow flow.

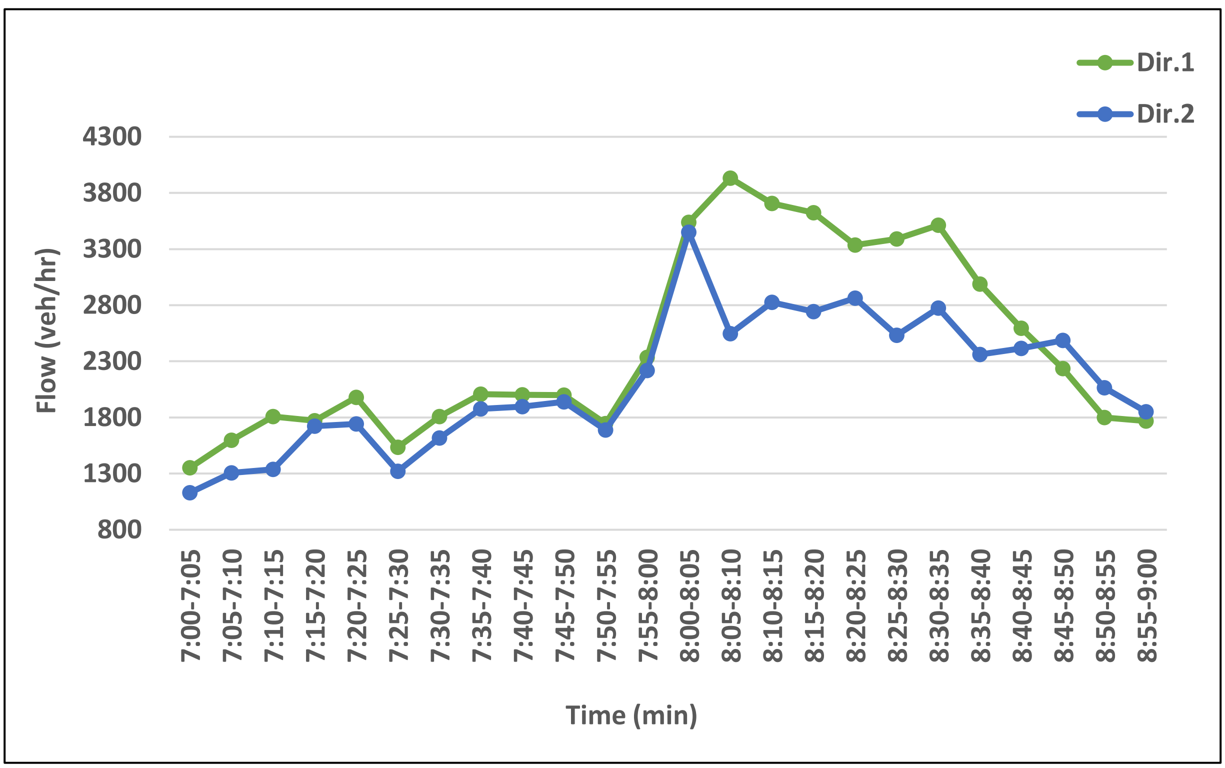

Figure (A-14): Karbala-Hindea Street traffic flow.

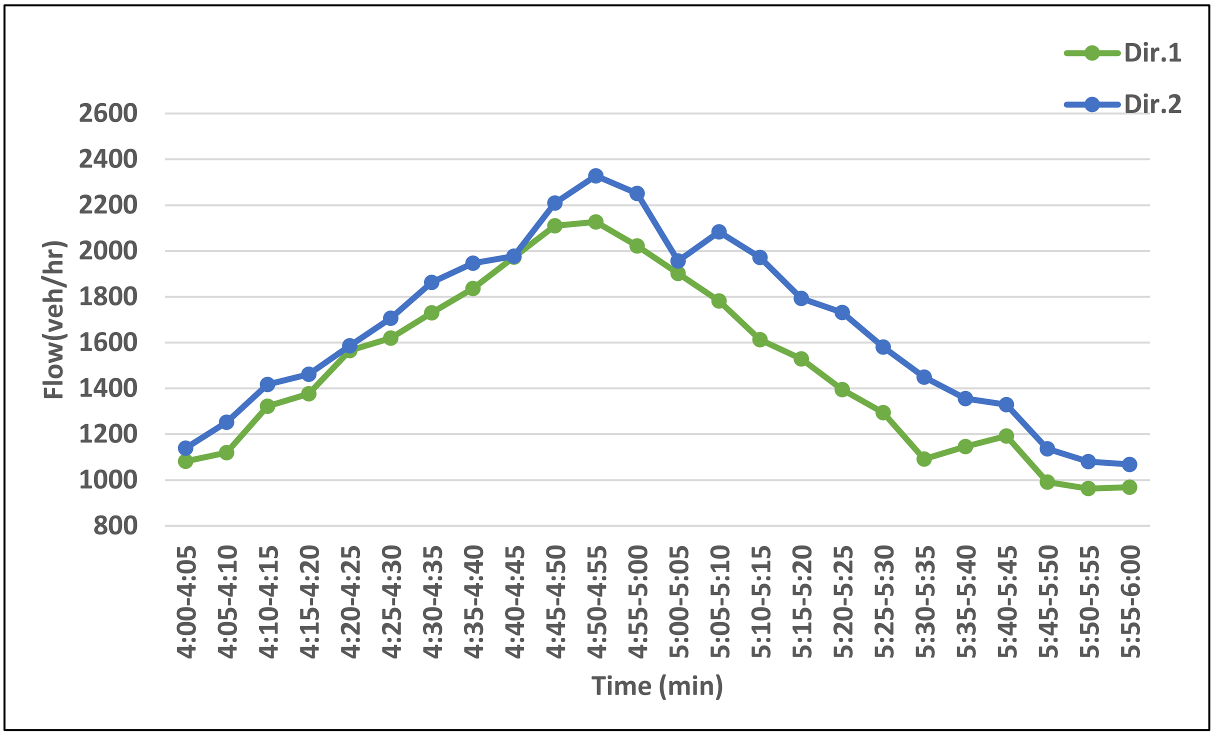

Figure (A-15): Maitham Al-Tammar 1 Street traffic flow.

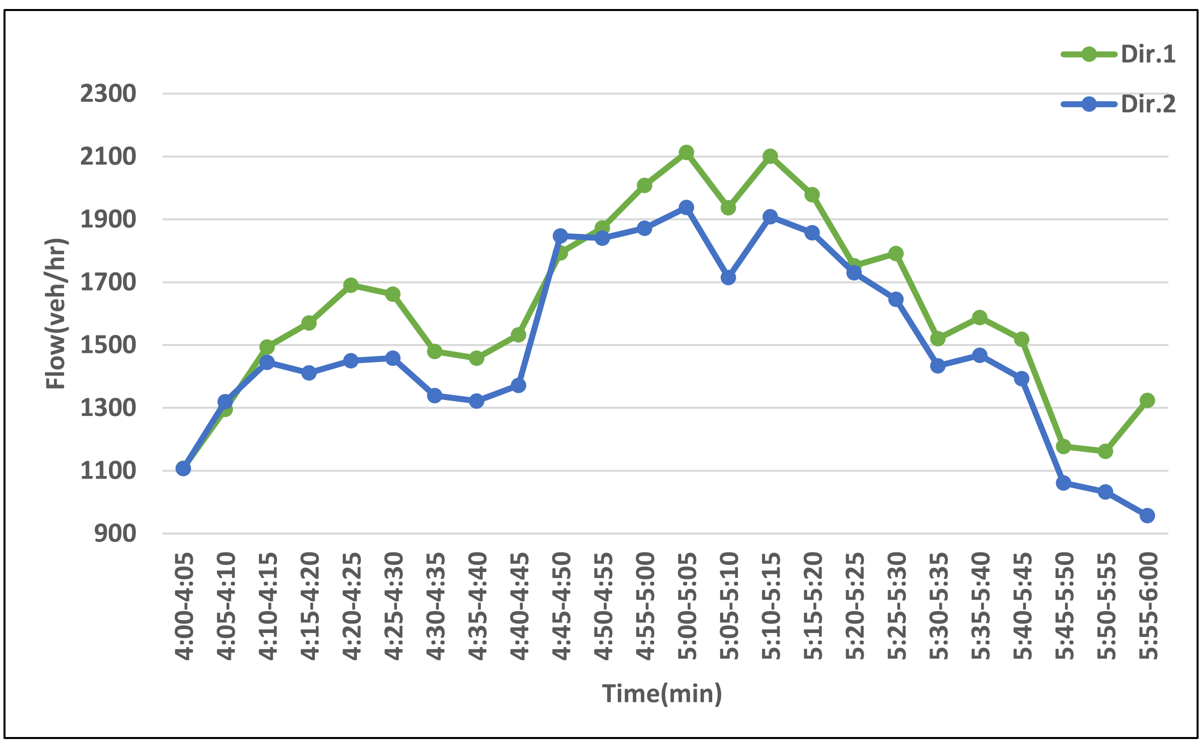

Figure (A-16): Maitham Al-Tammar 2 Street traffic flow.

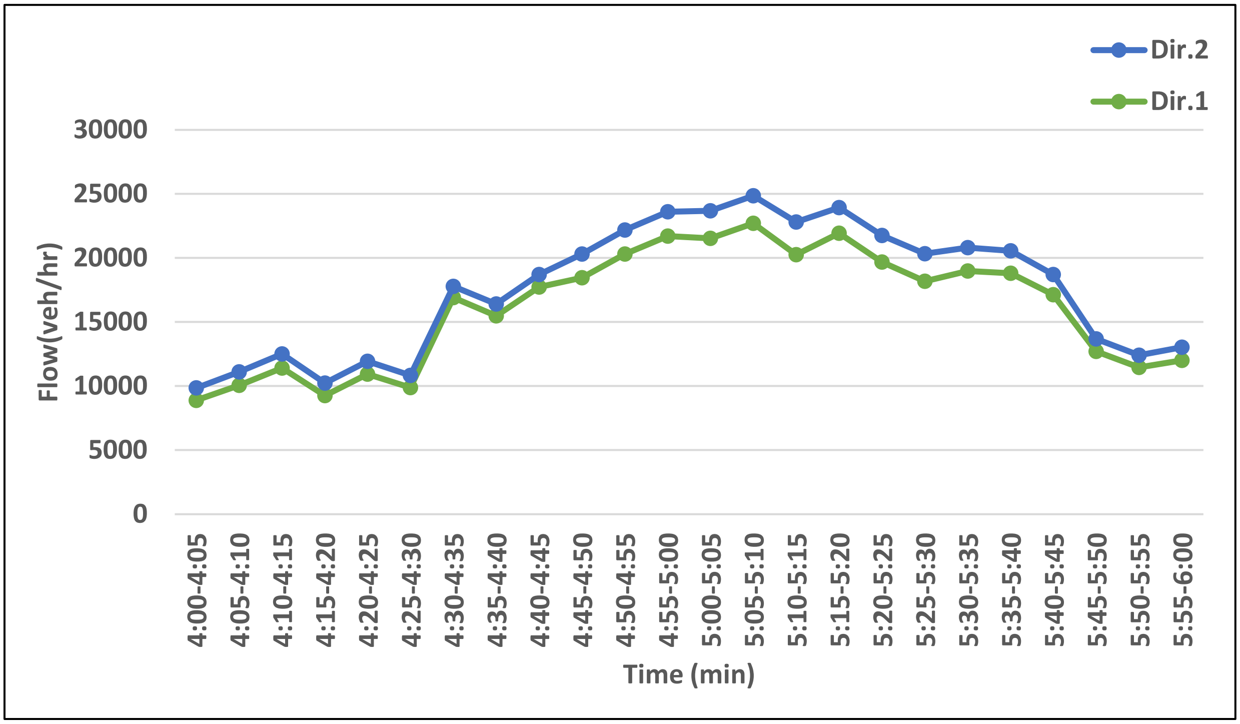

Figure (A-17): Maitham Al-Tammar 3 Street traffic flow.

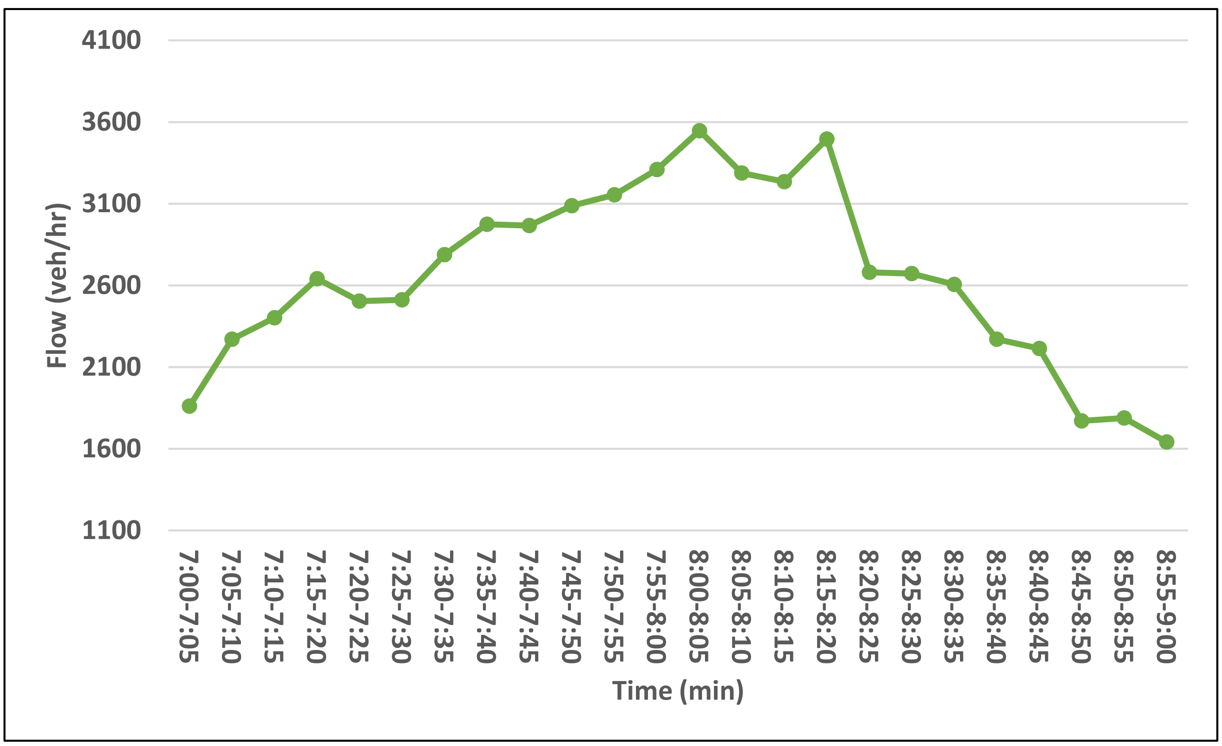

Figure (A-18): Al-Qebla Street traffic flow.

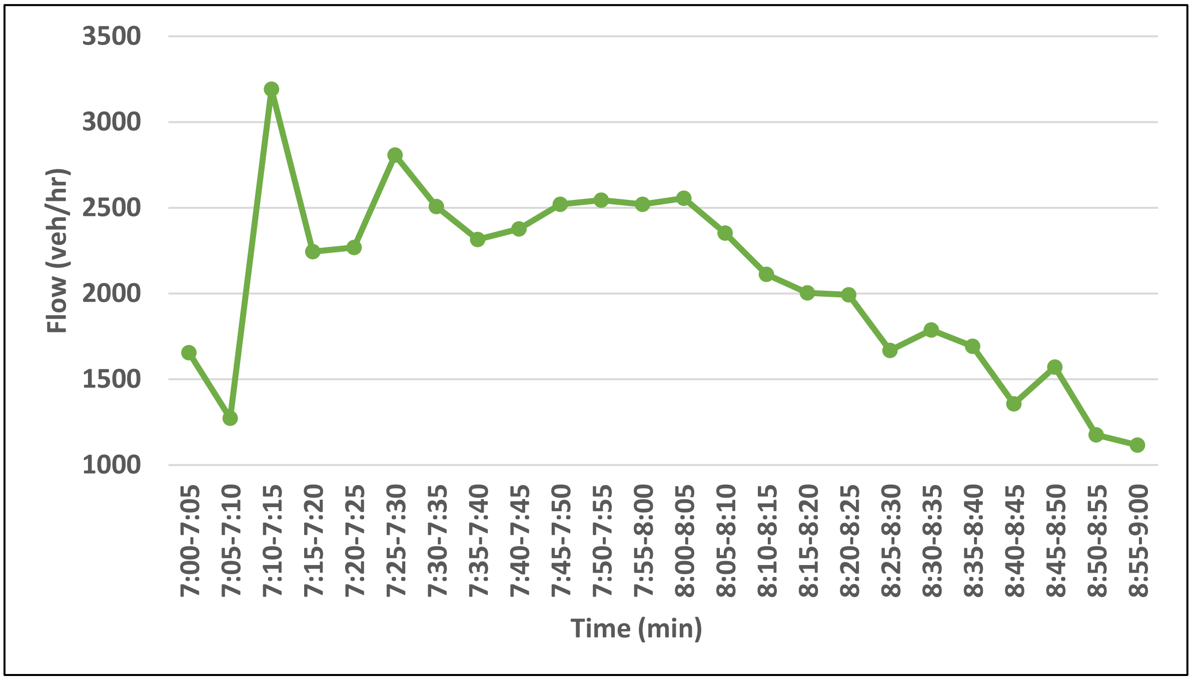

Figure (A-19): Karbala-Bagdad Street 1 to Bagdad Street traffic flow.

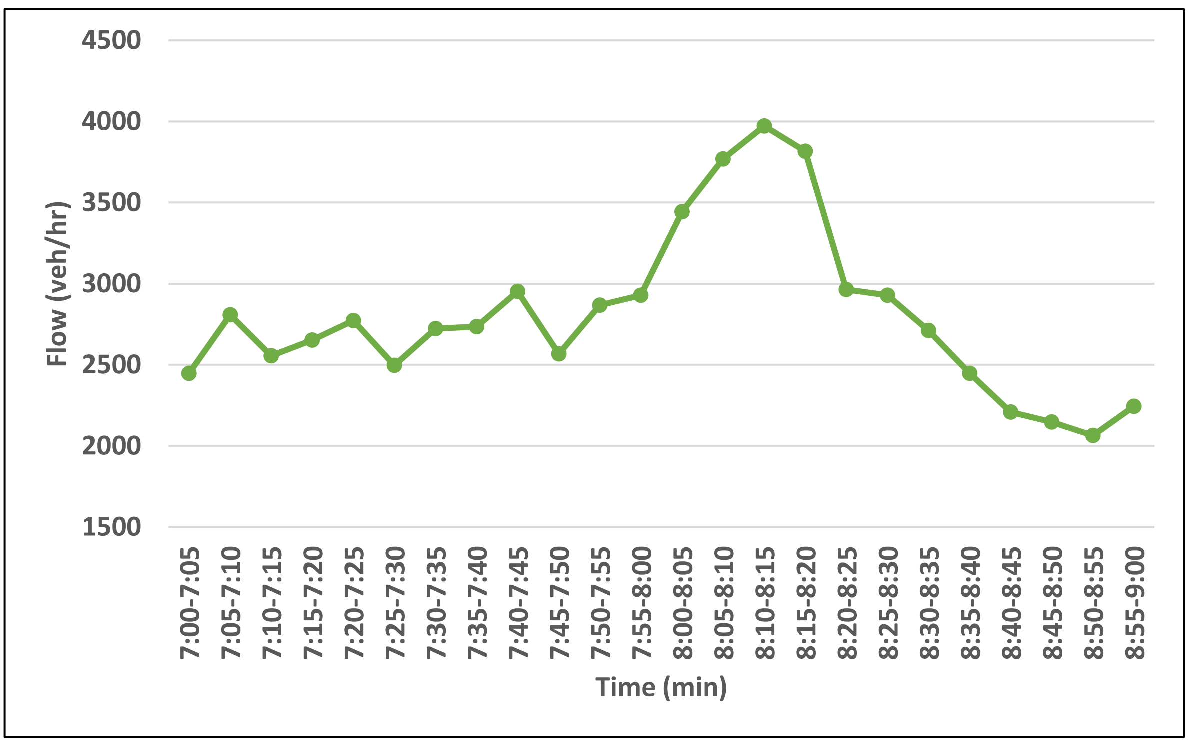

Figure (A-20): Karbala-Bagdad Street 2 from Bagdad Street flow.

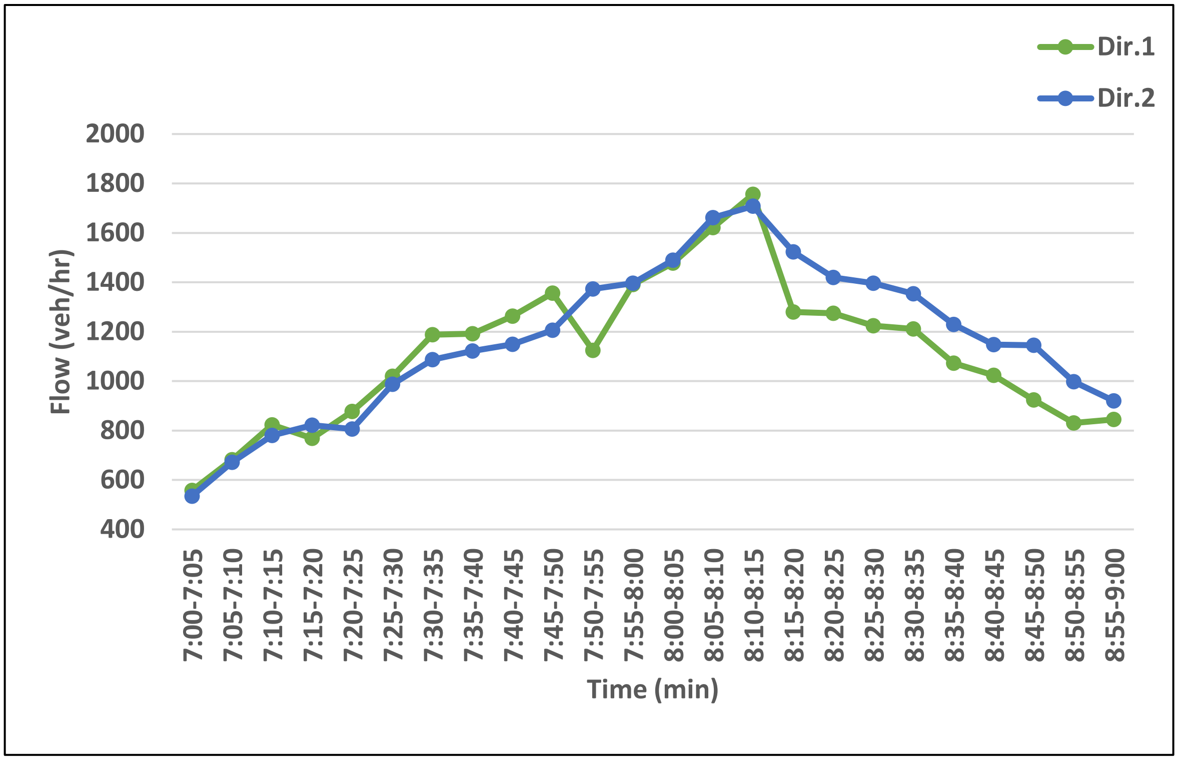

Figure (A-21): Al-Amel 2 Street traffic flow.

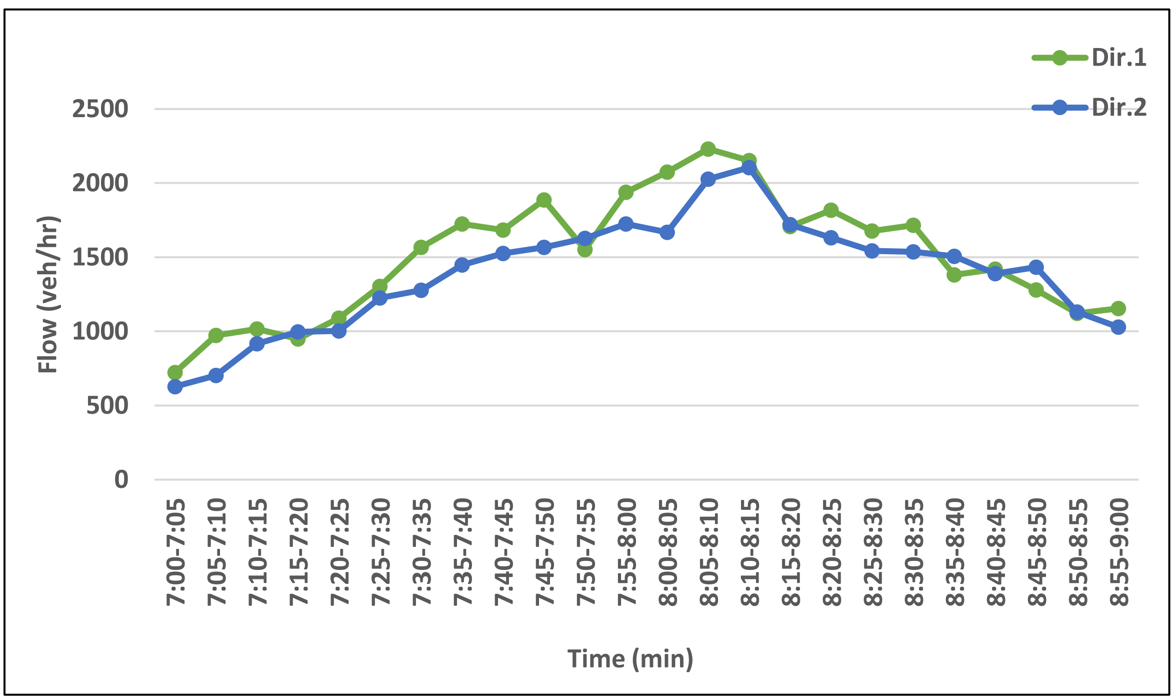

Figure (A-22): Al-Amel 1 Street traffic flow.

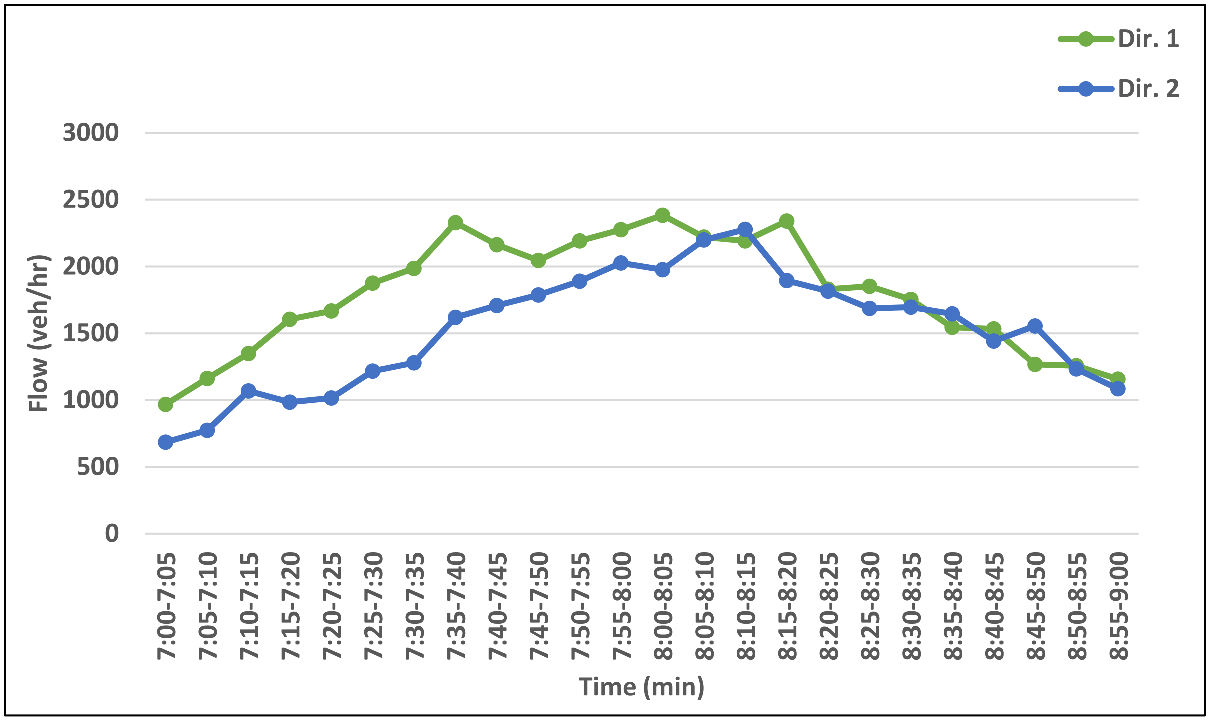

Figure (A-23): Hay Al-Hur Street traffic flow

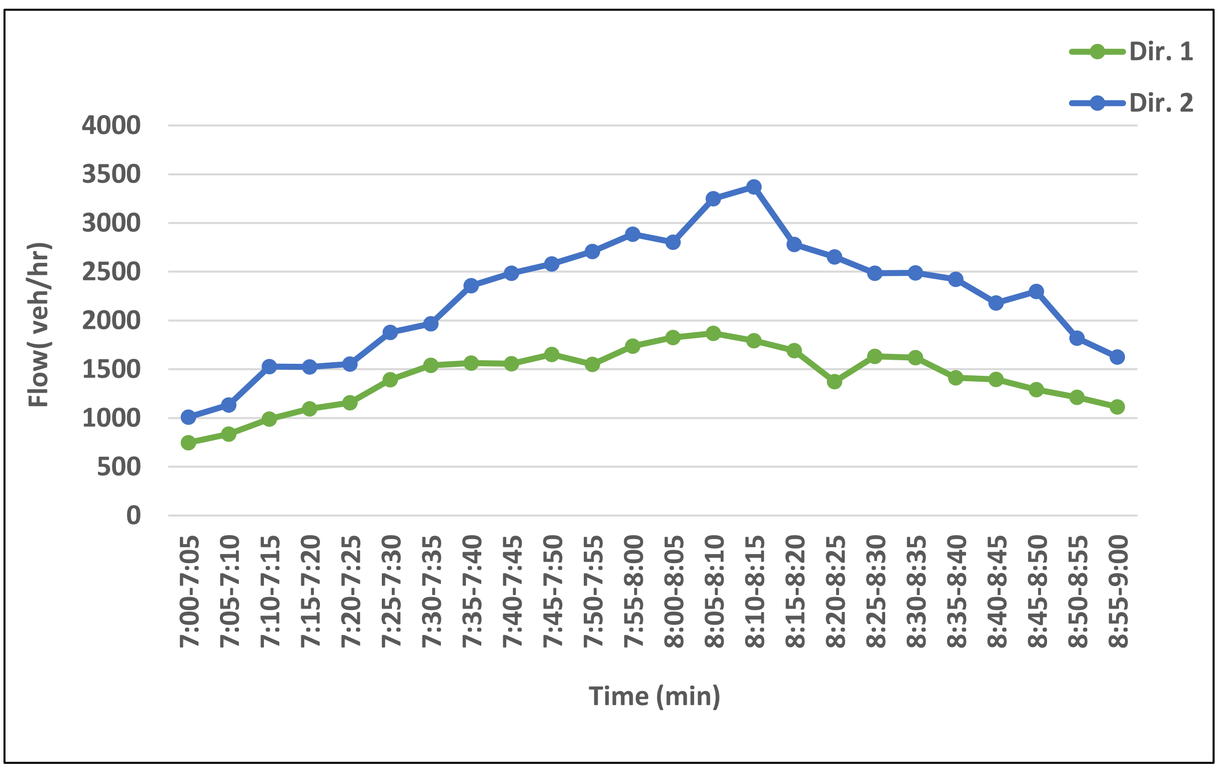

Figure (A-24): Hay Al-Moaalemin Street traffic flow.

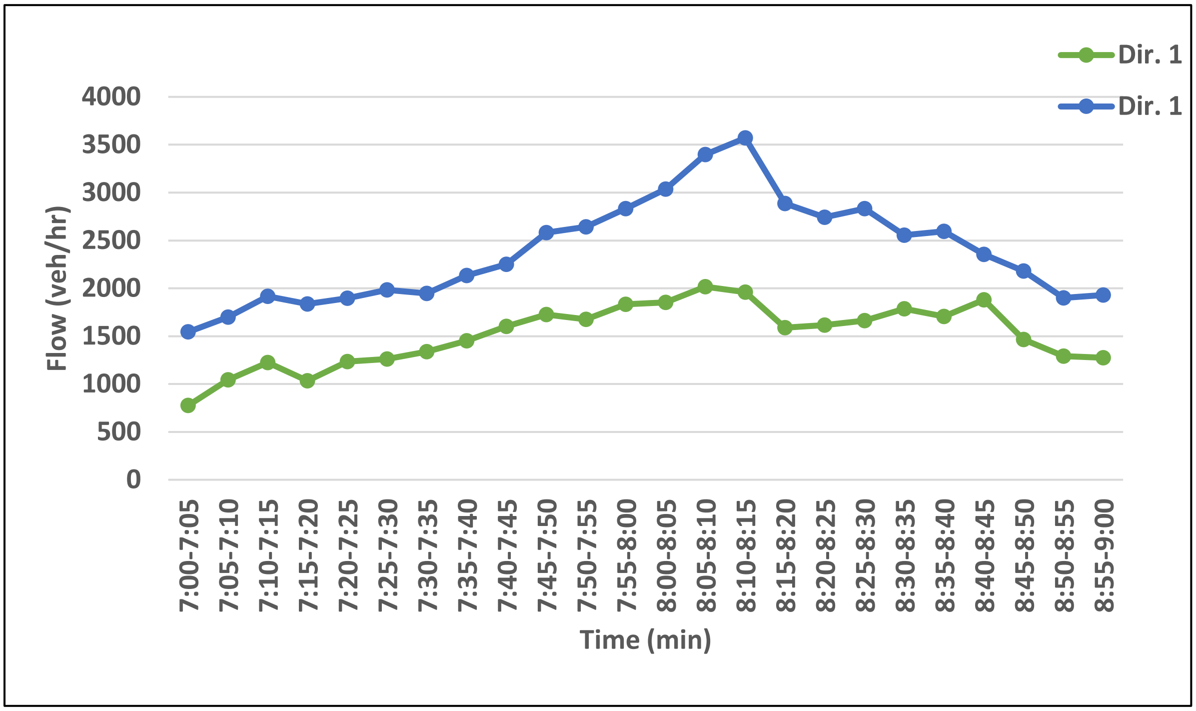

Figure (A-25): Al-Mowadhafin Street traffic flow.

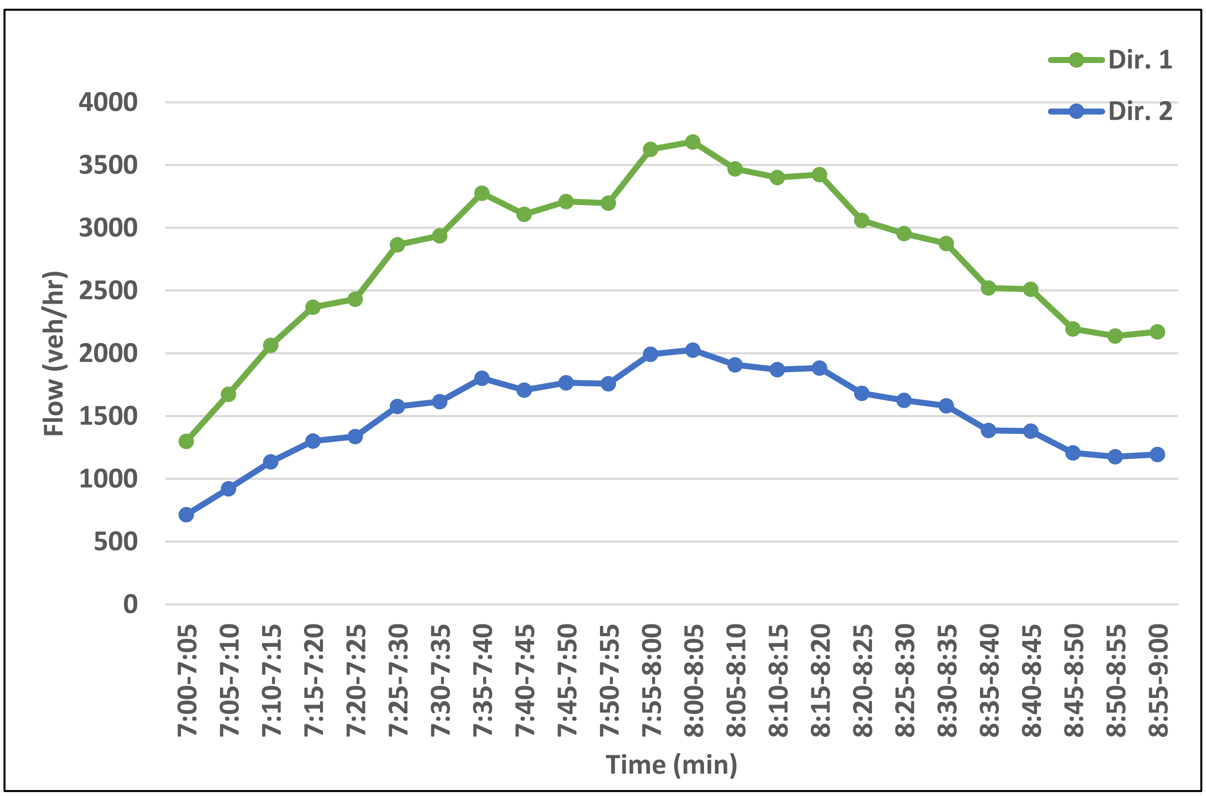

Figure (A-26): Al-Markaz Street traffic flow.

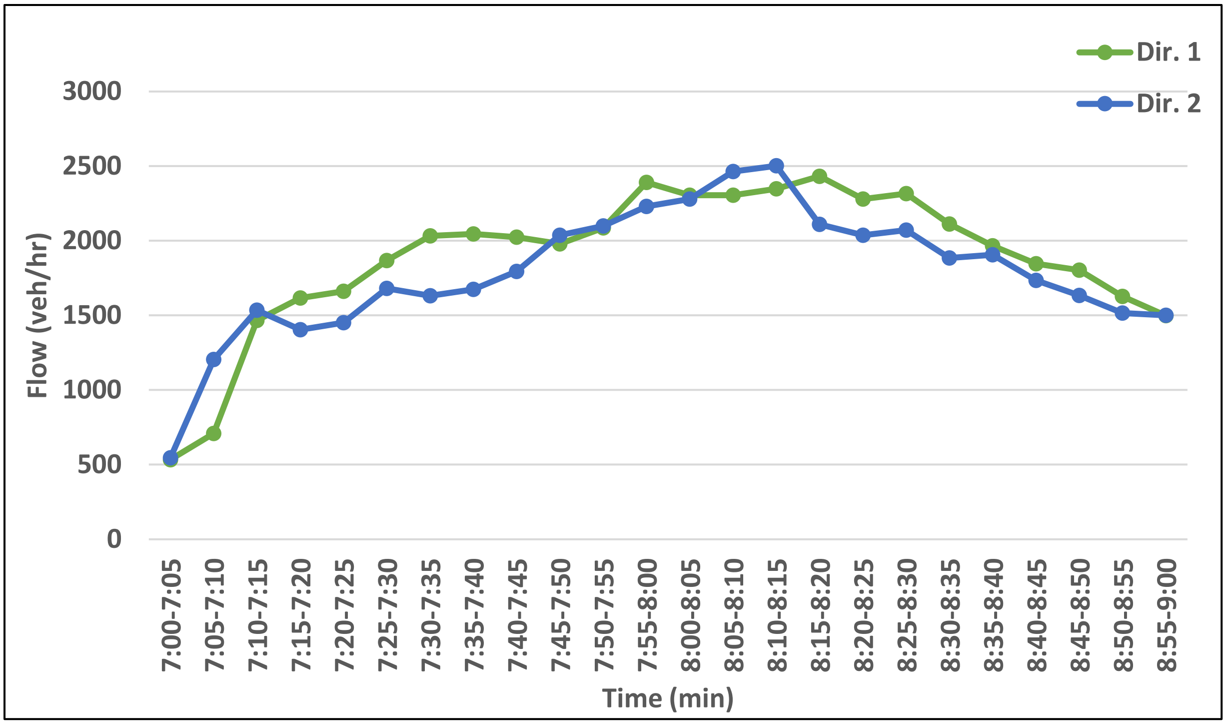

Figure (A-27): Imam Ali Street traffic flow.

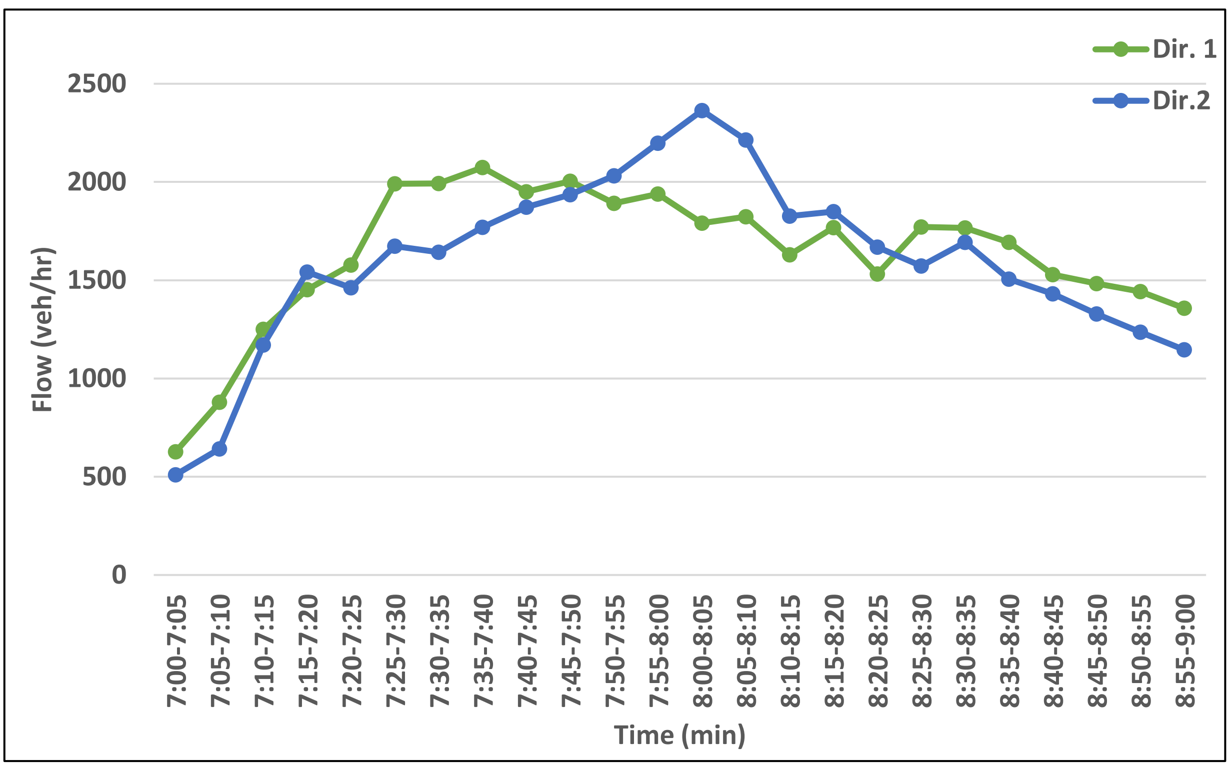

Figure (A-28): Al-Taalib Street traffic flow.

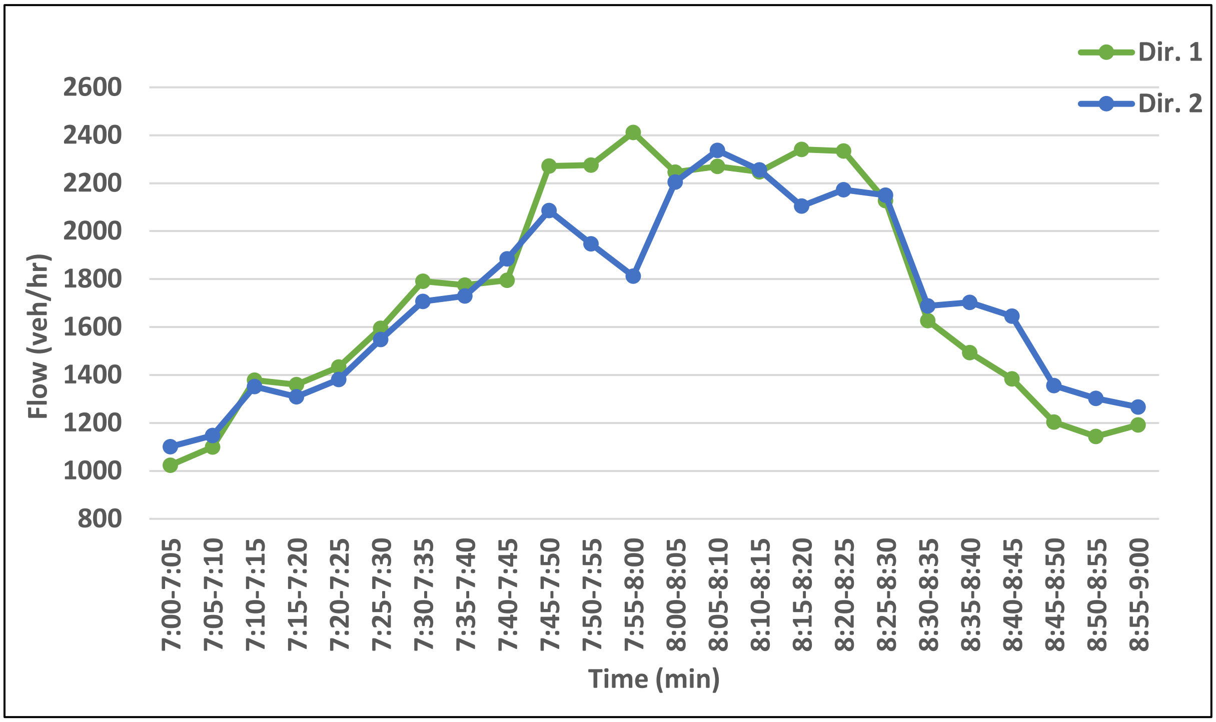

Figure (A-29): Al-Jahiz Street traffic flow.

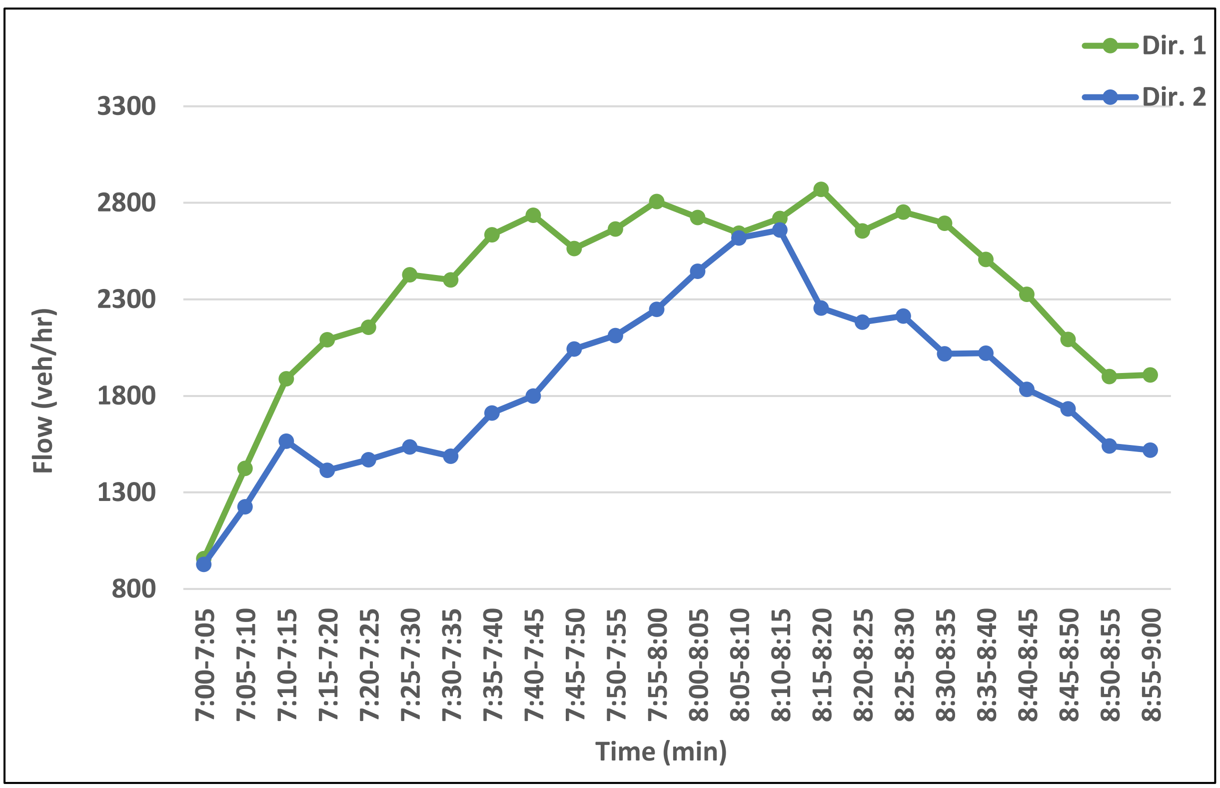

Figure (A-30): Shohadaa Al-Mowadhafin Street traffic flow.

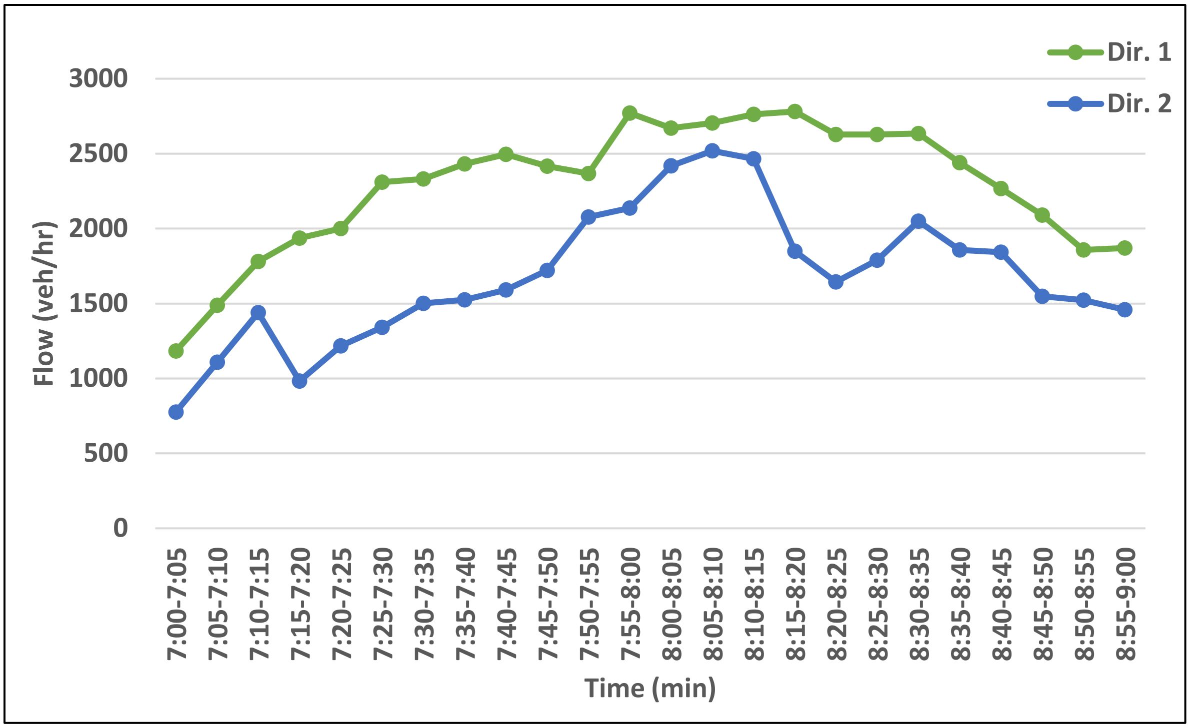

Figure (A-31): Al-Wilada Street traffic flow.

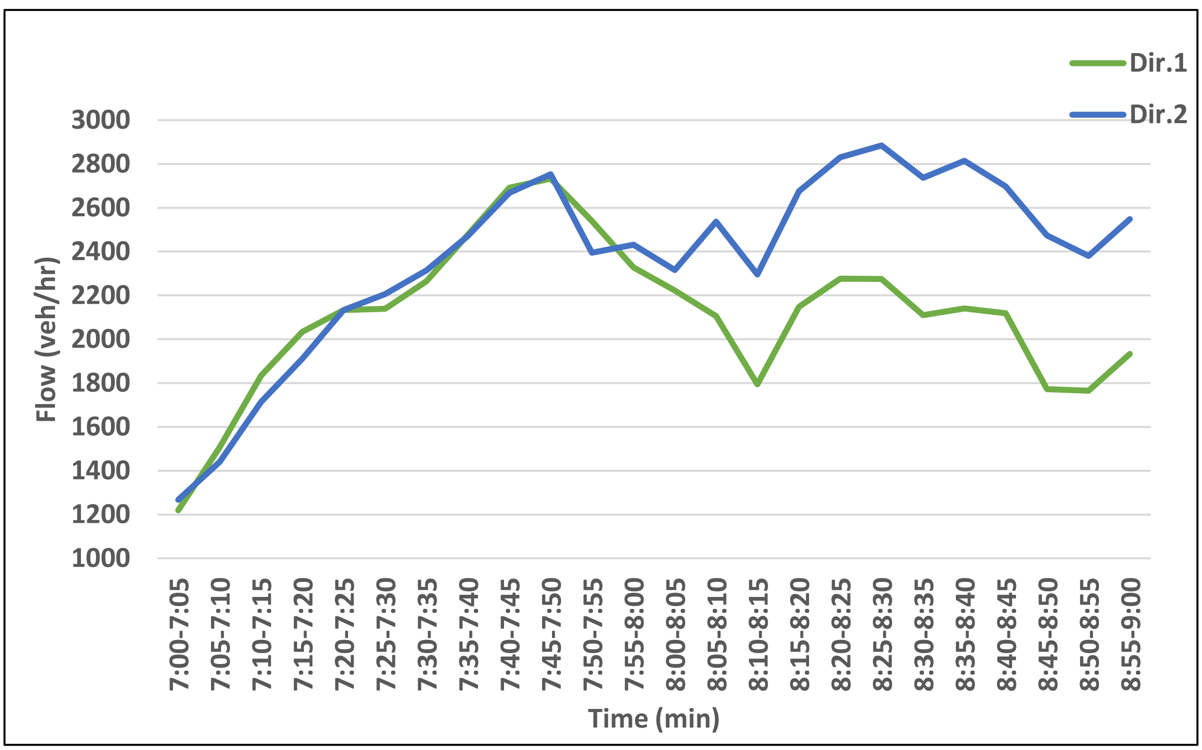

Figure (A-32): Al-Abbas Street traffic flow.

Appendix- B

Average Travel Time and Average Travel Speed

Table (B-1): Av.travel time and av.travel speed.

Hasan Al-Mojtaba Street		Al-Hur Street	
Av. Travel time (sec)	Av. Travel speed (km/hr)	Av. Travel time (sec)	Av. Travel speed (km/hr)
229.67	46.2	314.03	33.4
240.92	44.1	348.07	30.2
249.58	42.6	376.93	27.9
235.84	45.0	332.21	31.6
264.77	40.1	434.48	24.2
274.27	38.7	475.82	22.1
260.93	40.7	419.05	25.1
260.99	40.7	419.38	25.0
298.48	35.6	606.66	17.3
284.33	37.4	525.33	20.0
274.62	38.7	477.55	22.0
300.08	35.4	616.64	17.0
295.40	36.0	587.32	17.9
348.42	30.5	634.90	16.5
420.75	25.2	655.51	16.0
298.48	35.6	606.31	17.3
293.77	36.2	577.63	18.2
275.91	38.5	483.49	21.7
287.49	36.9	542.14	19.4
296.23	35.9	592.29	17.7
244.98	43.4	361.37	29.1
258.14	41.1	408.29	25.7
247.26	43.0	368.98	28.5
268.65	39.5	450.89	23.3
250.52	42.4	380.34	27.6
241.03	44.1	348.42	30.1
253.64	41.9	391.40	26.8
234.69	45.3	328.78	31.9
242.63	43.8	353.58	29.7
237.00	44.8	335.72	31.3

Table (B-2): Av.travel time and av.travel speed.

Bait Al-Mohafodh Street		Al-Tarbea Street	
Av. Travel time (sec)	Av. Travel speed (km/hr)	Av. Travel time (sec)	Av. Travel speed (km/hr)
162.1	37.9	45.6	29.0
181.2	33.9	54.6	24.3
189.6	32.4	64.9	20.4
194.0	31.6	47.9	27.6
226.7	27.1	78.9	16.8
270.1	22.7	65.3	20.3
206.8	29.7	44.8	29.6
239.3	25.6	54.5	24.3
312.7	19.6	89.8	14.7
283.5	21.6	93.0	14.2
357.1	17.2	92.5	14.3
390.8	15.7	96.6	13.7
256.7	23.9	112.3	11.8
336.4	18.2	90.0	14.7
257.1	23.9	104.3	12.7
247.6	24.8	71.1	18.6
227.7	26.9	100.2	13.2
193.0	31.8	84.6	15.6
220.4	27.8	79.7	16.6
228.4	26.9	132.3	10.0
155.2	39.5	131.4	10.1
181.0	33.9	87.5	15.1
173.1	35.5	72.7	18.2
193.3	31.7	103.7	12.8
174.8	35.1	74.5	17.8
162.7	37.7	61.8	21.4
180.3	34.0	71.8	18.4
154.8	39.6	52.7	25.1
166.7	36.8	57.2	23.1
162.1	38.3	51.7	25.6

Table (B-3): Av.travel time and av.travel speed.

Nabi Mohmmad Street		Al-Hawly Street	
Av. Travel time (sec)	Av. Travel speed (km/hr)	Av. Travel time (sec)	Av. Travel speed (km/hr)
69.6	36.0	190.6	42.8
81.1	30.9	201.9	40.4
78.9	31.7	211.0	38.7
74.7	33.5	205.7	39.7
98.3	25.5	236.6	34.5
93.6	26.8	238.8	34.2
82.5	30.4	209.2	39.0
94.5	26.5	211.4	38.6
116.0	21.6	231.3	35.3
99.8	25.1	241.0	33.9
133.2	18.8	252.6	32.3
143.6	17.4	263.3	31.0
120.9	20.7	286.6	28.5
216.8	11.6	339.2	24.1
210.8	11.9	378.2	21.6
212.4	11.8	321.2	25.4
205.2	12.2	309.3	26.4
211.5	11.8	239.9	34.0
129.3	19.4	284.7	28.7
199.2	12.6	295.4	27.6
85.6	29.3	232.1	35.2
99.1	25.3	235.4	34.7
83.8	29.9	241.6	33.8
95.9	26.1	262.8	31.0
82.6	30.3	242.7	33.6
75.0	33.4	226.9	36.0
85.7	29.2	238.7	34.2
70.4	35.6	213.9	38.1
77.1	32.5	220.7	37.0
73.2	34.2	211.4	38.6

Table (B-4): Av.travel time and av.travel speed.

Sarie Al-Moalemin Street		Sarie Ramadan Street	
Av. Travel time (sec)	Av. Travel speed (km/hr)	Av. Travel time (sec)	Av. Travel speed (km/hr)
250.8	45.4	109.6	46.3
283.3	40.2	131.5	38.6
286.2	39.8	139.0	36.5
256.9	44.3	136.7	37.1
332.3	34.2	168.2	30.2
380.0	29.9	196.5	25.8
350.5	32.5	148.9	34.1
376.4	30.2	171.5	29.6
508.8	22.4	212.0	23.9
508.8	22.4	168.7	30.1
431.7	26.4	141.7	35.8
549.0	20.7	214.5	23.7
549.6	20.7	172.2	29.5
905.7	12.6	228.6	22.2
957.6	11.9	246.6	20.6
554.4	20.5	224.9	22.6
452.3	25.2	252.8	20.1
323.9	35.1	226.8	22.4
402.5	28.3	274.8	18.5
366.5	31.0	218.7	23.2
281.4	40.4	143.3	35.4
334.2	34.0	146.8	34.6
341.0	33.4	149.4	34.0
370.8	30.7	161.8	31.4
320.5	35.5	141.2	36.0
292.5	38.9	129.6	39.2
327.3	34.8	141.2	35.9
273.6	41.6	120.6	42.1
294.9	38.6	127.5	39.8
280.1	40.6	121.2	41.9

Table (B-5): Av.travel time and av.travel speed.

Al-Mojamaat Street		Al-Dhariba Street	
Av. Travel time (sec)	Av. Travel speed (km/hr)	Av. Travel time (sec)	Av. Travel speed (km/hr)
125.0	23.0	89.6	31.3
219.0	13.2	98.3	28.6
208.5	13.8	96.6	29.1
167.1	17.2	93.8	29.9
286.0	10.1	131.8	21.3
243.7	11.8	145.9	19.2
273.8	10.5	131.2	21.4
254.2	11.3	143.6	19.6
271.2	10.6	191.7	14.7
260.9	11.0	170.0	16.5
259.7	11.1	172.3	16.3
277.7	10.4	157.9	17.8
241.2	11.9	144.1	19.5
273.0	10.6	236.6	11.9
291.5	9.9	236.4	11.9
244.3	11.8	221.1	12.7
257.1	11.2	250.7	11.2
243.2	11.8	222.5	12.6
282.9	10.2	275.8	10.2
277.2	10.4	270.3	10.4
192.5	15.0	152.9	18.4
270.4	10.7	165.2	17.0
218.0	13.2	123.4	22.8
273.2	10.5	147.7	19.0
223.1	12.9	125.9	22.3
170.5	16.9	114.1	24.6
214.3	13.4	129.2	21.7
138.5	20.8	106.4	26.4
156.2	18.4	115.6	24.3
136.6	21.1	109.4	25.7

Appendix- C

Traffic Noise Data

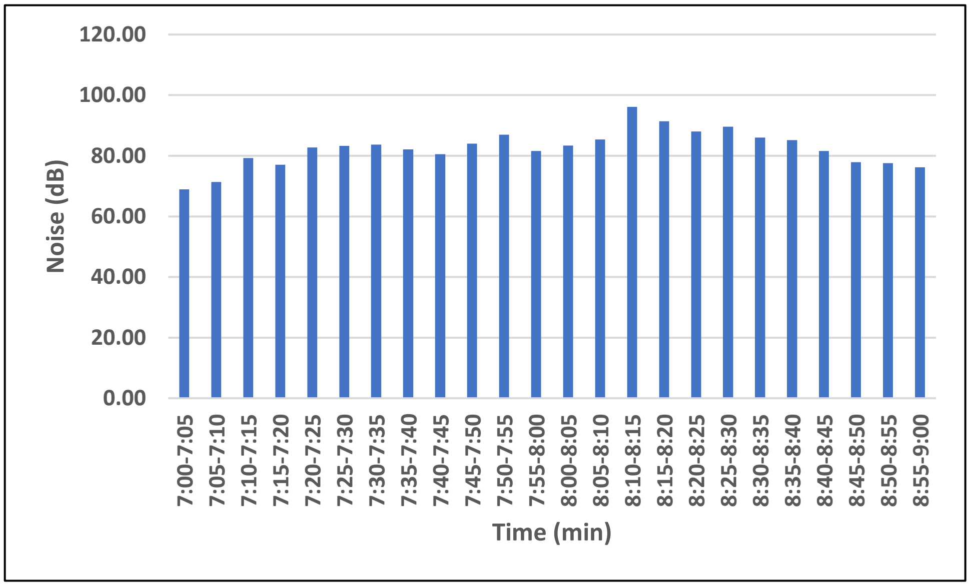

Figure (C-1): Traffic noise data at Hasan Al-Mojtaba Street.

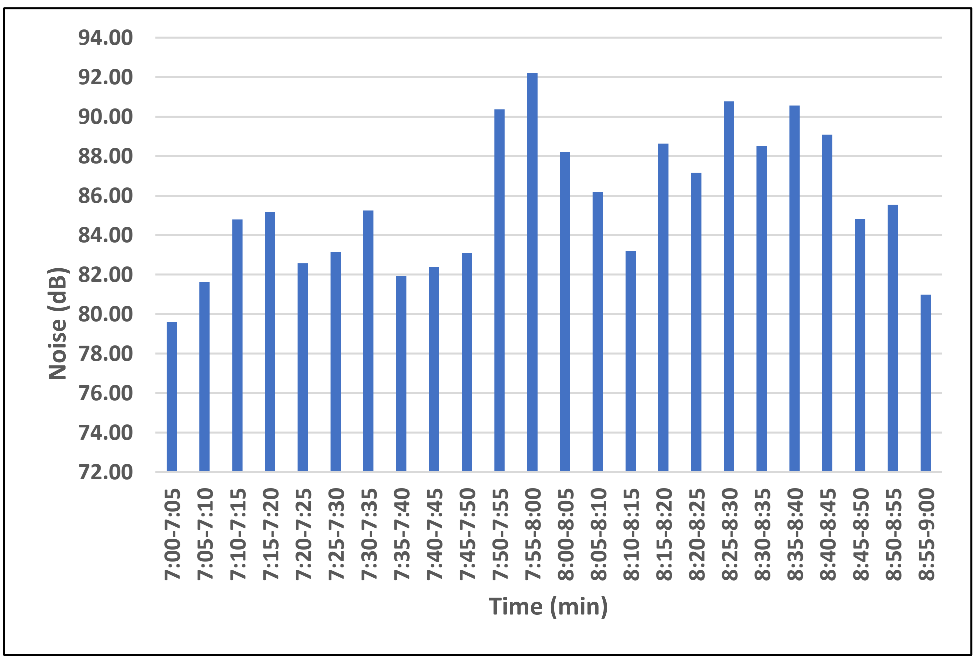

Figure (C-2): Traffic noise data at Al-Hur Street.

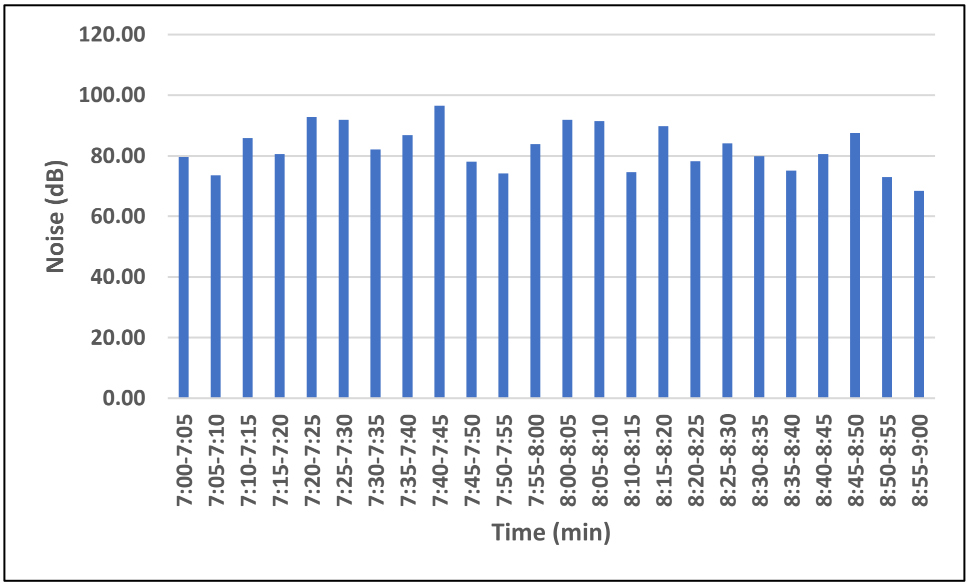

Figure (C-3): Traffic noise data at Bait Al-Mohafodh Street.

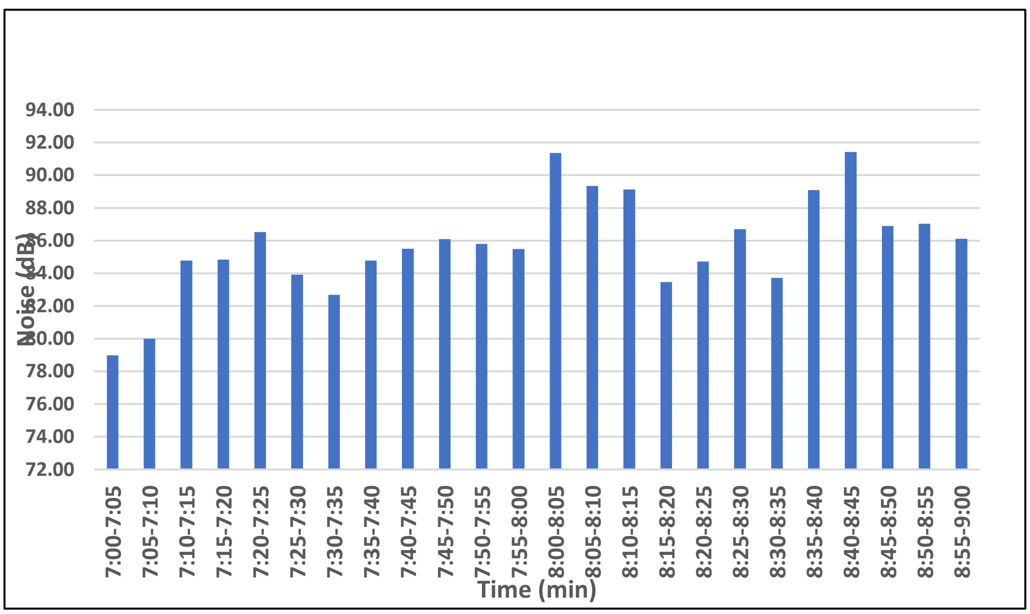

Figure (C-4): Traffic noise data at Al-Tarbea Street.

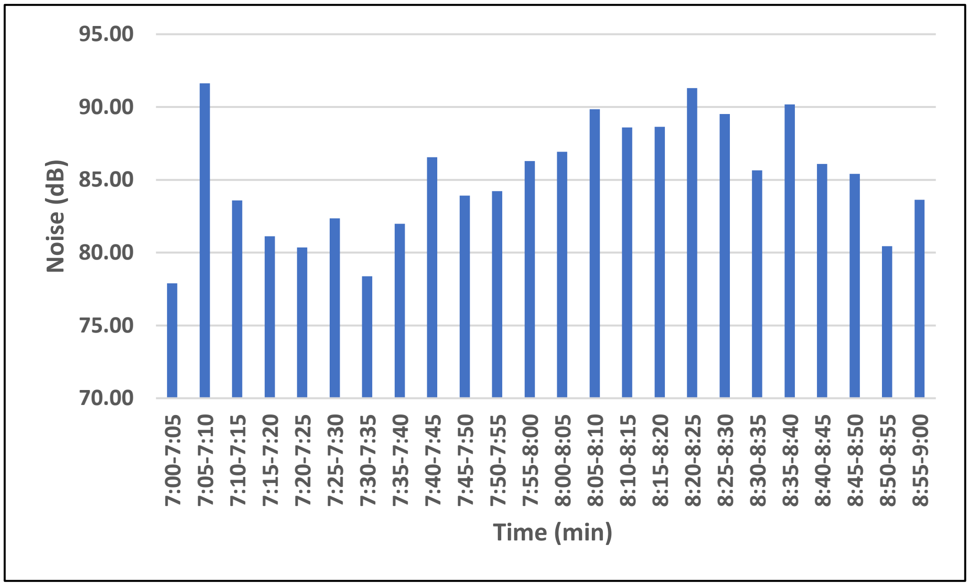

Figure (C-5): Traffic noise data at Nabi Mohmmad Street

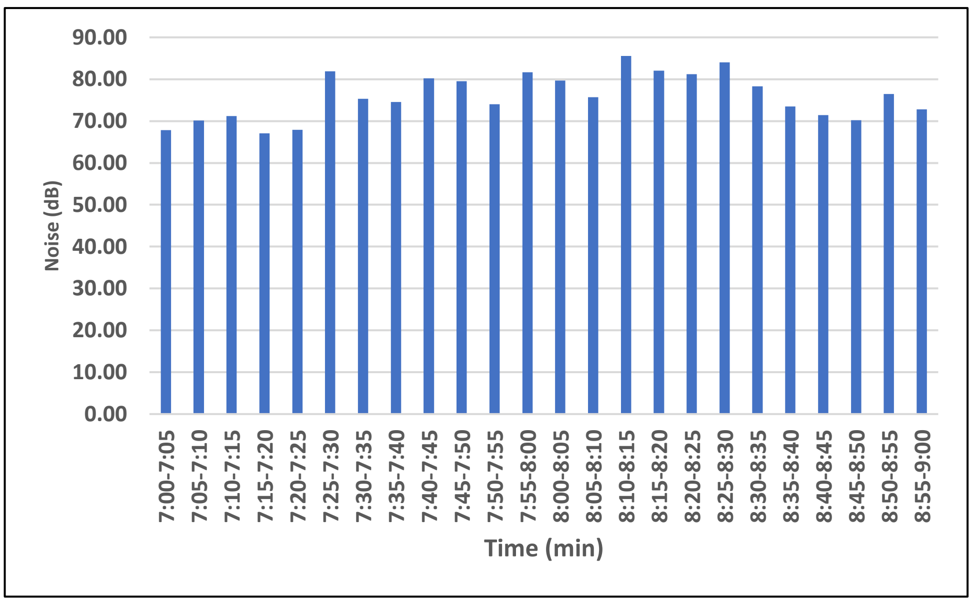

Figure (C-6): Traffic noise data at Al-Hawly Street.

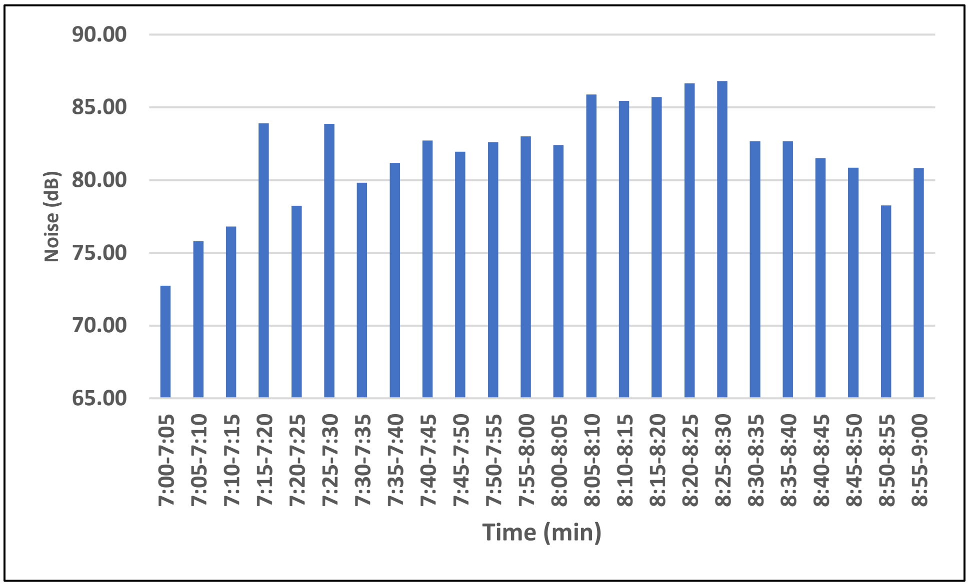

Figure (C-7): Traffic noise data at Sarie Al-Moalemin Street.

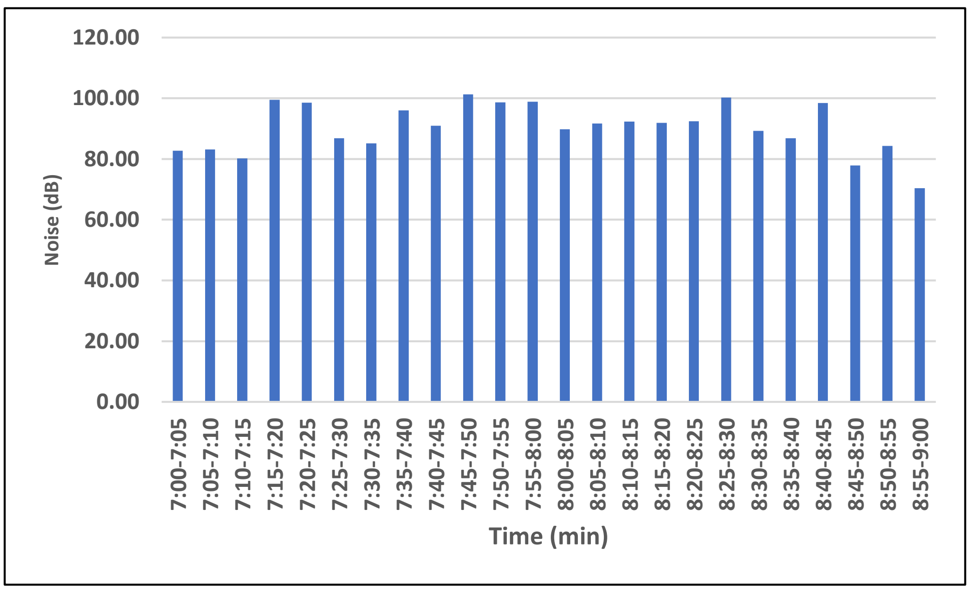

Figure (C-8): Traffic noise data at Sarie Ramadan Street.

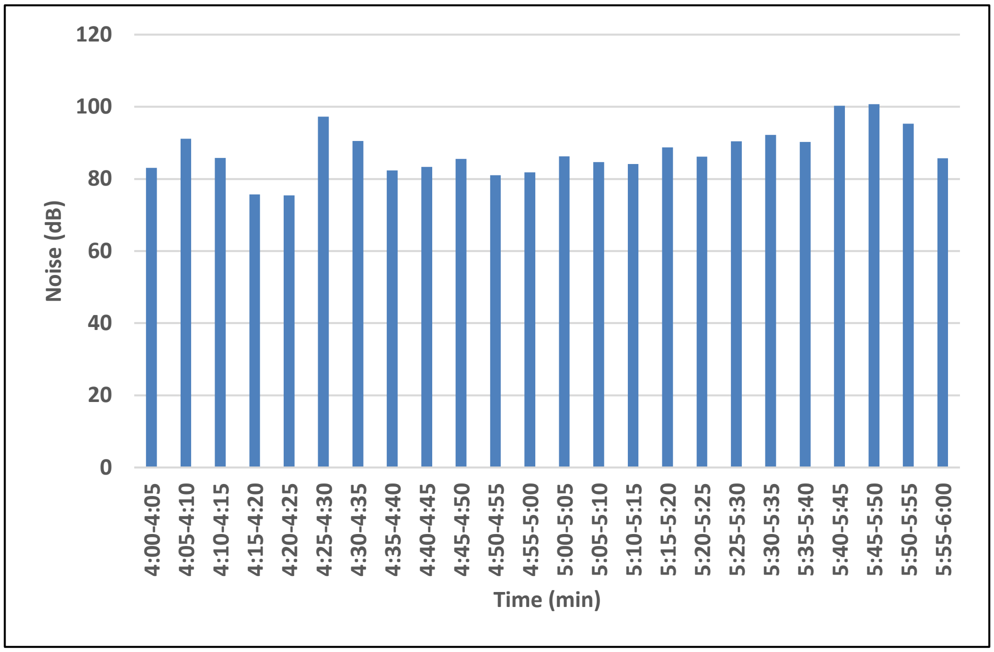

Figure (C-9): Traffic noise data at Al-Mojamaat Street.

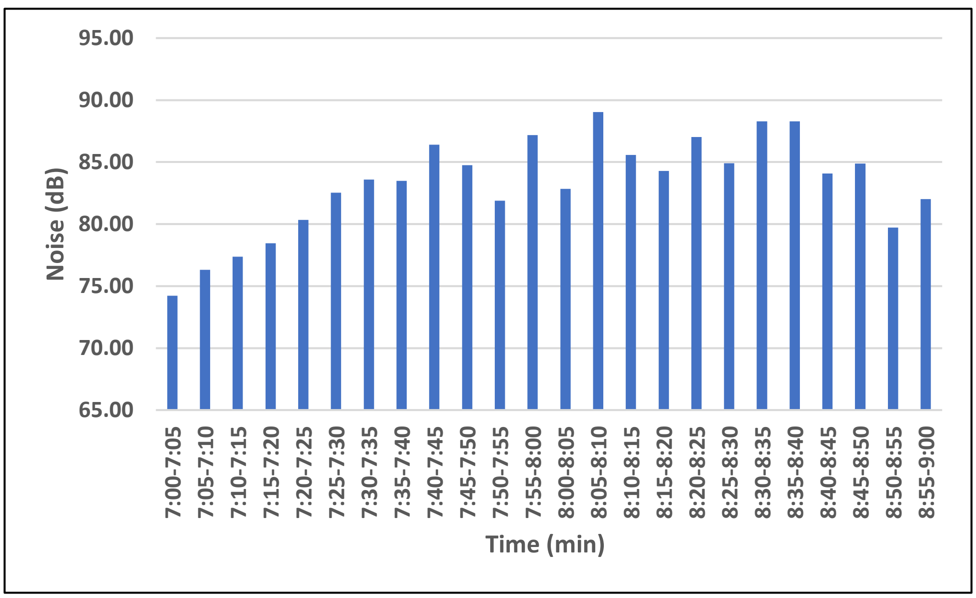

Figure (C-10): Traffic noise data at Al-Dhariba Street.

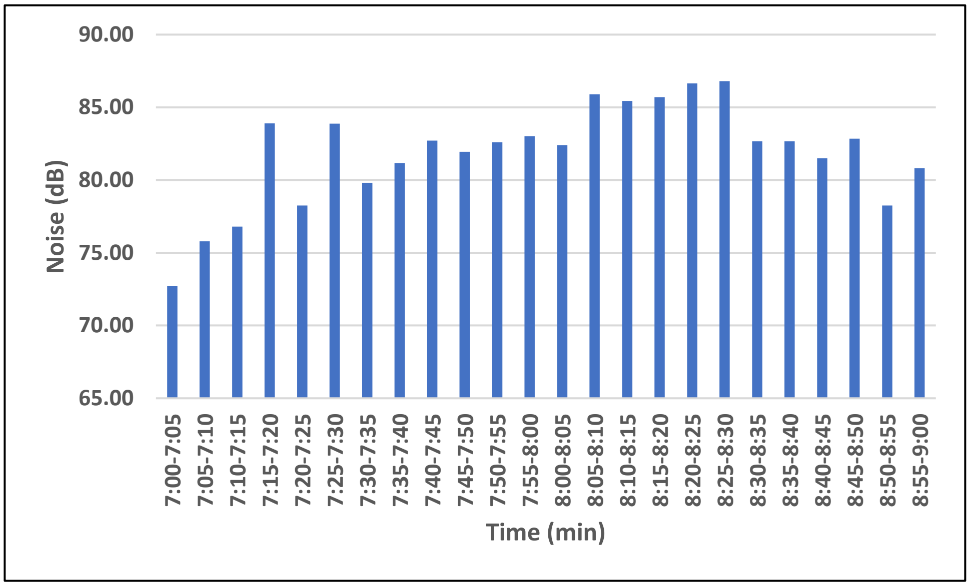

Figure (C-11): Traffic noise data at Qorfat Al-Tijara Street.

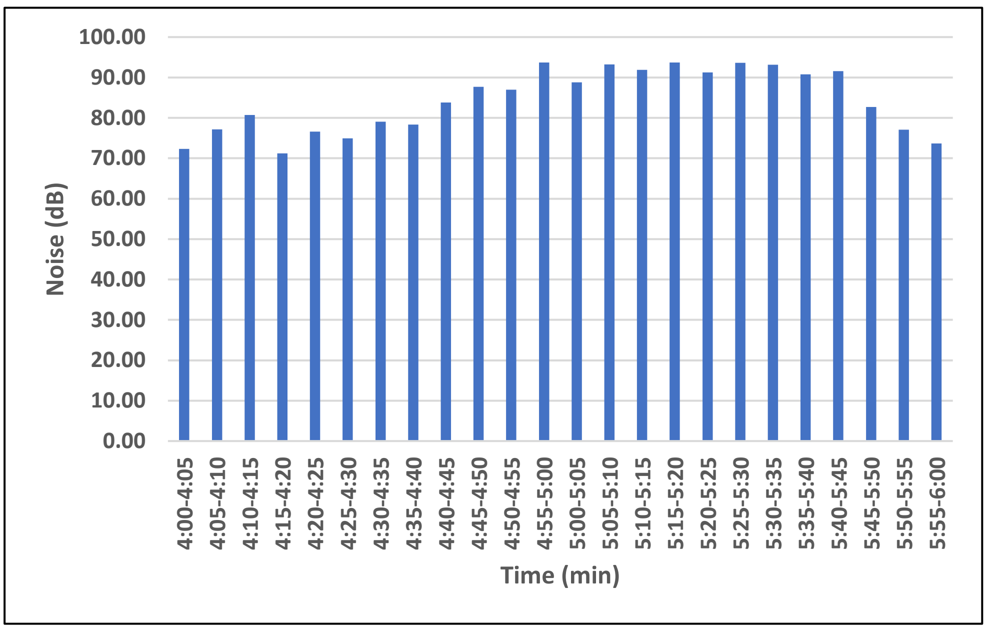

Figure (C-12): Traffic noise data at Al-Iskan Street.

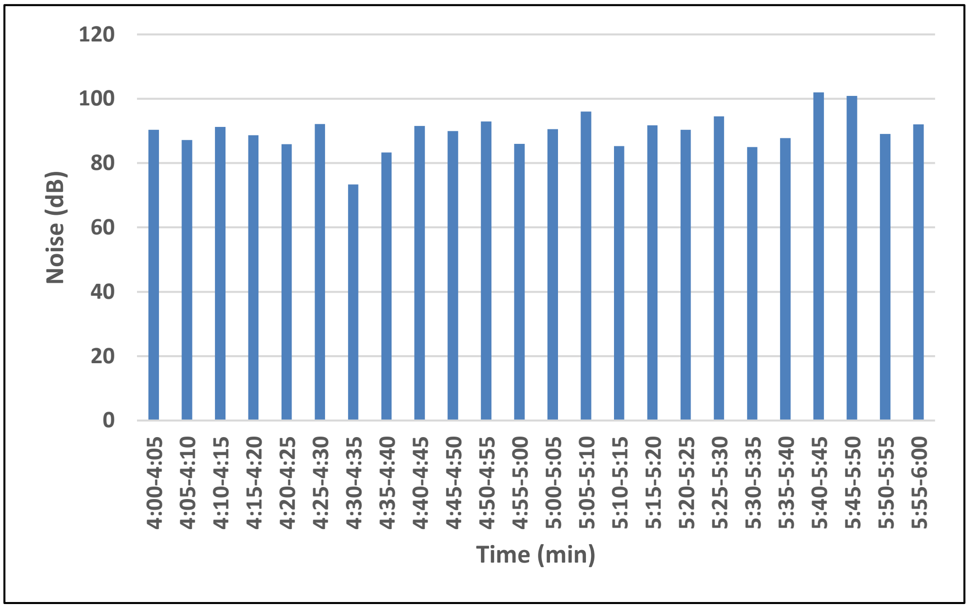

Figure (C-13): Traffic noise data at Ftima Al-Zahraa 1 Street.

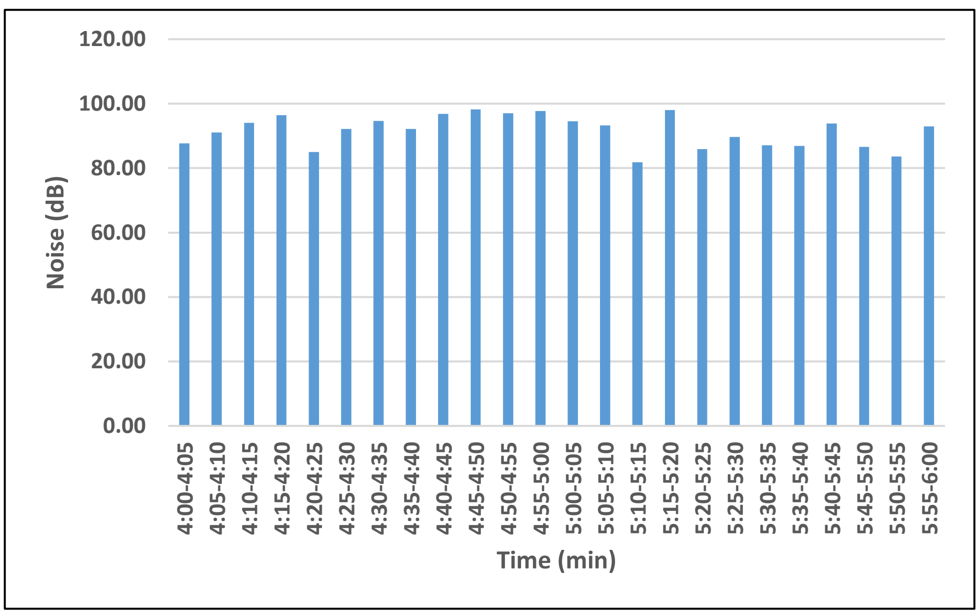

Figure (C-14): Traffic noise data at Ftima Al-Zahraa 2 Street.

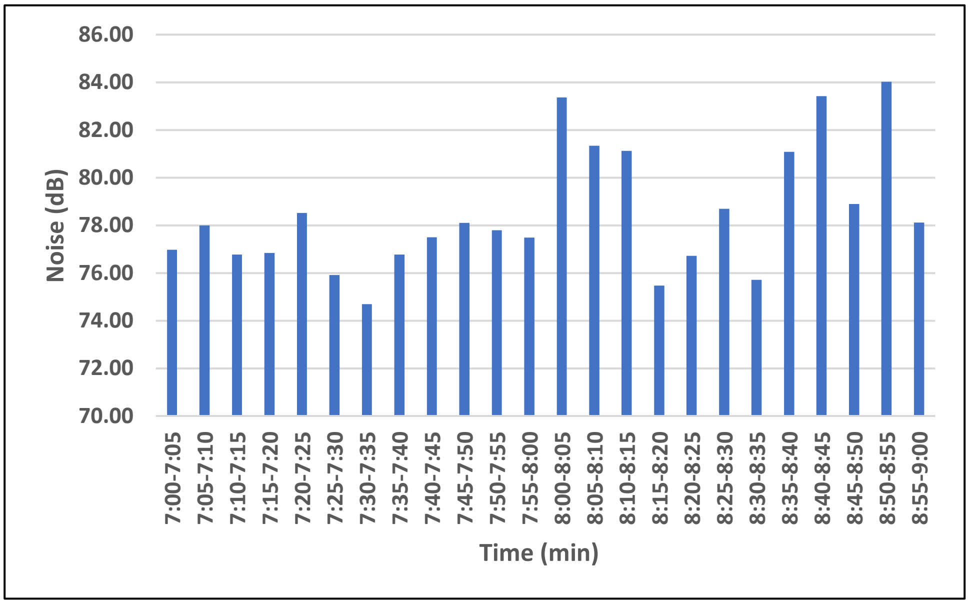

Figure (C-15): Traffic noise data at Haidar Al-Karrar Street.

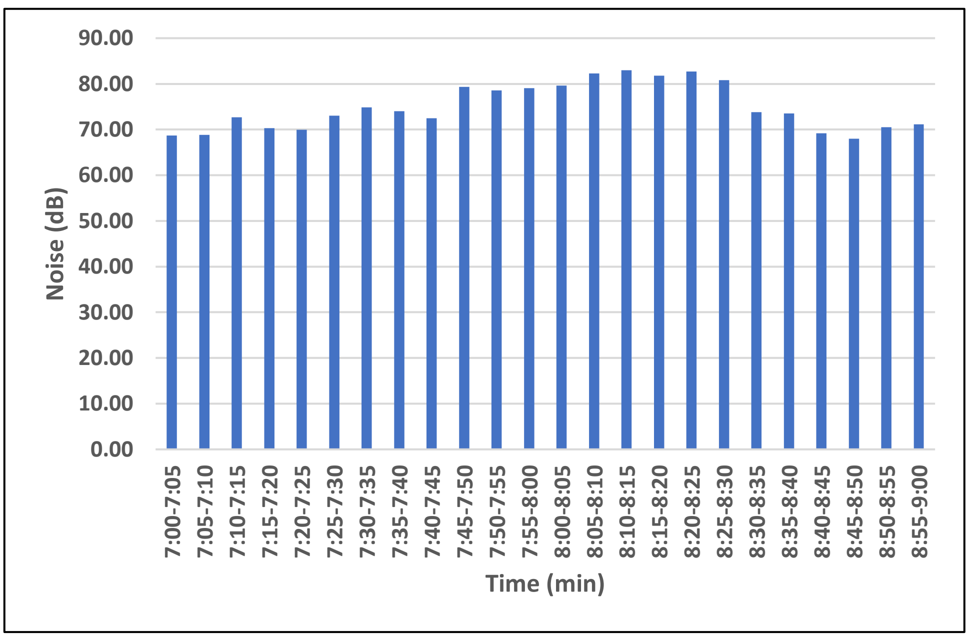

Figure (C-16): Traffic noise data at Al-Nasr Street.

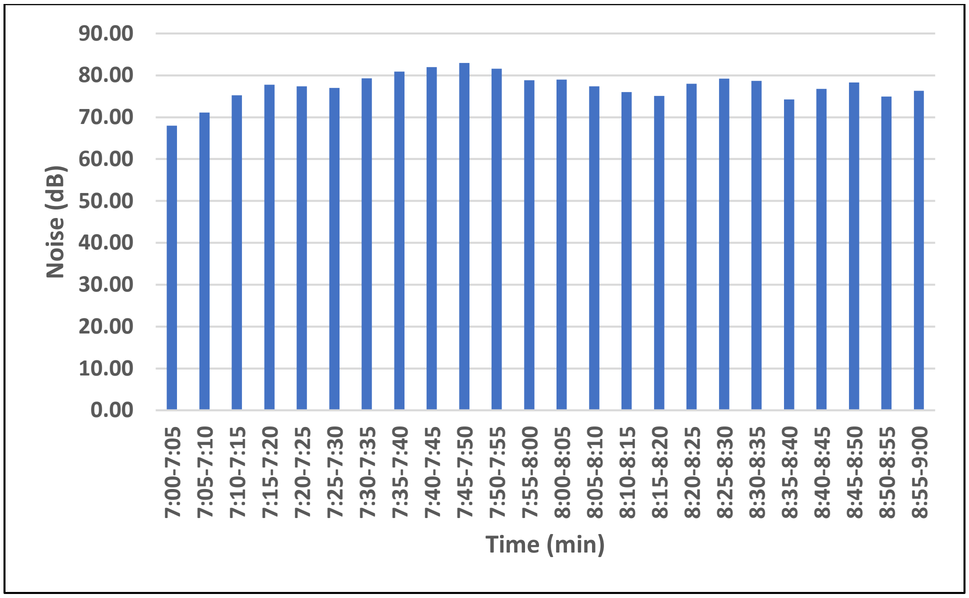

Figure (C-17): Traffic noise data at Al-Abbas Street.

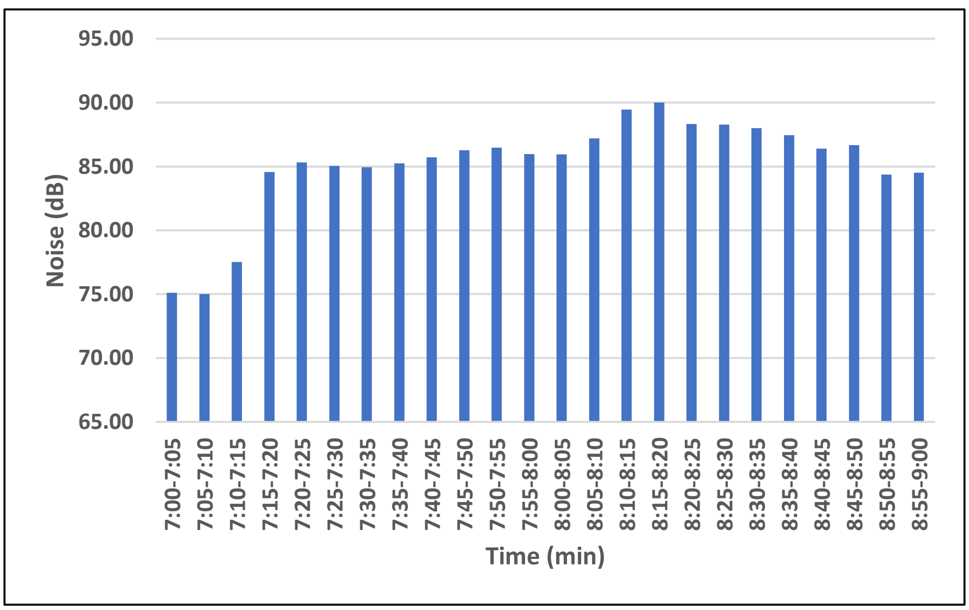

Figure (C-18): Traffic noise data at Karbala-Najaf Street.

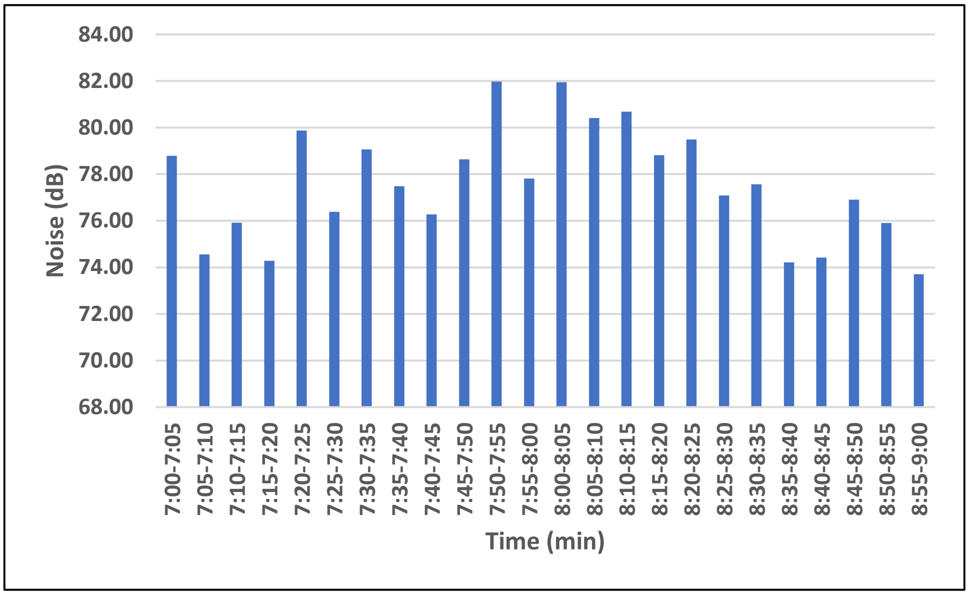

Figure (C-19): Traffic noise data at Bab Twerige Street.

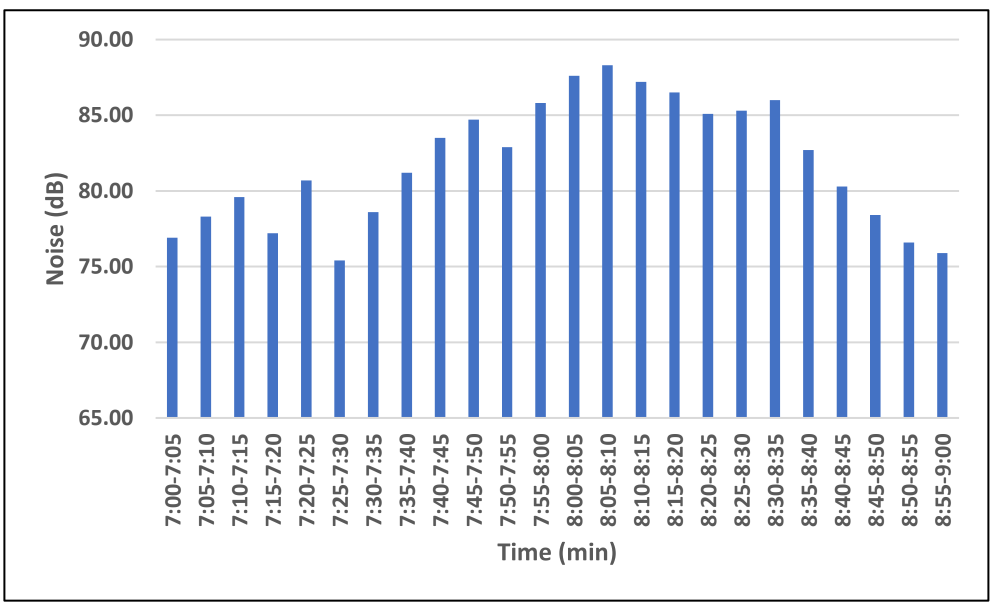

Figure (C-20): Traffic noise data at Karbala-Hindea Street.

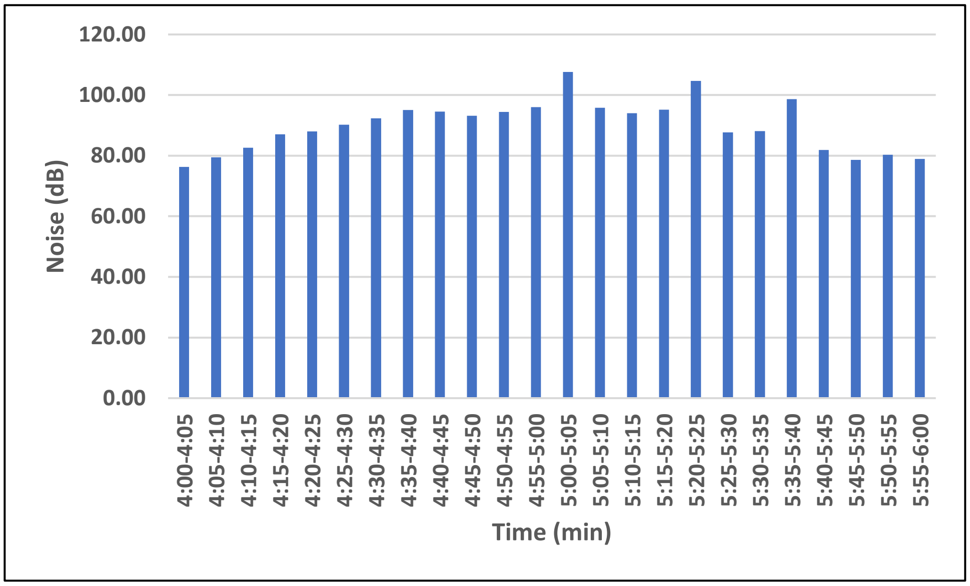

Figure (C-21): Traffic noise data at Maitham Al-Tammar 1 Street.

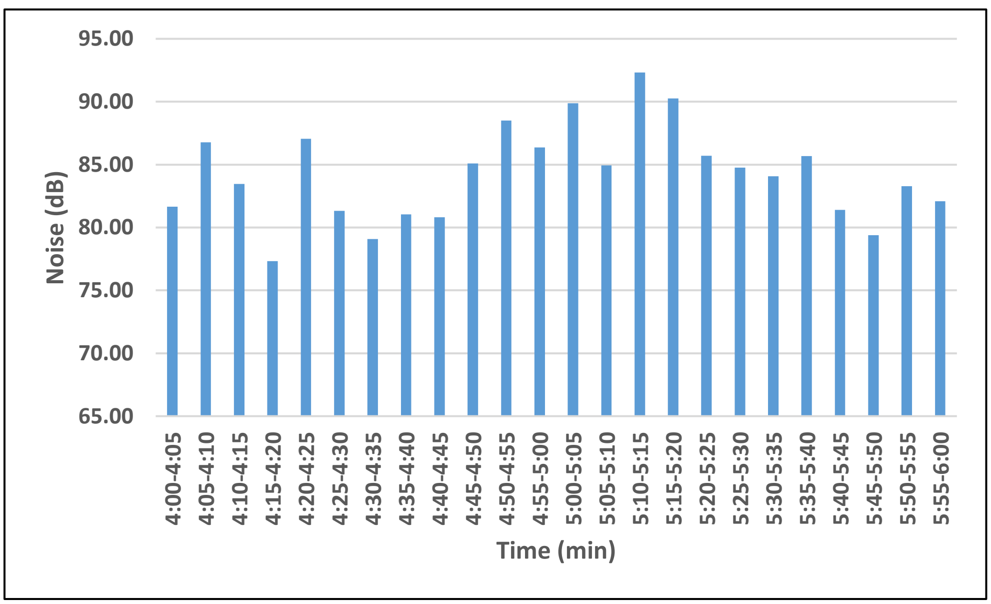

Figure (C-22): Traffic noise data at Maitham Al-Tammar 2 Street.

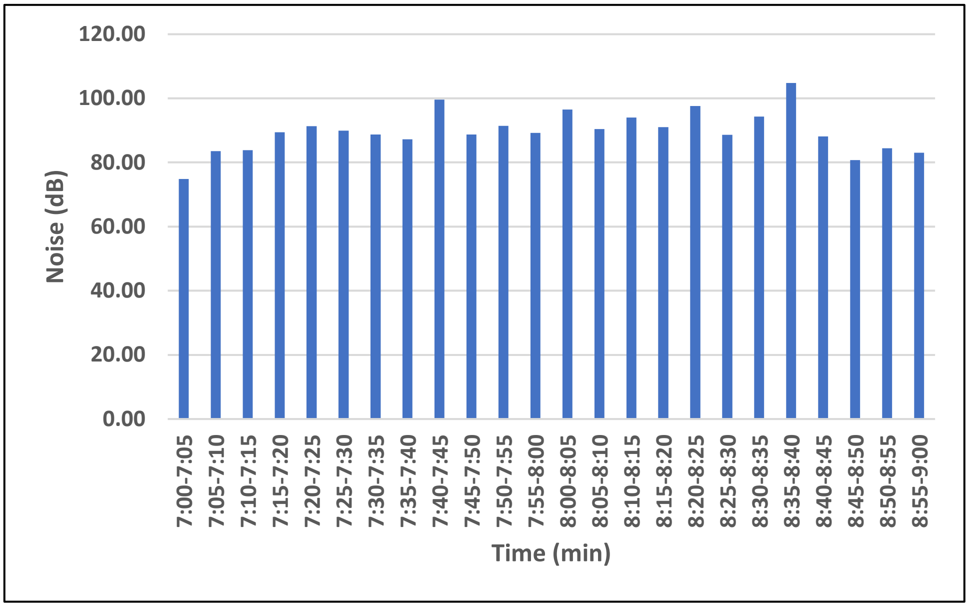

Figure (C-23): Traffic noise data at Shohadaa Al-Mowadhafin Street.

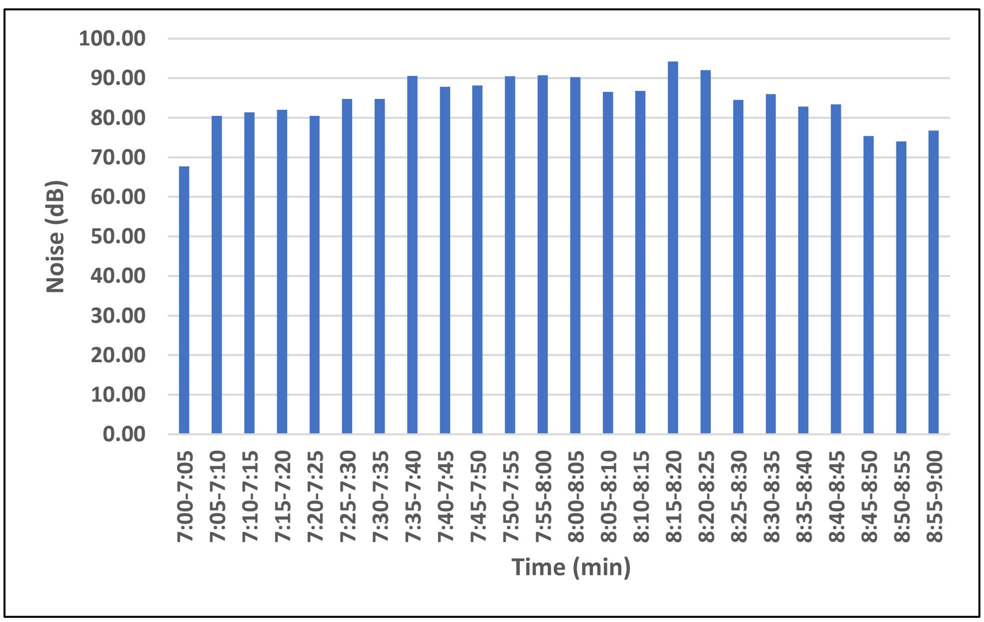

Figure (C-24): Traffic noise data at Al-Wilada Street.

Noise level after and before tram implementation.

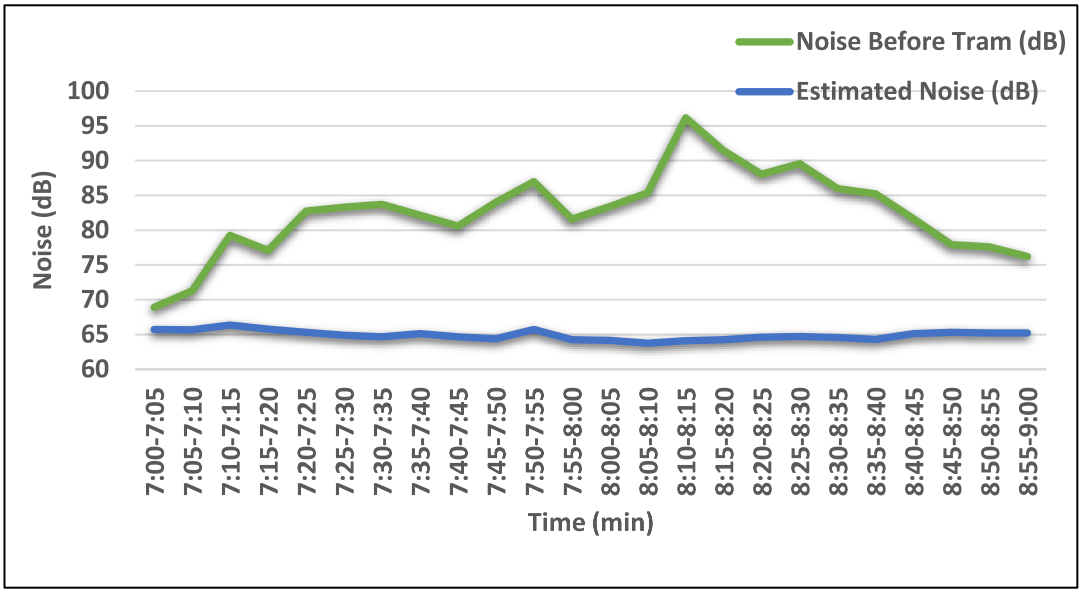

Figure (C-25): Traffic noise data at Hasan Al-Mojtaba Street.

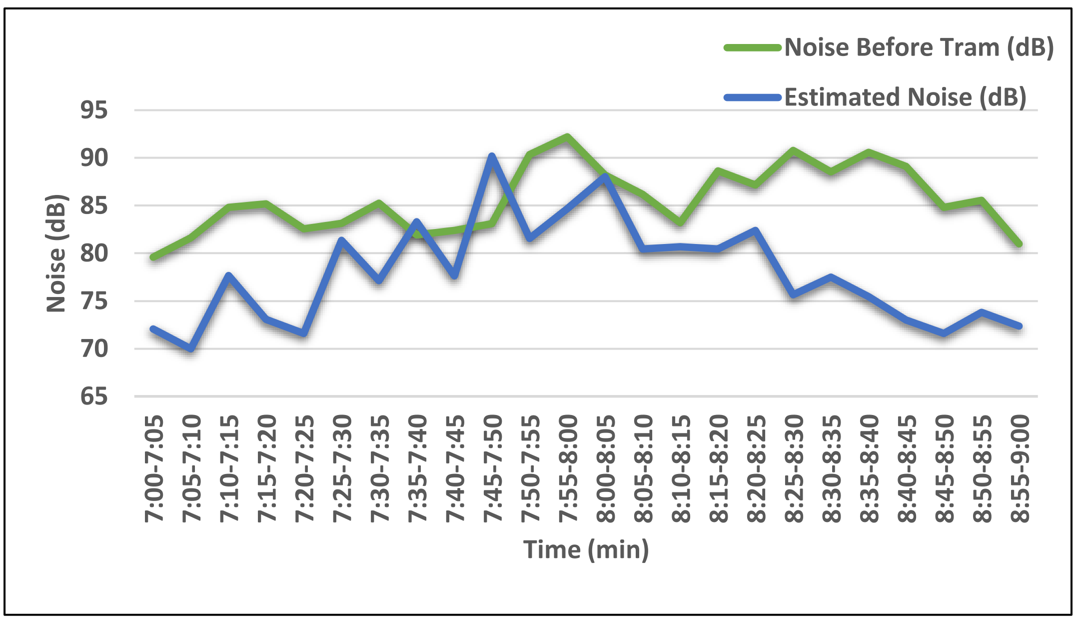

Figure (C-26): Traffic noise data at Al-Hur Street.

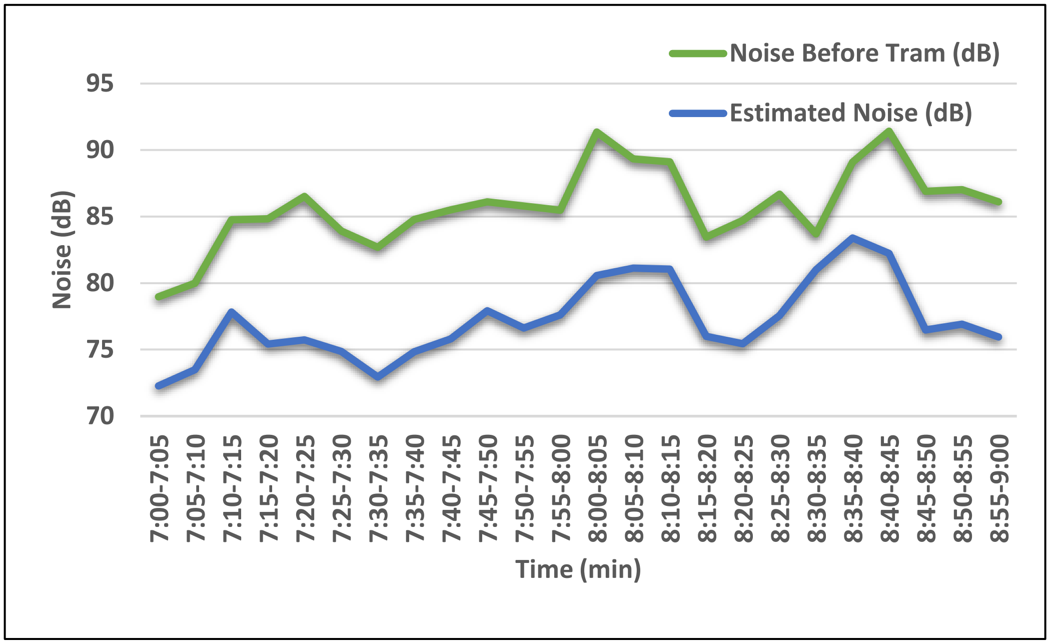

Figure (C-27): Traffic noise data at Al-Tarea Street.

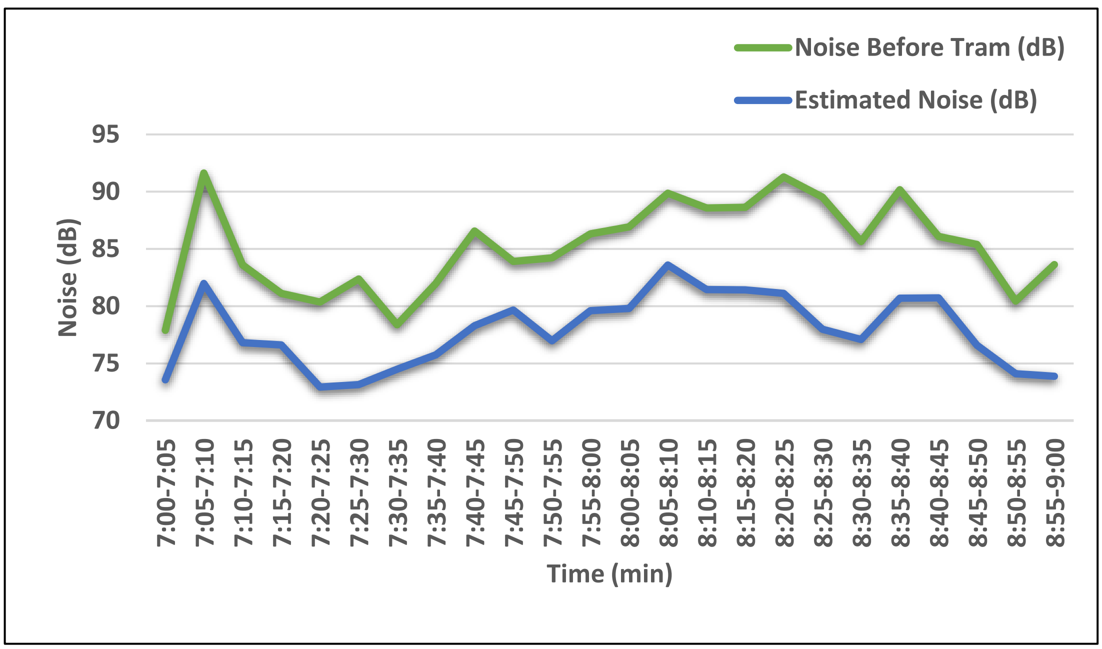

Figure (C-28): Traffic noise data at Nabi Mohammad Street.

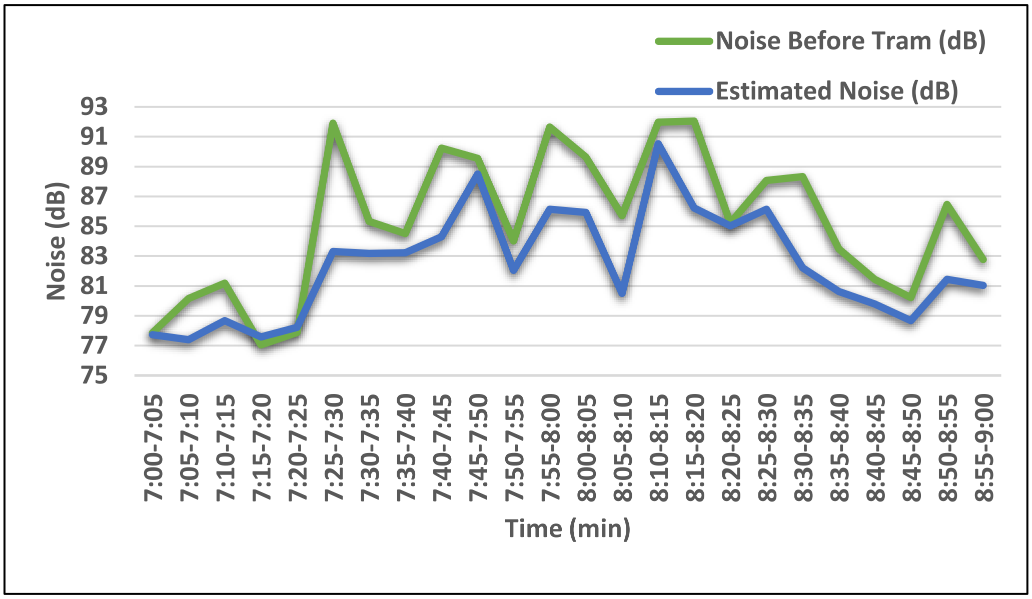

Figure (C-29): Traffic noise data at Sarie Al-Moalemin Street.

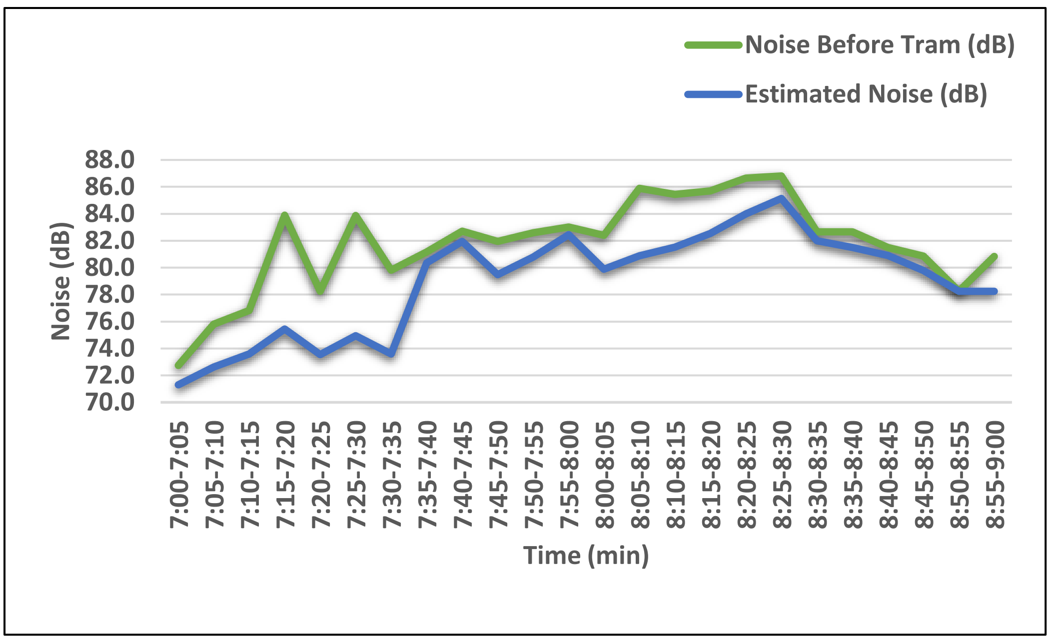

Figure (C-30): Traffic noise data at Sarie Ramadan Street.

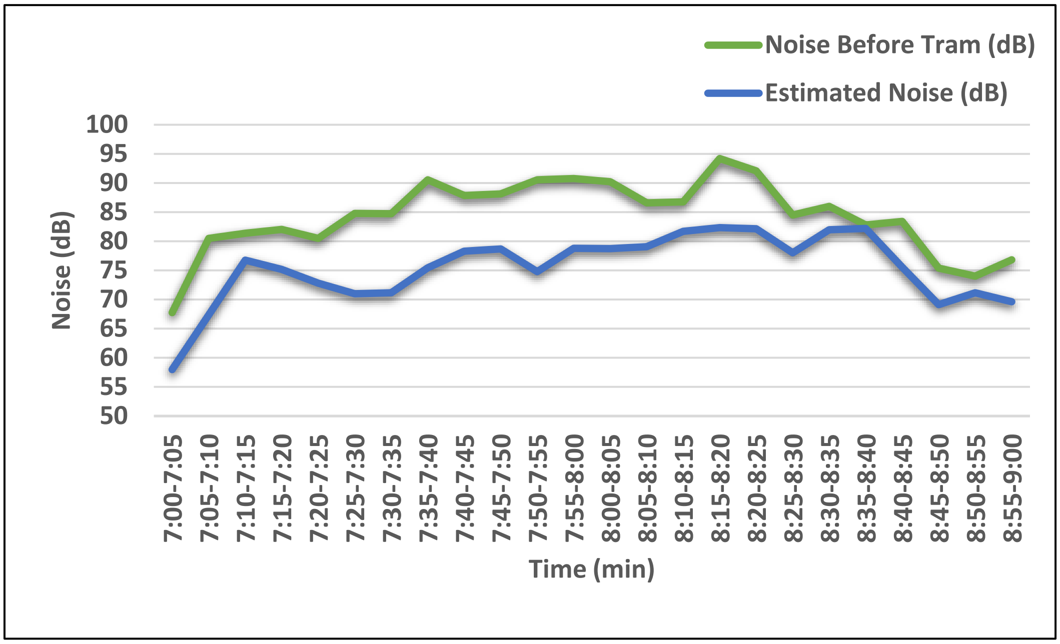

Figure (C-31): Traffic noise data at Al-Wilada Street.

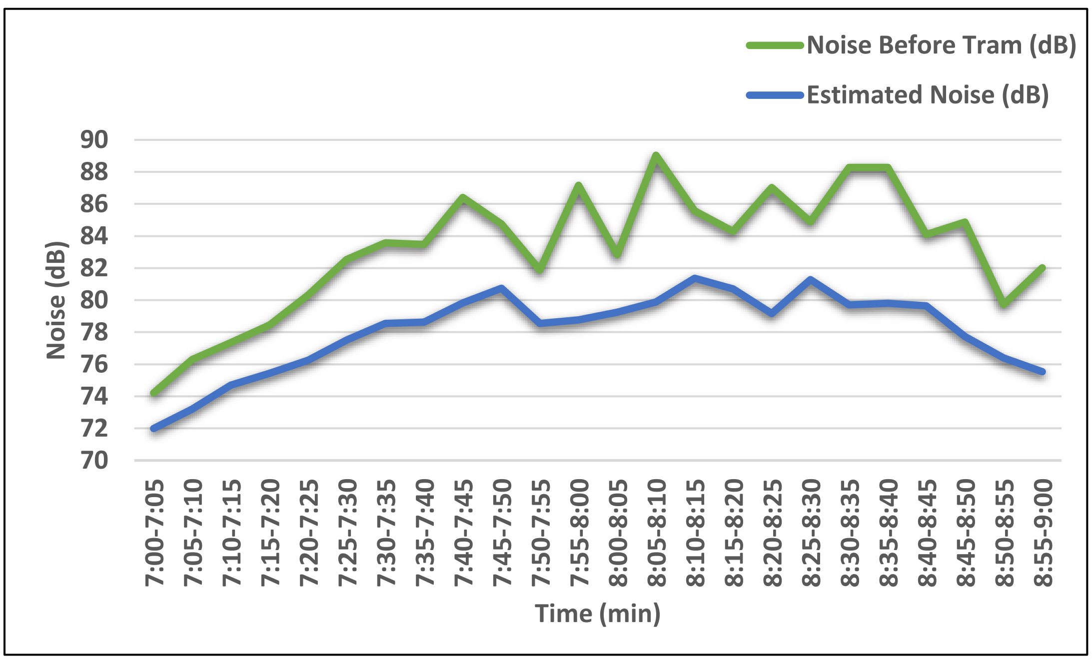

Figure (C-32): Traffic noise data at Al-Dhariba Street.

Appendix- D

Traffic Emissions Data

Table (D-1): Traffic emissions data for Hasn Al-Mojtaba Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	27.0	1.1	0.021	443.3	18.6	34.6
7:05-7:10	27.0	0.4	0.012	380.8	24.7	36.6
7:10-7:15	27.1	1.2	0.033	576.3	26.0	29.4
7:15-7:20	27.1	1.1	0.028	599.4	22.8	36.4
7:20-7:25	27.2	1.4	0.035	650.2	37.5	45.8
7:25-7:30	27.2	1.8	0.040	655.4	41.5	53.5
7:30-7:35	27.3	2.2	0.042	720.7	47.1	50.1
7:35-7:40	27.3	1.8	0.038	735.0	41.8	55.5
7:40-7:45	27.3	2.4	0.046	701.7	46.6	63.9
7:45-7:50	27.4	2.5	0.046	724.7	52.0	70.6
7:50-7:55	27.4	1.7	0.036	633.7	40.0	49.4
7:55-8:00	27.5	2.5	0.047	762.6	47.2	75.6
8:00-8:05	27.5	2.7	0.048	746.8	63.2	70.8
8:05-8:10	27.6	3.0	0.054	797.3	60.9	70.3
8:10-8:15	27.6	4.3	0.069	957.6	73.4	93.9
8:15-8:20	27.7	2.4	0.047	684.9	52.6	65.0
8:20-8:25	27.7	2.0	0.041	696.3	39.0	55.8
8:25-8:30	27.7	2.1	0.042	721.4	48.8	60.7
8:30-8:35	27.8	1.9	0.041	653.6	47.9	56.5
8:35-8:40	27.8	1.4	0.033	623.8	31.1	46.2
8:40-8:45	27.9	1.2	0.031	567.4	35.9	38.3
8:45-8:50	27.9	0.9	0.029	495.8	28.5	30.2
8:50-8:55	28.0	1.0	0.027	542.5	32.4	36.7
8:55-9:00	28.0	1.0	0.029	577.8	37.8	41.9

Table (D-2): Traffic emissions data for Al-Hur Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	24	1.5	0.011	552.9	14.9	44.6
7:05-7:10	24	2.0	0.011	560.2	28.3	50.3
7:10-7:15	24.7	3.6	0.012	584.1	35.3	57.1
7:15-7:20	24.3	2.0	0.012	568.1	46.1	45.3
7:20-7:25	24.6	3.5	0.013	612.3	36.6	67.5
7:25-7:30	25.2	5.6	0.014	626.4	45.5	71.9
7:30-7:35	24.7	4.4	0.015	622.8	50.9	75.7
7:35-7:40	25.1	3.1	0.014	594.1	40.7	63.6
7:40-7:45	24.9	6.9	0.016	624.6	64.6	79.2
7:45-7:50	25.1	5.7	0.016	663.0	58.4	76.0
7:50-7:55	25.8	3.4	0.014	604.0	54.5	61.4
7:55-8:00	25.6	6.0	0.015	634.1	63.3	80.6
8:00-8:05	25.5	6.4	0.016	643.4	55.7	66.8
8:05-8:10	26	7.1	0.015	672.2	67.8	89.4
8:10-8:15	26	8.9	0.020	716.1	99.3	115.9
8:15-8:20	26.4	7.8	0.015	648.2	68.7	79.4
8:20-8:25	26.3	7.1	0.014	629.4	51.2	79.1
8:25-8:30	26.1	4.2	0.014	612.3	53.7	70.3
8:30-8:35	27	3.8	0.014	599.8	42.3	68.3
8:35-8:40	26.7	3.9	0.013	616.5	59.5	71.2
8:40-8:45	26.9	2.9	0.013	591.1	29.8	63.0
8:45-8:50	27	2.4	0.012	578.1	39.4	57.5
8:50-8:55	27.3	1.8	0.012	559.0	31.9	54.7
8:55-9:00	27.7	2.0	0.012	579.8	36.2	55.4

Table (D-3): Traffic emissions data for Al-Mojamaat Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	26.5	0.9	0.019	478.3	16.7	36.8
7:05-7:10	26.58	4.1	0.022	633.9	30.9	59.8
7:10-7:15	26.67	4.3	0.023	736.9	45.6	87.7
7:15-7:20	26.75	4.1	0.022	699.9	68.6	80.6
7:20-7:25	26.83	6.3	0.024	663.0	70.1	83.5
7:25-7:30	26.92	8.0	0.026	860.8	74.4	98.6
7:30-7:35	27	8.6	0.027	865.1	82.6	161.7
7:35-7:40	27.08	8.4	0.024	880.0	79.7	151.8
7:40-7:45	27.17	9.1	0.027	890.6	95.4	185.2
7:45-7:50	27.25	9.5	0.024	809.8	77.2	146.9
7:50-7:55	27.33	9.3	0.024	779.6	79.3	127.2
7:55-8:00	27.42	11.0	0.024	726.0	60.8	135.5
8:00-8:05	27.5	9.8	0.028	873.3	95.6	117.4
8:05-8:10	27.58	10.5	0.030	1057.9	118.7	195.5
8:10-8:15	27.67	13.0	0.030	1073.9	111.7	213.8
8:15-8:20	27.75	9.1	0.027	884.5	95.9	170.7
8:20-8:25	27.83	9.1	0.028	886.6	86.3	168.8
8:25-8:30	27.92	9.3	0.028	895.4	94.3	165.5
8:30-8:35	28	8.3	0.027	868.8	82.3	160.0
8:35-8:40	28.08	7.2	0.026	836.6	71.8	144.6
8:40-8:45	28.17	6.1	0.024	773.6	72.2	112.7
8:45-8:50	28.25	5.1	0.025	708.4	59.6	125.2
8:50-8:55	28.33	3.2	0.021	606.8	63.0	83.7
8:55-9:00	28.42	4.3	0.023	550.9	81.8	116.5

Table (D-4): Traffic emissions data for Al-Dhariba Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	28	0.3	0.002	466.4	17.6	30.8
7:05-7:10	28.5	2.4	0.002	469.1	42.2	48.6
7:10-7:15	28.1	1.0	0.002	557.1	32.2	73.1
7:15-7:20	28.2	1.4	0.004	609.8	35.0	56.4
7:20-7:25	28.1	2.4	0.008	630.6	35.2	52.2
7:25-7:30	28.4	2.9	0.012	772.3	69.9	58.4
7:30-7:35	28.6	3.6	0.014	825.8	78.4	167.0
7:35-7:40	28.1	3.5	0.015	886.5	76.9	159.2
7:40-7:45	28.4	4.0	0.015	851.6	89.8	196.2
7:45-7:50	28.1	4.3	0.016	861.9	87.9	198.5
7:50-7:55	28.2	3.6	0.014	883.1	80.5	169.9
7:55-8:00	28.9	3.1	0.010	897.9	86.2	139.5
8:00-8:05	28.7	3.2	0.012	787.0	88.6	142.9
8:05-8:10	28.5	3.8	0.015	858.6	88.3	160.5
8:10-8:15	29.2	4.5	0.018	964.9	104.2	201.9
8:15-8:20	29.4	4.4	0.017	985.5	101.7	199.2
8:20-8:25	29.2	4.6	0.019	953.2	119.9	187.4
8:25-8:30	29	4.9	0.019	832.8	115.8	220.4
8:30-8:35	28.8	4.5	0.019	958.5	119.7	194.8
8:35-8:40	29.3	4.5	0.017	941.4	100.8	197.3
8:40-8:45	29.4	4.3	0.018	956.8	104.0	200.8
8:45-8:50	29.2	3.5	0.014	853.0	84.8	157.9
8:50-8:55	29.7	2.2	0.007	701.4	66.1	111.5
8:55-9:00	29.2	2.1	0.007	696.0	52.3	117.7

Table (D-5): Traffic emissions data for Fatima Al-Zahraa 1Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	27.0	2.7	0.004	684.6	28.8	59.5
7:05-7:10	27.0	3.8	0.010	648.8	45.0	55.2
7:10-7:15	27.1	3.3	0.011	725.3	36.0	68.0
7:15-7:20	27.1	5.7	0.015	750.6	36.0	55.4
7:20-7:25	27.2	7.6	0.017	777.4	50.3	75.1
7:25-7:30	27.2	7.6	0.015	792.7	59.0	93.6
7:30-7:35	27.3	3.5	0.004	798.4	19.6	97.6
7:35-7:40	27.3	2.4	0.004	564.0	29.0	60.5
7:40-7:45	27.3	5.5	0.007	705.8	54.6	109.5
7:45-7:50	27.4	8.5	0.016	798.0	32.4	130.1
7:50-7:55	27.4	9.0	0.013	730.8	57.2	106.1
7:55-8:00	27.5	8.6	0.011	752.0	51.2	72.8
8:00-8:05	27.5	11.2	0.025	1007.7	67.4	164.7
8:05-8:10	27.6	14.5	0.028	1049.9	83.5	233.9
8:10-8:15	27.6	12.5	0.023	1022.4	83.2	207.7
8:15-8:20	27.7	13.3	0.025	1090.0	113.8	219.1
8:20-8:25	27.7	12.7	0.025	1010.3	86.2	204.4
8:25-8:30	27.7	14.7	0.029	1087.8	101.5	220.9
8:30-8:35	27.8	7.7	0.012	825.9	56.2	143.1
8:35-8:40	27.8	6.2	0.013	700.2	37.4	102.0
8:40-8:45	27.9	7.5	0.009	874.6	62.6	121.7
8:45-8:50	27.9	4.3	0.001	701.9	35.3	70.3
8:50-8:55	28.0	3.5	0.003	635.5	28.7	50.0
8:55-9:00	28.0	5.0	0.000	589.8	22.1	49.0

Table (D-6): Traffic emissions data for Maitham Al-Tammar 1Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	23.6	2.7	0.001	392.2	24.4	56.6
7:05-7:10	23.4	3.4	0.003	468.1	36.2	46.7
7:10-7:15	23.3	4.2	0.007	575.4	46.8	60.4
7:15-7:20	23.2	4.6	0.007	597.0	49.4	72.7
7:20-7:25	23.9	5.0	0.011	667.6	45.6	58.4
7:25-7:30	24.4	4.9	0.009	642.7	47.8	67.8
7:30-7:35	23.9	4.2	0.007	556.0	39.1	61.7
7:35-7:40	23.9	4.1	0.004	575.9	31.8	60.4
7:40-7:45	24.3	4.5	0.008	588.7	43.4	54.8
7:45-7:50	24.7	6.4	0.015	818.7	64.0	89.7
7:50-7:55	24.8	6.9	0.017	893.0	69.2	73.3
7:55-8:00	25.2	7.5	0.018	926.7	71.3	82.9
8:00-8:05	25.4	7.9	0.021	992.4	69.3	83.7
8:05-8:10	25.2	7.0	0.016	862.7	62.7	75.4
8:10-8:15	25.4	7.9	0.021	966.3	66.3	92.2
8:15-8:20	25.8	7.2	0.018	898.3	67.3	82.5
8:20-8:25	25.7	6.1	0.013	803.9	51.5	76.8
8:25-8:30	26.4	6.2	0.013	778.8	60.2	73.6
8:30-8:35	26.4	5.1	0.008	682.4	55.1	79.8
8:35-8:40	25.8	5.4	0.010	663.1	56.5	57.8
8:40-8:45	26.4	5.0	0.010	644.3	48.7	76.9
8:45-8:50	26.3	2.8	0.001	426.9	39.4	35.9
8:50-8:55	27.1	3.5	0.002	526.1	38.4	42.0
8:55-9:00	27.3	3.5	0.004	490.8	35.2	54.6

Table (D-7): Traffic emissions data for Al-Wilada Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	27.7	3.3	0.002	628.1	12.0	41.9
7:05-7:10	27.8	3.0	0.000	647.0	25.5	30.0
7:10-7:15	27.9	4.6	0.009	742.2	40.6	100.2
7:15-7:20	27.8	6.0	0.037	770.2	46.4	97.6
7:20-7:25	27.1	5.9	0.043	801.5	68.8	87.3
7:25-7:30	27.3	7.8	0.053	797.5	76.3	127.8
7:30-7:35	28.2	7.9	0.059	777.4	76.5	100.4
7:35-7:40	27.4	8.8	0.061	827.1	70.5	118.7
7:40-7:45	27.4	9.1	0.066	788.1	79.8	122.7
7:45-7:50	27.8	8.4	0.055	835.9	76.0	130.4
7:50-7:55	27.6	8.1	0.061	825.8	89.4	139.3
7:55-8:00	28.1	10.6	0.080	848.9	74.9	150.1
8:00-8:05	28.3	10.1	0.075	858.8	93.7	134.2
8:05-8:10	28.3	10.2	0.076	838.4	90.9	145.4
8:10-8:15	28.2	10.4	0.081	864.5	96.6	151.8
8:15-8:20	28.8	10.7	0.073	868.8	93.8	144.7
8:20-8:25	28.7	9.9	0.074	854.4	91.9	145.0
8:25-8:30	28.9	9.8	0.076	830.3	80.1	139.0
8:30-8:35	29.1	9.6	0.075	844.3	90.5	134.4
8:35-8:40	28.4	8.8	0.067	829.7	78.0	124.6
8:40-8:45	28.9	7.3	0.055	753.2	84.9	119.7
8:45-8:50	29.3	6.8	0.025	792.4	81.3	101.9
8:50-8:55	28.6	5.4	0.041	766.1	68.2	90.4
8:55-9:00	29.3	5.1	0.032	746.7	55.0	92.6

Table (D-8): Traffic emissions data for Nabi Mohammad Street.

Time	**Temperature (°C)**	**CO (ppm)**	**NO_2 (ppm)**	**CO_2 (ppm)**	**$PM_{2.5}$ (Mg/m^3)**	**PM_{10} (Mg/m^3)**
7:00-7:05	26.5	2.9	0.001	379.2	21.4	34.2
7:05-7:10	26.5	3.4	0.005	302.9	14.3	43.7
7:10-7:15	26.6	3.1	0.005	525.4	22.8	56.1
7:15-7:20	26.7	4.3	0.006	526.6	31.9	58.7
7:20-7:25	26.8	4.5	0.011	633.4	39.9	74.8
7:25-7:30	26.9	4.4	0.010	596.0	43.4	73.4
7:30-7:35	27.1	5.2	0.011	691.8	47.3	68.8
7:35-7:40	27.0	5.0	0.015	634.9	54.0	67.6
7:40-7:45	27.1	5.2	0.018	680.2	36.4	83.1
7:45-7:50	27.2	5.2	0.015	709.2	42.7	73.5
7:50-7:55	27.3	5.8	0.018	805.7	61.0	76.0
7:55-8:00	27.4	6.3	0.019	716.7	53.2	93.3
8:00-8:05	27.5	5.9	0.021	757.8	56.6	109.9
8:05-8:10	27.5	6.2	0.017	875.1	63.4	90.0
8:10-8:15	27.6	6.7	0.026	914.1	60.0	88.2
8:15-8:20	27.7	7.6	0.031	989.2	84.9	111.9
8:20-8:25	27.8	7.6	0.032	977.7	75.2	109.8
8:25-8:30	27.9	8.7	0.038	1009.6	102.1	138.1
8:30-8:35	282	5.5	0.022	695.7	51.9	71.8
8:35-8:40	28.1	6.2	0.025	789.7	55.2	100.8
8:40-8:45	28.1	5.1	0.018	694.8	50.9	62.0
8:45-8:50	28.2	4.7	0.011	557.3	44.1	76.1
8:50-8:55	28.3	3.8	0.008	500.5	25.6	46.9
8:55-9:00	28.4	3.6	0.004	456.2	28.0	59.6

Table (D-9): Traffic emissions data for Sarie Ramadan Street.

Time	**Temperature (°C)**	**CO (ppm)**	**NO_2 (ppm)**	**CO_2 (ppm)**	**$PM_{2.5}$ (Mg/m^3)**	**PM_{10} (Mg/m^3)**
7:00-7:05	19.5	3.0	0.000	564.7	24.2	49.8
7:05-7:10	19.6	4.0	0.001	725.9	48.2	65.8
7:10-7:15	19.7	5.1	0.018	807.6	75.0	81.5
7:15-7:20	19.8	5.1	0.024	841.7	87.4	120.2
7:20-7:25	19.8	6.1	0.023	876.9	86.5	145.8
7:25-7:30	19.9	7.5	0.030	944.3	96.6	166.9
7:30-7:35	20.0	6.7	0.027	926.9	89.0	137.3
7:35-7:40	20.1	7.2	0.029	942.7	99.6	169.7
7:40-7:45	20.2	7.7	0.033	941.3	91.1	175.7
7:45-7:50	20.3	6.9	0.028	910.4	79.9	159.9
7:50-7:55	20.3	4.1	0.011	744.7	88.0	94.7
7:55-8:00	20.4	7.7	0.034	942.4	96.1	168.5
8:00-8:05	20.5	6.8	0.026	919.4	99.0	143.1
8:05-8:10	20.6	6.8	0.028	891.9	100.1	147.9
8:10-8:15	20.7	7.5	0.031	970.6	103.5	152.9
8:15-8:20	20.8	8.2	0.036	973.9	96.0	193.5
8:20-8:25	20.8	8.3	0.037	1005.9	100.7	170.4
8:25-8:30	20.9	9.1	0.041	1058.0	106.9	195.7
8:30-8:35	21.0	9.0	0.040	1027.0	122.3	173.7
8:35-8:40	21.1	6.9	0.029	913.1	85.0	140.3
8:40-8:45	21.2	6.3	0.025	883.7	83.1	134.9
8:45-8:50	21.3	4.7	0.018	793.6	68.8	106.4
8:50-8:55	21.3	5.3	0.018	813.2	73.8	110.3
8:55-9:00	21.4	4.7	0.015	774.5	62.9	106.1

Table (D-10): Traffic emissions data for Al- Tarbea Street.

Time	Temperature (°C)	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	21.0	2.8	0.001	555.3	20.9	51.7
7:05-7:10	21.1	3.8	0.004	568.0	51.7	60.2
7:10-7:15	21.2	6.8	0.012	771.1	52.2	79.7
7:15-7:20	21.3	5.7	0.006	731.4	43.7	62.9
7:20-7:25	21.3	7.0	0.012	862.2	49.6	70.4
7:25-7:30	21.4	6.0	0.007	732.3	43.8	67.1
7:30-7:35	21.5	5.2	0.004	683.5	24.2	35.4
7:35-7:40	21.0	5.9	0.007	701.7	59.3	69.2
7:40-7:45	21.1	7.3	0.012	844.4	68.3	72.8
7:45-7:50	21.2	8.4	0.019	929.6	60.8	80.2
7:50-7:55	21.3	9.4	0.021	991.8	85.4	93.3
7:55-8:00	21.3	9.8	0.023	1040.8	91.8	103.4
8:00-8:05	21.4	8.8	0.020	1004.7	68.9	94.4
8:05-8:10	21.5	8.5	0.018	904.0	70.4	91.8
8:10-8:15	22.0	8.5	0.017	902.1	61.5	83.0
8:15-8:20	22.1	6.0	0.006	777.2	50.4	76.4
8:20-8:25	22.1	7.2	0.014	845.4	63.0	76.3
8:25-8:30	22.3	7.8	0.015	852.1	69.8	105.7
8:30-8:35	22.3	11.4	0.029	1033.6	100.1	124.6
8:35-8:40	22.6	11.0	0.029	1058.5	83.5	112.1
8:40-8:45	22.5	10.5	0.026	1042.1	76.3	137.6
8:45-8:50	22.9	7.5	0.015	900.8	59.1	78.3
8:50-8:55	23.0	6.8	0.011	889.7	41.8	59.3
8:55-9:00	23.2	6.9	0.011	851.5	62.2	85.3

After tram implementation.

Table (D-11): Traffic emissions data for Hasn Al-Mojtaba Street.

Time	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	0.9	0.0001	160.5	11.5	21.2
7:05-7:10	1.2	0.0002	191.6	13.7	24.9
7:10-7:15	2.1	0.0010	322.4	23.3	39.0
7:15-7:20	2.3	0.0011	337.0	24.4	40.5
7:20-7:25	2.1	0.0010	318.0	23.0	38.6
7:25-7:30	2.1	0.0009	313.6	22.7	38.1
7:30-7:35	2.1	0.0009	313.6	22.7	38.1
7:35-7:40	2.1	0.0009	313.6	22.7	38.1
7:40-7:45	2.4	0.0013	349.7	25.4	41.7
7:45-7:50	3.9	0.0043	534.5	39.2	57.8
7:50-7:55	3.3	0.0028	460.4	33.6	51.8
7:55-8:00	3.8	0.0039	520.3	38.1	56.7
8:00-8:05	4.2	0.0052	570.8	42.0	60.6
8:05-8:10	3.7	0.0037	508.4	37.3	55.7
8:10-8:15	4.0	0.0046	550.5	40.4	59.1
8:15-8:20	3.3	0.0029	470.4	34.4	52.6
8:20-8:25	2.5	0.0014	365.3	26.5	43.2
8:25-8:30	2.8	0.0019	400.8	29.2	46.5
8:30-8:35	2.0	0.0009	306.4	22.2	37.4
8:35-8:40	2.5	0.0014	362.5	26.3	42.9
8:40-8:45	2.1	0.0009	314.0	22.7	38.2
8:45-8:50	1.2	0.0003	203.5	14.6	26.3
8:50-8:55	1.3	0.0003	217.5	15.6	27.8
8:55-9:00	1.6	0.0005	246.2	17.7	31.0

Table (D-12): Traffic emissions data for Al- Tarbea Street.

Time	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	1.0	0.0001	297.8	7.7	15.4
7:05-7:10	1.2	0.0002	319.1	8.9	17.3
7:10-7:15	2.7	0.0011	490.1	20.8	34.8
7:15-7:20	1.8	0.0005	400.4	14.0	25.2
7:20-7:25	1.8	0.0005	396.1	13.7	24.8
7:25-7:30	1.8	0.0005	397.0	13.8	24.8
7:30-7:35	1.4	0.0003	353.7	10.9	20.6
7:35-7:40	1.7	0.0004	383.2	12.9	23.5
7:40-7:45	2.1	0.0006	425.4	15.8	27.8
7:45-7:50	2.9	0.0013	508.2	22.3	36.8
7:50-7:55	2.3	0.0008	451.2	17.7	30.5
7:55-8:00	2.8	0.0012	497.5	21.4	35.6
8:00-8:05	2.7	0.0012	492.2	21.0	35.0
8:05-8:10	2.6	0.0011	481.3	20.1	33.8
8:10-8:15	2.9	0.0013	508.8	22.3	36.9
8:15-8:20	2.2	0.0008	445.3	17.3	29.9
8:20-8:25	2.1	0.0006	427.8	16.0	28.0
8:25-8:30	2.4	0.0009	466.4	18.9	32.2
8:30-8:35	4.2	0.0032	624.7	32.8	50.3
8:35-8:40	4.2	0.0034	631.5	33.5	51.1
8:40-8:45	3.9	0.0027	602.2	30.7	47.7
8:45-8:50	2.0	0.0006	419.1	15.3	27.1
8:50-8:55	1.5	0.0003	366.7	11.6	21.4
8:55-9:00	2.0	0.0006	416.0	15.1	26.8

Table (D-13): Traffic emissions data for Sarie Ramadan Street.

Time	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	$PM_{2.5}$ (Mg/m^3)	PM_{10} (Mg/m^3)
7:00-7:05	0.9	0.0000	329.3	7.7	11.8
7:05-7:10	1.2	0.0001	384.9	11.5	17.3
7:10-7:15	1.9	0.0003	479.8	20.1	29.9
7:15-7:20	1.7	0.0002	452.8	17.4	25.9
7:20-7:25	1.9	0.0003	480.5	20.2	30.0
7:25-7:30	2.0	0.0004	502.6	22.6	33.6
7:30-7:35	1.9	0.0003	483.9	20.5	30.6
7:35-7:40	2.0	0.0004	501.2	22.5	33.3
7:40-7:45	2.3	0.0007	540.2	27.1	40.1
7:45-7:50	2.4	0.0008	546.4	27.8	41.3
7:50-7:55	1.9	0.0003	479.5	20.1	29.9
7:55-8:00	2.3	0.0007	540.2	27.1	40.1
8:00-8:05	2.1	0.0005	509.5	23.4	34.7
8:05-8:10	2.1	0.0005	516.5	24.2	35.9
8:10-8:15	2.5	0.0010	563.6	30.1	44.6
8:15-8:20	2.6	0.0011	570.2	30.9	45.9
8:20-8:25	2.5	0.0009	560.0	29.6	43.9
8:25-8:30	3.0	0.0017	607.4	36.1	53.7
8:30-8:35	2.5	0.0009	557.5	29.3	43.4
8:35-8:40	2.4	0.0008	550.9	28.4	42.1
8:40-8:45	2.1	0.0005	513.5	23.9	35.4
8:45-8:50	1.8	0.0003	475.7	19.7	29.3
8:50-8:55	1.6	0.0002	449.2	17.0	25.4
8:55-9:00	1.7	0.0002	452.6	17.4	25.9

Appendix- E

Sample sizes

1- Free Flow Speed

Samples have been tested in Table (E-1) and (E-2) for minimum size at 95% confidence interval (z= 1.96) using the following formula:

$N = (\frac{\delta z}{\varepsilon})^2$ where:

N: minimum sample size.

$\delta =$ Sstandard deviation.

Z= Normal distribution value (1.96).

ε = Standard error (1.5).

Table (E-1): Minimum FFS sample size.

Street	Observed samples	Minimum samples
Hasan Al-Mojtaba Street	105	68
Al-Hur Street	101	77
Bait Al-Mohafodh Street	96	86
Al-Tarbea Street	112	57
Nabi Mohmmad Street	98	86
Al-Hawly street	89	81
Sarie Al-Moalemin Street	120	93
Sarie Ramadan Street	144	109
Al-Mojamaat Street	97	59
Al-Dhariba Street	96	50
Qorfat Al-Tijara Street	108	104
Al-Iskan Street	105	93
Ftima Al-Zahraa1 Street	105	99
Ftima Al-Zahraa2 Street	125	89
Haidar Al-Karrar Street	126	91
Al-Nasr Street	154	126
AL-Abbas Street	105	68
Karbala-Najaf Street	96	86
Bab Twerige Street	103	91
Karbala-Hindea Street	84	74

Table (E-1): Minimum FFS sample size (continued).

Street	Observed samples	Minimum samples
Maitham Al-Tammar1 Street	203	107
Maitham Al-Tammar 2Street	98	93
Maitham Al-Tammar 3Street	99	86
Al-Qebla Street	76	57
Karbala-Bagdad1 Street	109	96
Karbala-Bagdad 2Street	65	55
Abdolzahara Al-Kaaby Street	93	91
Al-Amel 2 Street	99	96
Al-Amel 1 Street	68	54
Hai Al-Hur Street	93	77
Hai Al-Moalemin Street	102	93
Al-Wilada Street	212	118
Al-Mowadhfin Street	112	101
Al-Markaz Street	86	74
Imam Ali Street	109	104
Al-Taalib Street	67	55
Al-Jahiz Street	87	77
Shohadaa Al-Mowadhafin Street	95	89

2- Tram Demand Shift Questionnaire

Table (E-2): Tram demand shift questionnaire results and

Region	Own cars, say yes	Don't own cars, say yes	Observed samples	Minimum samples
Al-Amel	57	38	340	181
Al-Hur	35	39	240	180
Al-Mohandesin	62	21	265	196
Al-Qadeer	36	108	375	202
Al-Salam	26	48	325	268
Al-Somod	39	31	370	165
Al-Tahaddy	60	63	310	115

Table (E-2): Continued.

Region	Own cars say yes	Don't own, say yes	Observed samples	Minimum samples
Al-Modara	15	28	140	120
Al-Husain	122	45	285	271
Al-Dorra	35	28	87	84
Al-Nasr	66	79	290	241
Al-Jahiz	31	53	275	76
Al-Eslah	6	25	160	70
Al-Resala	20	66	190	90
Al-Mulhaq	27	63	295	215
Al-Wafaa	67	88	315	239
Al-Taawon	43	25	275	239
Al-Milad	7	6	60	39
Al-Etarat	11	25	115	46
Al-Maamalechy	32	28	185	58
Al-Ramdhan	11	28	305	146
Al-Naqeeb	76	66	305	230
Al-Baladea	15	35	195	204
Al-Chayer	35	130	345	126
Al-Abbas	39	15	365	167
Al-Zahraa	17	19	60	71
Al-Nedhal	44	16	305	167
Alqudos	25	26	365	162
Al-Moaalemin	57	41	300	152
Al-Hur destrickt	132	32	375	325
Al-Osra	13	69	290	182
Al-Iskan	36	60	310	195
Al-Mowadhefin	131	52	350	325
Saif Saad	72	96	375	148
City Center	61	41	385	359
Eskan Askary	41	34	290	287
Sojanaa	66	63	270	214
Freha	27	134	300	169
Al-Shorta	55	114	100	102

Questionnaire Form

Dear Sir/Madam

My search title is:

Sustainable Public Transportation for Karbala City: TRAM As a Case Study

To complete the search requirement, we hope to give your opinions about the importance of criteria that are used to select the best location of metro routes and stations, based on your experiences in field of infrastructure engineering and transportation engineering.

Huda Hafoth Abd-Alhalim

Ph.D, Student

Civil Engineering Dept.

College of Engineering.

Kerbala University.

To create the Matrixes, please look at Table A-1 that represents Saaty's nine points scale, that is used to compare between two criteria.

Table F-1: Nine-point scale.

1	Equally important	Both criteria contribute to the objective equally
3	Moderately important	Based on experience and estimation, moderate preference is given to one criterion over the other
5	Strictly more important	Based on experience and estimation, strict preference is given to one criterion over the other
7	Very strict, proven importance	One criterion is strictly preferred over the other: its dominance has been proven in practice
9	Extreme importance	The evidence based on which one criterion is preferred over the other has been confirmed to have the highest confidence
2,4,6,8	Mid-values	

If row criterion is less important than the column criteria, put the scale (1/2,1/3,1/4,…..etc.), and if the row criterion is important than column criteria put (2,3,4,…..etc.). For example, one thinks that criteria **a** is Extreme importance than criteria **b**, he/she will insert scale 9 in the position, and scale 1/9 in the symmetrical position, as example shown in Table A2:

Table F-2: pairwise comparison matrix.

Matrix	a	b	c
a	1	9	4
b	1/9	1	3
c	1/4	1/3	1

Table F-3: Ranking of station criteria.

Stations	Population	Land use	Vital- distance
Population	1		
Land use		1	
Vital- distance			1

Table F-4: Ranking of route criteria.

Routes	LOS	Land use	Delay time	AQI	Traffic noise
LOS	1				
Land use		1			
Delay time			1		
AQI				1	
Traffic noise					1

الخلاصة

لقد أدى التوسع الحضري السريع والنمو السكاني والزيادة المستمرة في أعداد المركبات إلى تفاقم مشكلات الازدحام المروري وتلوث الهواء والضوضاء في مدينة كربلاء. وقد أسهمت هذه المشكلات في زيادة زمن الرحلة، وارتفاع معدلات التلوث البيئي، وتكرار الحوادث المرورية، فضلاً عن التأثيرات السلبية على راحة الركاب. ولمعالجة هذه التحديات، تم وضع سياسة إستراتيجية تضمنت إنشاء شبكة ترام في مدينة كربلاء لتلبية الطلب المتزايد على النقل، والتخفيف من حدة الازدحامات المرورية.

تم اختيار نظام الترام مقارنة بوسائل النقل الأخرى مثل الحافلات أو المترو لما يتمتع به من مزايا متوازنة؛ إذ يوفر سعة أكبر، وانبعاثات أقل، ومسارات ثابتة وموثوقة مقارنة بالحافلات، في حين يُعد أكثر جدوى من الناحية الاقتصادية وأكثر ملاءمة للمدن المتوسطة الحجم من أنظمة المترو.

بدأت الدراسة بتقييم واقع النقل الحالي، بما في ذلك تحليل التدفق المروري، والسرعة، وزمن التأخير، والملوثات الهوائية (CO, CO_2, NO_2, PM2.5, PM10) إضافة إلى مؤشر جودة الهواء (AQI) ومستويات الضوضاء. وقد أظهرت النتائج أن أكثر من 70% من مقاطع الطرق تعمل عند مستويات خدمة حرجة (D–F) وأن أكثر من نصف الممرات سجلت مستويات غير صحية لمؤشر جودة الهواء، بينما تجاوزت مستويات الضوضاء الحدود الموصى بها من قبل منظمة الصحة العالمية.

لتحديد المسارات المثلى للترام، تم اعتماد مجموعة من المعايير الأساسية شملت: مستوى الخدمة، استعمالات الأراضي، زمن التأخير، جودة الهواء، والضوضاء المرورية. أما معايير اختيار مواقع المحطات فقد تضمنت استعمالات الأراضي، الكثافة السكانية، وسهولة الوصول، مع اعتماد مسافة مشي مفضلة تتراوح بين 300–500 متر من المناطق الحيوية. وقد جرى استخدام أسلوب التحليل الهرمي (AHP) لتحديد أوزان المعايير الرئيسة بالاستناد إلى مقياس المقارنة ذي النقاط التسع لـ Saaty. وأظهرت النتائج أن مستوى الخدمة كان الأعلى وزناً، تلاه استعمالات الأراضي، ثم التأخيرات، وجودة الهواء، وأخيراً الضوضاء. أما بالنسبة لمعايير المحطات، فقد حظي معيار مسافة المشي بالأهمية الكبرى.

تم تطبيق إطار لاتخاذ القرار متعدد المعايير(MCDM) باستخدام نظم المعلومات الجغرافية (GIS) مما نتج عنه أربعة بدائل لمسارات الترام بطول إجمالي بلغ 61.23 كم مع 106 محطات. وقد جرى تقييم هذه المسارات من حيث إمكانية الوصول، نطاق الخدمة، التغطية السكنية، وتكاليف الإنشاء باستخدام طريقتي CRITIC وEDAS وجاء المسار الأول في المرتبة الأعلى، تلاه المساران الثاني والرابع، بينما كان المسار الثالث الأقل ملاءمة.

كما أجريت محاكاة مرورية باستخدام برنامج PTV VISSIM لمقارنة سيناريوهين: الوضع الحالي والوضع بعد تنفيذ الترام. وأظهرت النتائج تحسناً كبيراً؛ حيث انخفضت مقاطع الطرق عند مستويات الخدمة E وF من 70% إلى الصفر، وارتفعت السرعة المرورية بنسبة 131%، كما انخفضت التأخيرات بأكثر من 60%، وتراجعت الانبعاثات بنسبة تراوحت بين 13–60%. إضافة إلى ذلك، شهدت تغطية وكفاءة النقل العام تحسناً ملحوظاً.

وتخلص الدراسة إلى أن إنشاء نظام ترام في كربلاء يمثل حلاً مستداماً لمشكلات الازدحام المروري، والتلوث البيئي، وعدم المساواة في فرص التنقل. كما أن الإطار المقترح قابل للتطبيق في تخطيط النقل في مدن متوسطة الحجم أخرى ضمن الدول النامية.

جمهورية العراق

وزارة التعليم العالي والبحث العلمي

جامعة كربلاء

كلية الهندسة

قسم الهندسة المدنية

النقل العام المستدام في مدينة كربلاء: دراسة حالة الترام

رسالة مقدمة الى كلية الهندسة في جامعة كربلاء

كجزء من متطلبات نيل درجة الدكتوراه في الهندسة المدنية

(هندسة البنى تحتية)

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