



ADDIS ABABA UNIVERSITY

COLLAGE OF TECHNOLOGY AND BUILT

ENVIRONMENT

**Evaluating the Effectiveness of Reversible Lanes in Reducing Traffic
Congestion: A Case Study of Key Corridors in Addis Ababa, Ethiopia**

By

Ephrem Zeleke

A Thesis Submitted to the School of Built Environment at Addis Ababa
University, presented in partial fulfillment of the requirements for the
degree of Master of Science in Infrastructure Planning and Management.

Advisor: Dr. Ephrem Gebremariam

Addis Ababa, Ethiopia

June 2025

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DECLARATION

I, the undersigned, solemnly declare that this dissertation represents my original work and has not been submitted for a degree at any other university. I have diligently acknowledged all sources of material utilized in this dissertation under the academic standards and guidelines of Addis Ababa University.

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CONFIRMATION

The research completed by Ephrem Zeleke titled “Evaluating the Effectiveness of Reversible Lanes in Reducing Traffic Congestion: A Case Study of Key Corridors in Addis Ababa, Ethiopia” was conducted under our supervision and submitted to the examination in partial fulfillment of the requirements for the Master’s degree in Infrastructure Planning and Management.

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CERTIFICATION

This is to certify that the dissertation prepared by Ephrem Zeleke titled " Evaluating the Effectiveness of Reversible Lanes in Reducing Traffic Congestion: A Case Study of Key Corridors in Addis Ababa, Ethiopia" and submitted for the Master of Science degree in Infrastructure Planning and Management, adheres to the university's regulations and meets the required standards

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ABSTRACT

Traffic congestion is a pressing issue in Addis Ababa, Ethiopia's capital, requiring innovative traffic management strategies, beyond constructing and expanding infrastructure. This study evaluates the effectiveness of reversible lanes in reducing peak hour congestion. Two roads, Asko to Winget and Mexico to Mesqel Square, were selected, representing peripheral and central areas of the city, respectively. Traffic data were collected at major intersections along these roads using video recording, and SUMO traffic simulation was used to analyze key parameters, including travel time, speed, time loss and traffic volume under existing conditions and proposed reversible lane scenarios. From reversible lanes setups, a two-lane reversible configuration provided the best network wide performance, where travel time and time loss reduced by 27.44% and 32.33%, Speed increased by 2.84% while traffic flow slightly decrease by 7.91%. However, no improvement on Mexico to Mesqel Square is gained due to balanced flows and westbound losses. The study also identified directional volume imbalance, number of reversible lanes, traffic light systems, intersections number and spacing as the major factors influencing effectiveness. Based on the findings, this study recommends the implementation of reversible lanes on major roads connecting the outskirts of the city to the center to optimize capacity without land acquisition, supported by adaptive signals and bus priority lanes to minimize disruptions. Additionally, the research recommends road specific traffic simulation studies before implementing such strategies. Moreover, the research provides valuable insights for policymakers and urban planners seeking data-driven approaches to traffic management in Addis Ababa and other cities facing similar challenges.

Keywords: congestion, reversible lanes, microsimulation, intersections

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LIST OF ACRONYMS

BL	Baseline
CBD	Central Business District
CTM	Cell Transmission Model
ETB	Ethiopian Birr
GEH	Geoffrey E. Havers (Statistic)
GIS	Geographic Information System
GUI	Graphical User Interface
HCM	Highway Capacity Manual
HOV	High-Occupancy Vehicle
IDM	Intelligent Driver Model
ITS	Intelligent Transportation Systems
LCL	Lower Confidence Limit
LOS	Level of Service
LWR	Lighthill-Whitham-Richards
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
OECD	Organization for Economic Co-operation and Development
OSM	Open Street Map
PM _{2.5}	Particulate Matter (2.5 micrometers or less in diameter)
PM ₁₀	Particulate Matter (10 micrometers or less in diameter)
R1	Reversible Lane Scenario 1 (One Reversible Lane)
R2	Reversible Lane Scenario 2 (Two Reversible Lanes)
R3	Reversible Lane Scenario 3 (Three Reversible Lanes)
RMSE	Root Mean Square Error
SO ₂	Sulfur Dioxide
SUMO	Simulation of Urban Mobility
TRB	Transportation Research Board
TSM&O	Transportation System Management and Operations
UCL	Upper Confidence Limit

CHAPTER 1: INTRODUCTION

1.1 Background

Traffic congestion is a universal challenge in modern urban life (Lay, 2012) and time lost in traffic is not only wasted but often experienced as a source of frustration. Traffic congestion is closely linked to urbanization with the increase in population, vehicles, and demand for transport infrastructure (Zang et al., 2023).

As per the United Nations report, the urban population has increased from 2.29 billion in 1990 to 4.22 billion in 2018, and is expected to rise to 5.17 billion by 2030 (United Nations, 2018). In Ethiopia, an additional 50 million urban residents are projected to be added between 2018 and 2050. Particularly, the population of Addis Ababa is forecasted to surpass seven million by the end of 2050, with one of the highest urbanization rates in the world (United Nations, 2018). This growing number of city residents contributes significantly to increasing the demand for mobility

In Addis Ababa, urbanization fuels economic growth, increasing individual automobile ownership and mobility demand (Wang & Debbage, 2021). However, these factors also play intricate roles in the formation of traffic congestion:

- **High Urban Density:** urban areas are characterized by high density with mixed land use, which hinders the opportunity to expand roads, potentially leading to congestion at key intersections and narrow streets (Bogale, 2012).
- **Prevalence of Informal Transport:** Most of Addis Ababa's transportation is informal, like minibuses, which have unplanned stop-and-go behavior and frequent route change, contributing to traffic unpredictability (Kassahun, 2007).
- **Poor Road Infrastructure:** Addis Ababa's road infrastructure is predominantly old, damaged, and insufficient to service the current traffic, which worsens the congestion (Assefa, 2020).

Consequently, the resulting cost of congestion in terms of time lost, fuel waste, health, and environmental impact worldwide is significant. The U.S. lost over \$70.4 billion in 2023, a 15% increase from the previous year (Pishue, 2024). In Addis Ababa, the annual time loss due to congestion ranges between 38,687 to 49,011 hours, translating into an

economic cost of ETB 501.4 to 611.1 million in 2023 (Gunjo et al., 2024). Additionally, it has environmental impacts, with a 27–70% rise in peak-hour emissions at major intersections, and social costs, like commuter stress, further highlight the urgency for solutions (Teshager et al., 2021).

In response, traditional approaches such as expanding road infrastructure have shown limited success, due to high costs, long implementation times, and induced demand (Anupriya et al., 2023; Farahani et al., 2013)

Consequently, a shift towards optimizing existing infrastructure through traffic management is being explored. One of the alternatives from traffic management is reversible lane systems, which adjust lane directions to match peak flows and offer a cost-effective solution (Mihaita et al., 2014). However, their effectiveness in developing cities such as Addis Ababa with mixed traffic remains underexplored, necessitating context-specific research.

This study uses SUMO to simulate and study the before and after effects of reversible lane system by modeling road geometry and traffic demand. By simulating various scenarios, it evaluate the potential benefits of reversible lanes, providing evidence-based insights for urban traffic management (Hamid et al., 2021; Zhuravleva et al., 2020). Furthermore, this research addresses Addis Ababa's congestion crisis while contributing to global sustainable mobility solutions.

1.2 Statement of the Problem

Transport demand worldwide is projected to increase significantly; annual passenger traffic is expected to be more than 80 trillion passenger-kilometers in 2030, a 50% increase from 2015, as well as a 70% increase in freight volumes (Sustainable Mobility for All, 2017). Similarly in Ethiopia, the number of vehicle ownerships is predicted to double to 5 cars per 1000 people by 2035, with vehicles increasing from 552,000 in 2015 to 1,680,000 by 2030 (Gorham et al., 2017). This trend coupled with poor traffic management is expected to result sever traffic jams in Addis Ababa, Ethiopia, particularly in peak hours.

The economic costs of the resulting congestion are significant; Addis Ababa loses between Birr 501.4 million to 611.1 million annually due to time lost in traffic (Gunjo

et al., 2024; Sokido, 2024). In addition, environmental impacts including a 27–70% increase in peak-hour emissions, and social costs, such as commuter stress, further highlight the urgency for solutions (Teshager et al., 2021).

From potential solutions, the common approach of expanding road infrastructure. However, it requires substantial investment and an extended period for implementation. This approach is even more demanding in Addis Ababa since the city experiences high urban settlement density, where houses and commercial buildings are built close to the roads. Expansion of roads in such areas have severe consequences, displacing local populations and business (OECD, 2007).

In addition, if short term solution is not given, the city will potentially face additional economic and environmental loss, requiring an alternative, quicker traffic management solution.

In light of the above and given that Addis Ababa roads are predominantly two-ways, this research critically addresses congestion by proposing a reversible lane system, dynamically adjusting lane directions to match peak flows, optimizing existing infrastructure.

However, the literature on reversible lane systems shows inconsistent outcomes, some studies report benefits such as improved flow and reduced travel time (Başkan & Ozan, 2018; Karimi et al., 2022; Kit Meng & Thu, 2005; Zhang et al., 2020), others highlight drawbacks including increased long-term congestion and reduced trip-serving capacity (Bindzar et al., 2021; Chiu et al., 2007; Chow et al., 2021; Gayah & Daganzo, 2012). This mixed evidence underscores the need for context-specific assessment before implementation in cities like Addis Ababa.

Consequently, implementing such interventions without prior study risk worsening the congestion. This research addressed this gap by conducting the study with a tailored approach to match the traffic characteristic and actual road network of the city. The research also identify the key factors influencing the success of reversible lanes, such as the optimal number of lanes, which should be reversed and traffic signal types. Additionally, the study assess the limitations and implementation challenges of the proposed system. These insights will be useful to achieve sustainable urban mobility,

minimize economic losses and reduced environmental and health impact on the resident of the city.

1.3 Research Questions

The study investigates the potential of reversible lane systems to mitigate peak hour road congestion in Addis Ababa, Ethiopia focusing on effectiveness, influencing factors and implementation challenges within the city's traffic and infrastructure context. The following general and specific questions guide the research to evaluate these aspects using traffic simulation.

- 1) How effective are reversible systems in alleviating road congestion, particularly during peak hours in Addis Ababa?
- 2) What key factors determine the effectiveness of reversible lane systems in reducing road congestion within Addis Ababa?
- 3) What are the primary challenges associated with implementing reversible lane systems?

1.4 Research Objectives

1.4.1 General Objective

The objective of this research is to critically evaluate the effectiveness of reversible lane systems to mitigate congestion, identify the key factors that determine its success and explore implementation challenges in Addis Ababa, Ethiopia context.

1.4.2 Specific Objective

- i) To evaluate the effectiveness of reversible lane systems in reducing peak hour congestion in Addis Ababa.
- ii) To identify key factors that determine the effectiveness of reversible lanes in reducing congestion in Addis Ababa.
- iii) To identify the primary challenges associated with implementing reversible lane systems.

The objectives addresses conflicting results from previous studies by focusing on local traffic conditions, providing a localized study that considers Addis Ababa's unique infrastructure and vehicle composition.

1.5 Scope and Significance of the Study

1.5.1 Significance of the Study

Traffic congestion in Addis Ababa is exacerbated by the limited infrastructure, which is not being expanded in the same pace as the traffic demand and urbanization. This study is aimed to make a contribution to this pressing issue by evaluating the potential of reversible lane systems in mitigating congestion.

The research also contribute to policy and city planning of Addis Ababa by providing empirical evidences on feasibility of reversible lane systems under budgetary and spatial constraints, dense urban development, and increasing traffic.

In addition, this research also informs on determinants' of the success of reversible lane systems, such as the number of converted reversible lanes and the comparative effectiveness of different traffic signal types (delay based versus fixed signals). These results will provide city planners and traffic engineers with the knowledge required to enhance traffic management strategies, both from flow efficiency and safety perspectives.

Globally, the findings offer lessons for cities facing urbanization challenges, supporting sustainable mobility, rigor and feasibility, contributing to traffic engineering by:

- Improving Flow: Proposing tailored reversible lane solutions.
- Informing Policy: Providing evidence for dynamic traffic systems.
- Setting Precedents: Modeling innovative congestion solutions.

1.5.2 Scope of the Study

The study is conducted in Addis Ababa, focusing on application of reversible lane systems to mitigate congestion on two key corridors that experience sever congestion. To achieve this, the scope of the research is defined as follows:

- **Geographical Boundaries:** The study is based on two key roads in Addis Ababa which experience severe congestion during peak hours. The roads are Asko to Winget (starting at Asko, 9.04°N, 38.69°E; ending at Winget, 9.02°N, 38.71°E) and Mexico to Mesqel Square road (starting at Mexico, 9.02°N, 38.75°E; ending at Mesqel Square, 9.01°N, 38.76°E).
- **Conceptual Focus:** The research is focused on assessing the impact of reversible lanes impact on road performance indicators such as travel time, speed, time loss and traffic volume excluding other strategies.
- **Methodological Boundaries:** SUMO traffic simulation software is used to model the existing traffic flows and the proposed reversible lane systems. Additionally, the data used are manually collected traffic count as primary data and road geometry from openstreetmap website as a secondary data source.
- **Temporal Scope:** The research is limited to current traffic conditions.

1.6 Limitations of the Study

1.6.1 Limitations

The study uses traffic simulation as the primary tool for assessing the impact of reversible lane systems, and it is an efficient analysis method. However, the accuracy depends on the input data quality, model assumptions, and complexity of actual traffic flow patterns. The conclusions should therefore be interpreted with such potential limitations.

Moreover, the research did not consider all the factors, which could influence the performance of reversible lane systems, such as the influence of pedestrians and non-motorized transport. It didn't also cover the socio-economic impact of implementing reversible lane systems.

1.7 Structure of the Thesis

This thesis is organized into five chapters to systematically address the research objectives: Chapter 1 introduces the study; Chapter 2 reviews literature on congestion and reversible lanes; Chapter 3 details data types and collections methods, analysis methodology and the SUMO-based modeling; Chapter 4 presents simulation results

and discussions; and Chapter 5 offers conclusions, recommendations, and future research directions, ensuring actionable insights for Addis Ababa's traffic management.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature regarding traffic congestion and reversible lanes. It begins with conceptual and theoretical foundations covering definitions, causes, and impacts of traffic congestion. Next, an empirical review examines global, regional, and Addis Ababa-specific studies on congestion and reversible lanes. The chapter then identifies research gaps, particularly in context-specific applications, and concludes with a conceptual framework to guide the study's evaluation of reversible lanes using SUMO simulation in Addis Ababa's key corridors.

2.2 Conceptual and Theoretical Literature

2.2.1 *Traffic Congestion*

2.2.1.1 *Definitions and Scope of Traffic Congestion*

There are numerous definitions of traffic congestion and its extent. As such, there are several parameters used to define and measure traffic congestion including travel time, speed and traffic flow. This indicates that traffic congestion has an intricate nature (Downs, 2004).

One of the definitions is that traffic congestion is a state of traffic stream on a transportation facility that is characterized by low speeds and high densities (Hoogendoorn & Knoop, 2013). It can also be described as a state in which traffic moves at a rate lower than the capacity for which a roadway was originally designed (Downs, 2004).

In a general, it can be asserted that congestion is when there is more traffic demand than the capacity of roads, resulting in reduced speeds and higher travel time (OECD, 2007). These definitions demonstrate that traffic congestion has several aspects with different dimensions, illustrating various perspectives of traffic capacity and flow.

2.2.1.2 *Types of Traffic Congestion*

Traffic congestion can be categorized in to two general types: recurrent and non-recurrent congestion, depending on predictability and frequency of the congestion.

Recurrent congestion occurs daily and is usually the result of a large number of vehicles attempting to enter the road at the same time (Skabardonis et al., 2003). This congestion usually occurs on weekday's morning and afternoon peak hours, when everybody commutes to and from work and schools (Hallenbeck et al., 2003).

In contrast, non-recurrent congestion is caused by unexpected events such as traffic accidents, bad weather, emergency maintenance, special events, or careless driving behavior (Hallenbeck et al., 2003).

2.2.2 Causes of Traffic Congestion

The underlying causes of congestion include traffic influencing events such as traffic accidents, ongoing constructions and road maintenance and adverse weather, alongside high traffic demand during rush hours and special events that overwhelm road capacity (Federal Highway Administration, 2020). Additionally, transportation design and infrastructure play a significant role in congestion, including physical bottleneck such as narrow roads or poorly designed intersections, which accounts approximately 40% of congestion (Litman, 2023). This is also exacerbated by inadequate traffic control devices, insufficient road networks and unplanned land-use that extends travel distances (Litman, 2023).

In general, physical bottlenecks (40%), traffic accidents (25%), inclement weather (15%), road construction zones (10%), and incorrect timing of traffic signals and special events (5% each) are the primary causes of traffic congestion (Federal Highway Administration, 2005).

2.2.2.1 Measurement of Traffic Congestion

Traffic congestions can be measured and evaluated in various ways, and can be broadly categorized into two general categories: those that measure temporal aspects and those that measure spatial aspects of congestion (Federal Highway Administration, 2005). The table below provides a list of key congestion performance measures:

Table 2-1: Congestion Performance Metrics

Metric	Definition	Formula	Remark
Travel Time Index	Ratio of actual to free-flow travel time	$TTI = \text{Actual Travel Time} / \text{Free-flow Travel Time}$	Measures congestion severity
Total Delay	Hours beyond free-flow conditions	$\text{Delay} = \Sigma(\text{Vehicle-Hours} - \text{Free-flow Hours})$	Quantifies total impact
Average Travel Speed	Speed between two points	$\text{Speed} = \text{Distance} / \text{Travel Time}$	Reflects flow efficiency
Throughput	Total vehicle-kilometers traveled	$\text{Throughput} = \text{Vehicles} \times \text{Distance}$	Indicates network usage

Source: Federal Highway Administration (2005)

2.2.3 Traffic Flow Theory and Dynamics

Traffic flow theory provides a foundation for understanding vehicular movement and traffic conditions on highway networks providing a basis for evaluating reversible lanes in Addis Ababa. Greenshields' model, one of the first, formalized the connection between speed, flow, and density, on which modern traffic flow analysis is built (Greenshields, 1935). A number of subsequent models have been introduced, which are categorized as theoretical models and spatial scale-based models. These models scalability and usability in evaluating the impact of reversible lanes on traffic flow performance and congestion are explained in this section.

i) Greenshields' Model

Greenshields' model is a linear model between speed and density, in which speed reduces in proportion as density increases. The model is given as:

$$V = V_f \left(1 - \frac{K}{K_j}\right)$$

Where V_f is free-flow speed (100 km/h) and K_j is jam density (vehicles/km). This model predicts optimal flow at intermediate density, informing reversible lane design to maintain efficiency (Greenshields, 1935). However, its simplicity limits applicability in complex urban networks like Addis Ababa's.

ii) Lighthill-Whitham-Richards (LWR) Model

The LWR model builds upon Greenshields' work by incorporating the principle of vehicle conservation. The LWR model describes traffic flow using a partial differential equation:

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0$$

Where q is traffic flow, k is density, and t and x are time and space. Flow is defined by a fundamental relationship, typically $q = f(k)$, where $f(k)$ is a function of density ($q = k \cdot V(k)$, with $V(k)$ as speed dependent on density). This models traffic waves, supporting reversible lane analysis by simulating flow disruptions (Lighthill & Whitham, 1955; Richards, 1956).

iii) Kinematic Wave Model

The kinematic wave model is a generalization of the LWR model in that it uses a more general flow-density relation. The model accurately describes actual traffic phenomena, i.e., stop-and-go traffic and queuing. The model highlights that free flow conditions (high speed, low density) result in stable traffic flow, while congestion conditions (high density, low speed) destabilize traffic flow and generate longer queues. This model is suitable for reversible lane planning since it addresses traffic's dynamic flow as a function of evolving demand in a proper manner (Newell, 1993).

iv) Car-Following Models

Car-following models focus on the motion of a single vehicle, based on how drivers react to the leading vehicle. Key models include:

- Gipps' Model: It models safe driving speed and distances (gap), taking reaction time of a driver in account, suitable for reversible lane scenarios where driver decisions are critical (Gipps, 1981).
- Intelligent Driver Model (IDM): IDM continues Gipps' work with more complex rules, such as acceleration rates and safe distance dynamics. IDM is applied in most microscopic traffic simulations (e.g., SUMO, VISSIM) to investigate congestion and traffic wave formation (Treiber et al., 2000).

v) Cell Transmission Model (CTM)

The CTM is a mesoscopic model that describes traffic flow as a sequence of connected "cells." One cell is equivalent to a road segment, and vehicles are classified according to speed, density, and flow. The CTM simulates very well the spread of congestion and shockwave response and is therefore suitable for reversible lane analysis in huge networks (Daganzo, 1994).

2.2.3.1 Spatial Scale Classification of Traffic Models

Traffic flow models vary in spatial scale, ranging from microscopic to macroscopic. All have application in traffic flow simulation and in calculating the impact of interventions like reversible lanes.

- i) Microscopic Models:** Microscopic models imitate vehicle performance in terms of vehicle-to-vehicle interaction. They are ideal to model local traffic and driver response to lane change like reversing lanes (Treiber et al., 2000; Treiber et al., 2000). IDM and Gipps' models are microscopic models.
- ii) Macroscopic Models:** Macroscopic models mimic collective traffic flow, on the basis of quantities like density, speed, and flow. Macroscopic models are applicable everywhere in the network and computationally cheap. Some of them include LWR and Greenshields' models (Greenshields, 1935; Lighthill & Whitham, 1955; Richards, 1956).
- iii) Mesoscopic Models:** Mesoscopic models bridge the microscopic and macroscopic methods. They simulate traffic flow at an intermediate scale and, in most cases, use groups or cells to depict automobiles. Cell Transmission Model (CTM) is a high-performance illustration of this, simulating the propagation of congestion and shockwave characteristics perfectly (Daganzo, 1994).

2.2.4 Congestion Mitigation Strategies

Congestion mitigation strategies aim to reduce traffic congestion by optimizing existing infrastructure and dictating urban settlement based on transportation and urban planning. These strategies include Transportation System Management Operations (TSM&O), strategic capacity improvement, and land use planning.

Transportation System Management Operations aim to decrease traffic congestion by making the maximum use of the existing infrastructure using Intelligent Transportation Systems (ITS). Other techniques include:

- **Congestion Pricing:** Reduces peak-hour travel but faces public resistance in Addis Ababa (Federal Highway Administration, 2008). Dedicated Bus Lanes: Enhance transit reliability, as in Nairobi, reducing vehicle numbers (Hensher, 2007).
- **Signalized Traffic:** Synchronized signals tailored to local patterns reduce delays (Xu et al., 2021).
- **Directional Flow Management:** Reversible lanes address directional imbalances, tested via SUMO (Tsuboi, 2021).
- **Intelligent Traffic Systems:** Provide real-time data for adaptive control, improving efficiency (Ravish & Swamy, 2021).

Strategic capacity improvement focuses on optimizing existing road infrastructure to mitigate congestion, avoiding costly expansions. This approach emphasizes efficient use of resources through strategies like reversible lanes and adaptive signal control (Litman, 2023).

Additionally, Land use planning can have a significant contribution towards reducing traffic congestion. Urban sprawl tends to increase travel demand since commercial and residential land use shifts to lower-cost fringes, congesting transport systems (Litman, 2023).

2.2.5 Traffic Analysis and Simulation Tools

2.2.5.1 Types of Traffic Analysis Tools

Traffic analysis tools are traditionally classified into two types based on approach; Highway Capacity Manual (HCM)-based tools and traffic simulation tools (Dowling, 2007). Both types of tools have their nature, strength, and limitations and are more appropriate for various kinds of analysis.

2.2.5.2 Highway Capacity Manual (HCM)-Based Tools

Highway Capacity Manual (HCM), which was developed by the Transportation Research Board (TRB), is used extensively to provide quantitative estimates of vehicular capacity, level of service (LOS), and other measures to quantify roadway capacity.

HCM employs theoretical formulas of traffic flow along with empirical findings in estimating traffic activity (National Research Council, 2000).

- **Strengths Standardization:** HCM is an accepted and standard procedure of capacity and LOS analysis used in transportation engineering and planning (National Research Council, 2000). It is also relatively simpler with less data intensity and computer power in comparison to simulation software.
- **Limitations:** The HCM relies on homogeneous and steady-state traffic flow assumptions that have no ability to capture real-world variability, i.e., dynamic lane reconfiguration or heterogeneous driver behavior (Li et al., 2023). The manual is also less ideal for analysis of intricate traffic states, i.e., reversible lanes, which consist of dynamic traffic stream modeling and driver interactions.

2.2.5.3 Traffic Simulation Tools

Traffic simulation tools consist of computer software that mimics realistic driving scenarios within a proposed road network. Simulation software is a better alternative for traffic management solution analysis, hypothesis testing, and on handling intricate cases that are not effectively solved by analytical models such as HCM (Dorokhin et al., 2020).

In addition, traffic simulation can add dynamic traffic state, behavior, and other input from parameters such as weather into results to make them more realistic and accurate under different circumstances (Ejercito et al., 2017).

- **Strengths:** Traffic simulation software can simulate realistic and dynamic traffic movement, including lane change, signal change timing, and driver psychology (Lopez et al., 2018). It also enables researchers to test various scenarios and

hypotheses, and check whether alternative traffic management strategies would be effective prior to implementation (Barceló, 2010).

- **Limitations:** Computation in traffic simulations is intensive and entails large input data, including high-level geometric data, traffic volume, and driver behavior parameters (Dowling et al., 2004). The degree of detail required for simulation can also limit their application in large-scale analysis or where data is limited (Ejercito et al., 2017).

2.2.5.4 Overview of Traffic Simulation Software

There are several software varying in accuracy, computation complexity, and user requirement. Some of the usually used software packages includes VISSIM, AIMSUN, TRANSYT, and SUMO differ in strengths and weaknesses (Ejercito et al., 2017).

Microsimulation tools, such as VISSIM and AIMSUN, provide detailed traffic simulation and can be used in analysis of complex driver behavior and intersection capacity. They can be computationally and data-intensive. Macro simulation tools, such as TRANSYT, are network-efficient but do not consider in-depth vehicle interactions (Barceló, 2010). SUMO is open-source code that is adaptable and scalable and can be utilized in big metropolitan traffic studies (Krajzewicz et al., 2012; Lopez et al., 2018)

Traffic simulation software has a number of benefits to transport planners and engineers, including the capacity to foretell traffic problems, try out solution strategies, and improve network efficiency and safety (Ejercito et al., 2017). Nevertheless, caution should be observed over their limitations, i.e., cost, user friendliness, and sensitivity to assumptions and inputs (Dorokhin et al., 2020).

2.3 Contextual Framework

Addis Ababa presents a unique context due to the character of traffic, nature of urbanization, and problems of governance at stake.

- **Geographical Context**

Addis Ababa's city sits on high elevation (2,200–2,600m) and its challenging topography limits road expansion, which complicates the traffic management Gunjo et

al. (2024). Additionally, the road plan, which is a radial road network converging on the city center make traffic management more complex.

- **Policy Context**

Ethiopian national and local transport policy seeks to support economic development and enhance people's wellbeing through mobility promotion in urban areas (World Bank, 2020). Reversible lanes ensure these policy aims are attainable through providing a flexible and scalable intervention that maximizes congestion alleviation with no further major investments.

The current traffic management system in Addis Ababa is largely based on fixed-time traffic signals and fixed lane usage, which cannot accommodate the changes in traffic patterns (Gunjo et al., 2024). Reversible lanes and adaptive signal control systems can introduce dynamic and effective city traffic management, as other cities with similar limitations have also done (Mahadevan et al., 2019; Papageorgiou et al., 2003).

- **Socioeconomic Context**

Addis Ababa roads are shared with diversified users like private cars, buses, taxis, pedestrians, and cyclists. Proportional distribution of road space is also a significant matter as reversible lanes have to serve all transport users with no decline in safety or accessibility. A study by Sitotaw (2019) argue that reversible roads should be established in the realm of non-motorized transport so that change does not reinforce existing mobility inequities.

2.4 Empirical Review of the Literature

2.4.1 Global Perspective

2.4.1.1 Reversible Lanes and Urban Traffic Management

Reversible lane system is based on dynamic lane allocation theory, where directional demand is managed without an expansion of the infrastructure. The method maximizes existing infrastructure, providing a low-cost solution.

Papageorgiou et al. (2003) pointed out that dynamic lane allocation is best applied in the urban setting with extreme peak-hour directional imbalances. Adaptive solutions, like reversible lanes, are harmonious with overall plans in order to reduce congestion and maximize infrastructure utilization (Zhou et al., 2018). This is proven through real world implementation in cities such as Washington, D.C., and Jakarta that demonstrated how reversible lanes can reduce peak-hour congestion and travel times (Litman, 2023).

2.4.1.2 Implementation Challenges

Implementation of reversible lane systems to manage urban traffic congestion met with numerous challenges, warranting the right consideration for effective implementation. Driver behavior poses a significant challenge since misinterpretation of dynamic lane changes increases risks of collision. Research emphasizes the need for adequate signage and education to ensure compliance (Wolshon & Lambert, 2006). In addition, integration with the public transport system is essential, particularly in Addis Ababa because minibuses are prevalent (Sitotaw, 2019). Moreover, reversible lanes will disrupt bus travel unless priority is accorded to them.

2.4.2 Reversible Lane Systems as a Mitigation Strategy

Reversible lane systems efficiency in controlling urban traffic congestion has been under the scope of research for long. Some studies have shown that the implementation of reversible lane has positive impacts on traffic. For instance, research in China's central region of Changsha demonstrated that reversible lanes improved traffic operation of the district (Shi et al., 2023)

Similarly, research in Isfahan, Iran, showed that reversible lane implementation led to a saving of approximately 9% of overall travel time (Hausknecht et al., 2011). Another source of supporting evidence for the benefits of reversible lane systems is from Zhang et al. (2020), where it reduced the overall flow-weighted shortest path travel distance compared to existing conditions. Another research study also showed that reversible lane networks performed better than two-way street networks at 95% confidence level. (Wolshon & Lambert, 2006).

Conversely, some other research highlighted that conversion of road has potential drawbacks. Gayah & Daganzo (2012) stated that two-way networks have higher trip-serving capacities than reversible lane networks. Additionally, Chiu et al. (2007) stated that with the passage of time, congestion on roads with reversible lane can prove to be twice more worse than two-way street congestion. Furthermore, a study by Cao et al. (2020) claimed that reversible lanes have no effect at all on the traffic condition in the internal traffic circuit of the city.

Overall, the literature on the effectiveness of reversible lanes to address traffic congestion produces contradicting results, with some studies producing positive effects while others produce negative effects. Hence, implementation of reversible lanes in Addis Ababa requires prior assessment.

2.4.3 Regional Perspective

Limited studies address reversible lanes in African contexts. Nairobi's dedicated bus lanes enhanced transit reliability, reducing vehicle numbers (Hensher, 2007), suggesting potential for directional flow management strategies like reversible lanes in similar settings.

2.4.4 Addis Ababa-Specific Perspective

2.4.4.1 Impacts of Traffic Congestion

- **Economic Impacts**

At a global level, congestion results a massive economic harm in the form of reduced productivity, additional fuel consumption, and higher transportation cost. The cost as a result of traffic congestion in US was estimated at \$190 billion in 2019, 8.7 billion hours of delay and 3.5 billion gallons of wasted fuel (Schrang et al., 2021).

Similarly, in Addis Ababa, a congestion cost study on Mesqel Square to Kaliti Interchange road put an estimated Birr 53.2 million every year in terms of delay, fuel consumption, and vehicle operating cost (Andargie, 2017).

- **Environmental, Social and Health Impacts**

Congestion is one of the key causes of environmental degradation through increased emissions. Global health cost of PM2.5 from congestion in 2020 was estimated at \$13 billion in 2020, and expected to grow to \$17 billion by 2030 (Levy et al., 2010).

In Addis Ababa, major intersections is experiencing increase in emissions of 27-37% for cars, 30-39% for minibuses, 49-63% for buses, and 45-70% for trucks during peak hours (Teshager et al., 2021).

In addition, a survey along Mexico to Ayat road found that 46.3% of the respondents interviewed were losing 2-3 hours daily in traffic, and claimed to result more increased stress, and potential mental illness (Tazzie, 2022). There is likely some element of bias in using self-reported data, but it still indicates the challenges society faces due to congestion.

Table 2-2: Summary of Traffic Congestion Impacts in Addis Ababa

S.N.	Description	Extent	Reference
1	Economic Losses	Birr 53.2 million/year	Andargie (2017)
2	Environmental Impact	Increased emissions by 27-70% for various vehicle types	Teshager et al., (2021)
3	Public Health	Up to 46.3% of respondents lose 2-3 hours daily in traffic	Tazzie (2022)

Note: Data compiled from Andargie (2017), Teshager et al., (2021) and Tazzie (2022).

2.5 Research Gap

Research has been conducted to analyze the impact of reversible lane systems on congestion, travel time, and mobility in cities. It has, through research, been proven that well-implemented reversible lane systems increase the efficiency of traffic and remove bottlenecks. Road network features, coordinated signals, and integration of public transport contribute significantly to making the systems efficient. Other urban studies include negative outcomes, with some registering decreased congestion while others report unforeseen negative effects, including increased travel distances and effects on local business.

This underlines that a gaps still exist about the localized effects of reversible lane on traffic flow systems in rapidly changing urban cities like in Addis Ababa. Some of the most outstanding gaps are:

- **Restricted Context-Specific Analysis:** The majority of the research is carried out on cities with highly developed traffic management, and limited study is done in developing cities like Addis Ababa, which is characterized with informal transportation.
- **Inconsistent Findings on Effectiveness:** Variation in study findings suggests that determinants of success of reversible lane traffic systems are not well established.

By leveraging SUMO's microsimulation capabilities and focusing on Addis Ababa's unique urban context, this study fills a critical knowledge void, providing actionable insights for policymakers and traffic engineers to mitigate congestion, reduce economic losses, and promote sustainable urban mobility.

2.6 Conceptual Framework

These models have far-reaching implications in traffic flow, speed, and density relationships. These must be examined to see the effectiveness of reversible lanes in three key aspects:

- **Dynamic Lane Allocation:** Reversible lanes dynamically change lane orientations based on prevailing demands to provide optimal density levels and prevent congestion. Microscopic and mesoscopic models such as the IDM and CTM are best used in modeling such dynamics.
- **Improved Flow Efficiency:** Through redistribution of road capacity, reversible lanes minimizes delay and travel time. As such, macroscopic models like Greenshields' model help to predict how redistribution of capacity in the form of flow gives optimal efficiency.
- **Minimizing Congestion:** Reversible lanes minimize directionally mismatched traffic flow and thus peak-hour congestion bottlenecks. Models like the LWR and Kinematic Wave Model help to simulate such effects for large-scale

networks.

Based on these models, in this research, the feasibility of reversible lanes in reducing traffic congestion in Addis Ababa roads is assessed.

Simulation modeling is one of the key methods to conduct traffic intervention analysis as it allows to model scenarios under a virtual environment. SUMO (Simulation of Urban Mobility) in this research is used to model reversible lane configurations and examines their feasibility on two main roads in Addis Ababa, Ethiopia. Barceló (2010) emphasizes that simulation modeling not just predicts traffic conditions but also identifies anticipated challenges for implementation. As such SUMO is used for this study to address the research questions and proposed appropriate solutions with consideration of Addis Ababa's unique traffic condition.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the methodology employed to evaluate the effectiveness of reversible lane reconfiguration in reducing traffic congestion in Addis Ababa, Ethiopia. It covers the quantitative research approach, study area description, research design, data collection methods, traffic simulation modeling using SUMO, data analysis, and a summary linking to research objectives.

The methodology used for this research utilizes traffic simulation as a primary means to address the research questions and objectives. The overall framework of the methodology involves selecting roads that can be reconfigured with reversible lanes, among candidates by criteria derived from literature review. A traffic count is then carried out on the selected roads. Following this, the data collected is imported into a traffic simulation software (SUMO traffic simulator) to model the existing road network and traffic.

Subsequently, calibration and validation of the simulation was done by comparing the virtual model with the existing traffic conditions. The virtual model is used to simulate different scenarios, including the current road configuration and reversible lane reconfiguration scenarios. The simulation provides road performance indicators including travel time, speed, time loss, and volume, which are used to evaluate the effectiveness of reversible lanes in reducing congestion.

Overall, the research adopted a quantitative methodology to gather and analyze data, and construct meaningful insights. In the subsequent sections, the discussion delve into the specific tools and approaches used to address the research questions and objectives.

3.2 Study Area

The research focuses on two major roads in Addis Ababa, Ethiopia: Askto to Winget Road and Mexico to Mesqel Square Road, which are selected for their severe peak-hour congestion and representation of different urban contexts. Askto to Winget road connects peripheral part of the city to the central areas, while Mexico to Mesqel Square road is located in the central business district of the city.

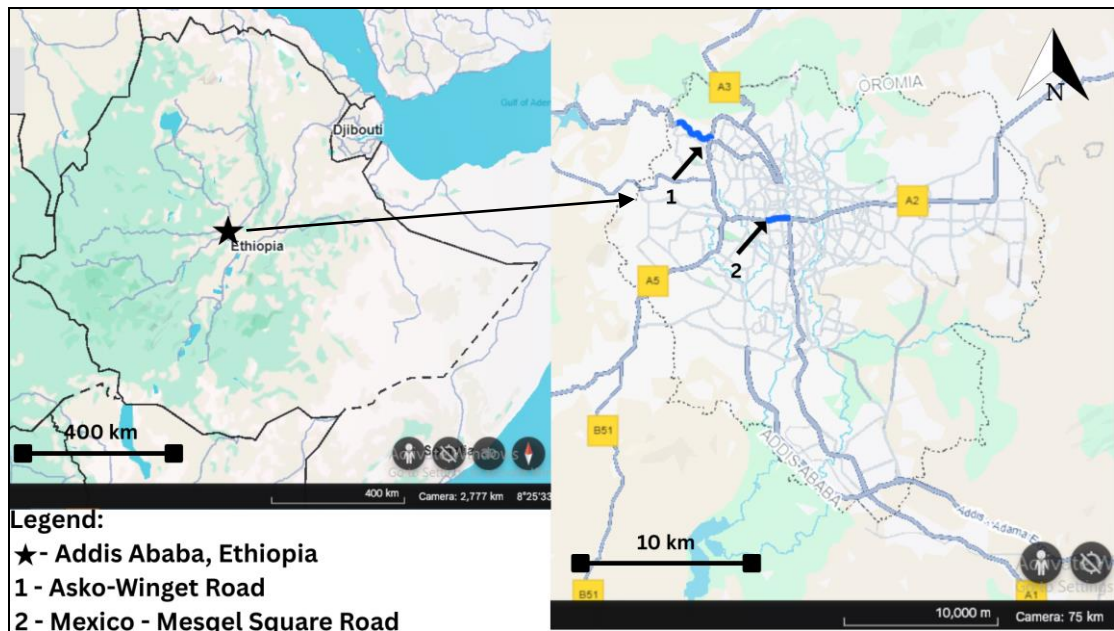


Figure 3-1: Location Map

Source: Google (2024)

The following subsections present details the characteristics of each corridor and the criteria guiding their selection, ensuring alignment with the research objectives to evaluate reversible lanes' impact on congestion.

1) Asko to Winget Road

The Asko to Winget Road, which start at 9.04°N, 38.69°E and ends at 9.02°N, 38.71°E, is 3.7 km arterial road with 3 lanes to each direction and have 4 intersections (Asko, Menahriya, Birchiko and Winget Roundabout)

The road serves as a major connection of residential zones on the periphery of the city to central zones. The road experiences high volumes of commuter traffic during rush hours and is also used by public transport vehicles, including minibuses and buses, regularly.

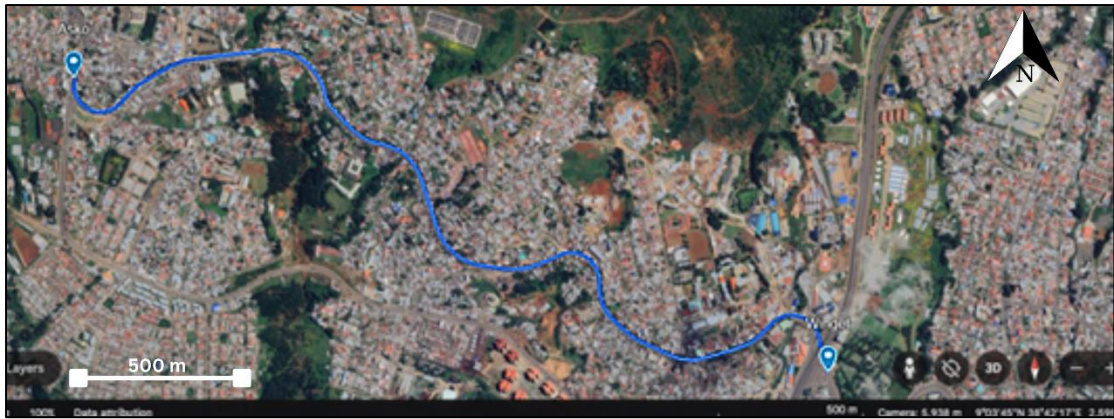


Figure 3-2: Location Map of Askto to Winget Road,
Source: Google (2024)

2) Mexico to Mesqel Square Road

The Mexico to Mesqel road, which starts at 9.02°N, 38.75°E; and 9.01°N, 38.76°E, is 2 km arterial road with 4 lanes (3 in some sections) and has four major intersections (Mexico, Telebar, Legehar and Mesqel Square)

The road is part of a longer road that extend from the west edge of the city at Torhayloch to the East edge to Ayat. But this part is also where most of the traffic moves from south to north as well and vice-versa, thus this is one of the most crowded road in the city. For that reason, it forms an ideal part of the route that represent the central part of the city.

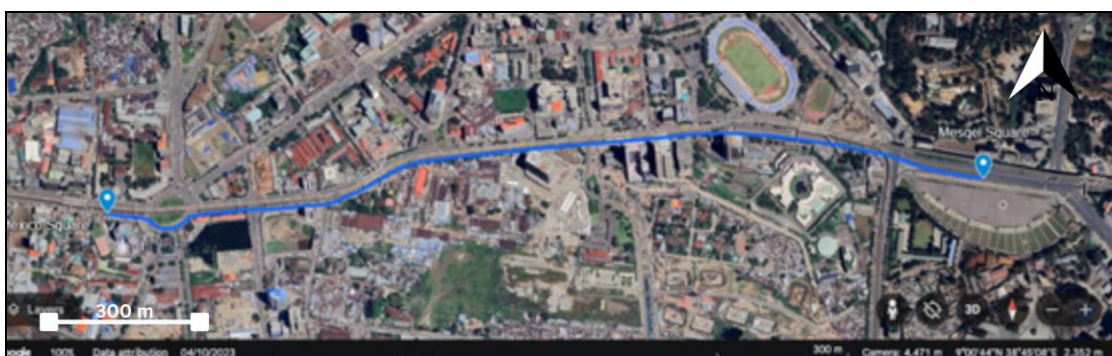


Figure 3-3: Location Map of Mexico to Mesqel Square Road
Source: Google (2024)

3.2.1 Criteria for Selecting Streets for Reversible Lane Reconfiguration

The selection of Asko to Winget and Mexico to Mesqel Square roads for reversible lane reconfiguration was guided by specific criteria developed based on a literature review and field assessments to ensure their suitability for evaluating reversible lanes in Addis Ababa's urban context (Chiu et al., 2007; Wolshon & Lambert, 2006). The criteria's are discussed as follows:

1. **High Traffic Volume and Severe Congestion:** The roads were selected for their heavy traffic during peak hours, identified through Google Traffic Data and field observations, to test reversible lanes' potential to alleviate congestion.
2. **Representation of Urban Contexts:** Asko to Winget represented a residential corridor with commuter-dominated traffic, while Mexico to Mesqel Square served the central business district (CBD) with commercial activity, ensuring diverse urban settings.
3. **Proximity to Alternative Routes:** Selected roads had nearby streets capable of handling redirected traffic to prevent new congestion points.
4. **Intersection Availability:** Roads featured multiple intersections to facilitate traffic distribution, critical for managing reversible lane operations during peak hours.
5. **Physical Expansion Constraints:** Roads were chosen where lane expansion was infeasible due to surrounding residential, commercial, or infrastructural limitations, necessitating alternative solutions like reversible lanes.

3.2.2 Justification for Selected Roads:

- **Asko to Winget Road:** This 3.7-km, three-lane corridor linked residential suburbs to the city center, exhibiting severe morning congestion due to commuter traffic. Its residential surroundings and intersecting roads made it ideal for testing reversible lanes' impact on peak-hour flows without physical expansion.
- **Mexico to Mesqel Square Road:** This 2-km, three-to-four-lane corridor in the CBD connected commercial and administrative hubs, facing severe congestion spilling into adjacent areas. Its high intersection density and infrastructural constraints made it suitable for assessing reversible lanes' effectiveness in a commercial urban setting.

These roads were chosen for their strategic locations, high congestion, and varying characteristics (traffic volume, land use, geometry), enabling a comparative analysis of reversible lanes' effectiveness in peripheral and central contexts.

3.3 Research Approach

The research questions and objectives necessitate characterization of the existing as well as simulated scenarios of traffic conditions, which require analysis of numerical data, hence quantitative approach is adopted.

The quantitative approach involves traffic count, traffic simulation and statistical analysis. The traffic count is intended to represent the actual traffic condition of the selected roads, while traffic simulation uses to model the traffic flow on the study road segments and to estimate the congestion levels and other characteristics under different scenarios based on the traffic count. The results of the simulation then are used to make statistical analysis and compare the scenarios with the existing traffic conditions to answer the research questions.

3.4 Research Design

The research is based on traffic simulation of reversible lane scenarios and existing traffic condition. It synthesis finding by comparative analysis of the road parameters including travel time, speed, time loss and traffic flow, which is calculated from the output of the simulations.

3.4.1 Case Study Design

In order to experiment with different scenarios, existing roads are selected to be simulated and make comparisons. The roads are selected based on criteria developed by literature review and actual road conditions in Addis Ababa, which is discussed in the later sections.

By combining and employing these research designs, the research aimed to provide a detailed examination and determination of the effectiveness of reversible lanes in reducing congestion within the specific urban context of Addis Ababa.

3.4.2 *Experimental Design*

Experimental design is employed to assess the effectiveness of reversible lanes in reducing congestion. This design involves comparing road performance indicator of reversible lane scenarios (R1: one reversible lane, R2: two reversible lanes, R3: three reversible lanes) with the existing traffic condition and to each other, where the results are fundamental to answer the research questions and objectives.

i) **Independent Variables**

- **Lane Configuration:** Lane configuration refers to how lanes are arranged and assigned, especially the presence of reversible lanes that adjust according to demand. Liu & Chang (2011) . The research evaluated the effectiveness of the reversible lane by assessing their impact by introducing and changing the number of reversible lanes.
- **Signal Timing:** Signal timing defines the duration of each traffic signal phase Papageorgiou et al. (2003). The research evaluated the impacts of fixed signal timing against the delay based signal system with the reversible lane reconfiguration.

ii) **Dependent Variables**

- **Travel Time:** Travel time is defined as the duration of time taken by a vehicle to travel along the road.
- **Average Speed:** Average speed is a method of how fast a traffic is traveling along a section of a road.
- **Time Loss:** Time loss is the amount of excess time spent stationary in congestion beyond optimal.
- **Traffic Flow:** Traffic flow is the volume of cars moving through a point on the road, expressed in vehicles per hour.

iii) **Control Group:**

- The base scenarios of the roads that retained their two-way configuration served as the baseline.

3.5 Data Collection Overview

3.5.1 Data Type and Source

The methodology relied on traffic simulation and statistical analysis, requiring multiple data sets. Primary data was collected from traffic counts conducted as per FHWA guidelines (Wunderlich et al., 2019), providing traffic volume, turn count and travel times. The traffic counts also included vehicle composition. Secondary data, including road geometry, was extracted from OpenStreetMap (OSM) for accurate modeling.

➤ Primary Data

The primary data was collected through traffic counts including the following parameters:

- Travel Time: Measured across the selected road segments to analyze traffic flow level.
- Traffic Volume: Recorded during morning peak (07:30:00–08:30:00 AM).
- Vehicle Type and Composition: Classified data on the types of vehicles and their proportions in the traffic.
- Vehicle Turn Distribution: Information on turning movements at intersections to model traffic flow accurately.

➤ Secondary Data

- Road Geometry: Extracted from OpenStreetMap (OSM), providing detailed information on lane configurations, road width, and junction layouts.

3.5.2 Vehicle Characteristics and Related Data

Vehicle classification followed Federal Highway Administration (2022) but was simplified to support scenario analysis.

Table 3-1: Vehicle Classification of Federal Highway Administration

Broad Categories	Classification Number	General Description	Definition	Sub-class
Passenger carriers	1	Motorcycles	2 axles, 2 or 3 wheels.	
	2	Passenger cars	2 axles. Can have 1- or 2-axle trailers.	

Commodities Carriers	3	Pickups, panels, vans	2-axle, 4-tire single units. Can have 1- or 2-axle trailers.	
	4	Buses	2- or 3-axle, full length.	
	5	Single-unit trucks	2-axle, 6-tire, (dual rear tires), single-unit trucks.	
	6	Single-unit trucks	3-axle, single-unit trucks.	
	7	Single-unit trucks	4 or more axle, single-unit trucks.	
	8	Single-trailer trucks	3- or 4-axle, single-trailer trucks.	2S1, 2S2 3S1
	9	Single-trailer trucks	5-axle, single-trailer trucks.	3S2 3S2-Split
	10	Single-trailer trucks	6 or more axle, single-trailer trucks.	3S3 3S4
	11	Multi-trailer trucks	5 or less axle, multi-trailer trucks.	2S1-2
	12	Multi-trailer trucks	6-axle, multi-trailer trucks.	2S2-2
	13	Multi-trailer trucks	7 or more axle, multi-trailer trucks.	3S1-2 3S2-2

Source: Federal Highway Administration (2022)

However, to effectively address the research questions and objectives and get deterministic answers, the classification is tailored, considering the study areas. The following points were used to categorize the vehicles.

- **Scenario Assessment:** The research involves comparison of various simulations, thereto the classification shall afford to run different scenarios.
- **Deterministic Answers:** The classification shall simplify the data analysis without losing the important distinctions among the vehicle types. It also enabled the simulation to provide precise answers.

In general, the classification is simplified and tailored to make the methodology effective and produce relevant results. As the result the following classification is formulated for this research.

Table 3-2: Adopted Vehicle Classification

Categories	Classification Number	General Description
Passengers, Private Vehicles	1	Passenger, Pickups, panels, vans
Passengers, Public Vehicles	2	Mini buses
	3	Buses
Commodities Carriers	4	Trucks

Source: Adapted by the author from Federal Highway Administration (2022).

3.5.3 Data Collection

3.5.3.1 Traffic count

The research adopted FHWA guidelines (Federal Highway Administration, 2022) to conduct the traffic count on the two selected roads; Askto to Winget and Mexico to Mesqel Square Roads.

The count included road segment (volumes, speeds, classifications) and intersection (turning movements, classifications) data.

3.5.3.2 Manual Count

Manual counts collected vehicle numbers, composition, turning movements, and travel direction. Video-based counting was used due to budget constraints and congested conditions

3.5.3.3 Video-Based Manual Counting

Video-based manual counting ensured accurate traffic data. Videos were recorded at key intersections and analyzed to count vehicles, classify them, and record turning movements.

- **Video Recording:** Recorded at Askto to Winget and Mexico to Mesqel Square during morning peak (07:30:00–08:30:00 AM) based on Google Traffic Data.
- **Data Extraction:** Observers classified vehicles and recorded movements.
- **Data Compilation:** Data was compiled over 15 minute's interval.
- **Advantages:** Replay capability, time flexibility, and reduced bias.
- **Limitations:** Video quality errors, large data volume.
- **Mitigation:** Standardized protocols, multiple reviews, statistical checks

i) Traffic Count Locations and Duration

Traffic counts were conducted at the target road segments' starting and ending points as well as at major nine intersections: Winget, Birchiko, Asko Menahriya, Asko, Mexico Roundabout, Kker, Telebar, Legehar, Mesqel Square. The counts were carried out during morning rush hour (07:30:00–08:30:00 AM) per Federal Highway Administration (Federal Highway Administration, 2022) recommendations. Detailed results of turning movements, are presented in the appendix.

3.6 Traffic Analysis and Simulation Tools

3.6.1 Criteria for Selecting Traffic Simulation Type

Microscopic simulation was selected to evaluate reversible lane reconfiguration in Addis Ababa's Asko to Winget and Mexico to Mesqel Square corridors, based on criteria derived from U.S. Federal Highway Administration guidelines (Jeannotte et al., 2004) and tailored to the study's objectives and local traffic conditions. The selection criteria included:

- **Analysis Context:** The simulation supported operational analysis of reversible lane configurations.
- **Geographical Scope:** It modeled road segments and corridors, aligning with the study's focus on principal arterials.
- **Arterial Roads:** It accommodated arterial road characteristics of the selected corridors.
- **Travel Modes:** It simulated private vehicles, buses, minibuses, and trucks prevalent in Addis Ababa.
- **Traffic Management:** It enabled modeling of reversible lanes and traffic signal controls critical to the research.
- **Performance Metrics:** It provided outputs for travel time, speed, time loss, and traffic volume to assess congestion reduction.
- **Cost-Effectiveness:** It was open-source, suitable for limited budgets.

Microscopic simulation was chosen for its ability to model individual vehicle interactions, dynamic lane reconfigurations, and traffic signal systems, ensuring accurate representation of reversible lanes' impact during peak hours. It allowed

calibration with real-world traffic data, including Addis Ababa's unique informal transport modes, and supported scenario testing (varying reversible lane numbers) to measure performance metrics precisely. This approach aligned with the research's aim to evaluate reversible lanes' effectiveness in reducing congestion.

3.6.2 Traffic Simulation Software Selection Criteria

The selection of SUMO as the traffic simulation software was based on criteria tailored to the research's objectives of evaluating reversible lane reconfiguration in Addis Ababa's Asko to Winget and Mexico to Mesqel Square corridors. These criteria were adopted from (Miller et al., 2021) recommendations and the study's operational requirements. The Criteria selected were the following:

- 1) Data Input Flexibility: SUMO supported OpenStreetMap (OSM) data integration for accurate road geometry modeling.
- 2) Calibration Capability: It allowed calibration with field traffic counts to reflect Addis Ababa's unique traffic patterns.
- 3) Traffic Control Modeling: It simulated reversible lanes and traffic signal systems critical for testing lane reconfiguration.
- 4) Simulation Speed: It processed complex scenarios efficiently, suitable for multiple simulations.
- 5) Road Network Representation: It modeled arterial corridors with high intersection density.
- 6) Visualization: It provided clear outputs for traffic flow analysis.
- 7) Customization and Cost: As an open-source tool, it offered customization without licensing costs, aligning with budget constraints.

In consideration of the above, software package (AIMSUN, ARCHISIM, CORSIM, MITSIM, PARAMICS, SUMO, VISSIM) was rated on a scale of 0–5 for each criterion, with scores assigned based on literature evaluations (Miller et al., 2021) and compatibility with the study's needs, particularly reversible lane modeling and Addis Ababa's traffic conditions. The evaluation results are shown in Table 5.

The ratings were developed by assessing software documentation and articles including Dorokhin et al. (2020) , Ejercito et al. (2017), Steven Jones et al. (2004), Barceló & Casas (2005), Akhter et al. (2020) and Aliro et al. (2012).

Legend: Aimsun (A), Archisim (Ar), Corsim (C), Matsim (M), Paramics (P), Sumo (S), Vissim (V).

Table 3-3: Traffic Simulation Software Rating

No.	Criteria	A	AR	C	M	P	S	V
1	Data Input and Integration (OSM and GIS/shapfile)	5	5	3	5	5	5	5
2	Model Validation and Calibration Tools	5	5	3	5	5	5	5
3	Traffic Control and Signal Modeling	5	5	3	5	5	5	5
4	Simulation Performance and speed	0	3	3	3	3	5	3
5	Road network and transport demand development	5	3	0	3	3	3	5
6	Visualization and Reporting	5	3	0	3	3	3	5
7	Customization and Extensibility	5	3	0	5	3	5	5
	Sum	30	27	12	29	27	31	33

Source: Ratings developed by the researcher based on evaluation criteria from Dorokhin et al. (2020), Ejercito et al. (2017), Steven Jones et al. (2004), Barceló & Casas (2005), Akhter et al. (2020), and Aliro et al. (2012).

SUMO was chosen over VISSIM, despite VISSIM's higher score (33 vs. 31), due to SUMO's open-source nature, which eliminated licensing costs critical for the study's budget constraints. SUMO's compatibility with OSM ensured precise modeling of the study corridors, while its ability to simulate reversible lanes and traffic signals supported scenario testing (e.g., one to three lanes). VISSIM, while robust, required costly licenses and offered marginal advantages in visualization and network modeling irrelevant to the research's focus on congestion metrics. SUMO's calibration with real-world data accurately reflected Addis Ababa's dynamic traffic, aligning with the research's aim to evaluate reversible lanes' effectiveness.

3.7 Road Performance Measures

Road performance measures were selected to quantify the impact of reversible lanes based on Federal Highway Administration guidelines (Federal Highway Administration, 2005). The selected measurement are the following:

- 1) Travel Time: Time taken by vehicles to traverse the corridors, indicating congestion levels.

- 2) Average Speed: Speed of traffic flow, reflecting efficiency of lane reconfiguration.
- 3) Time Loss: Excess time spent in congestion, measuring delay reduction.
- 4) Traffic Volume: Number of vehicles passing a point, assessing capacity improvements.

3.8 Model Building Process

The SUMO model was constructed to simulate reversible lane following a structured process to ensure accurate representation of traffic conditions. The process follows the recommendations set out on Lopez et al. (2018) and tailored to the research's objectives of evaluating congestion reduction. The following components are used in building the models:

- i) **Road Geometry:** Road geometry for the Asko (3.7 km, 3 lanes) and Mexico (2 km, 3–4 lanes) corridors was extracted from OpenStreetMap (OSM) and refined using SUMO's netedit tool to match field surveys. This included lane numbers, widths, junction layouts, and parking areas, ensuring compatibility with reversible lane configurations.
- ii) **Traffic Data:** The traffic data was collected from the manual traffic count. The traffic count provided traffic volume, traffic signal timing and valid turn configurations at the selected nine junctions during the selected peak hour.
- iii) **Route and Flow Generation:** Vehicle routes were generated using SUMO's JTRRouter tool, converting traffic count data into turn probabilities to reflect observed flows. This ensured realistic vehicle movements, particularly for reversible lane scenarios during morning peak hours (07:30:00–08:30:00 AM).

3.8.1 Traffic Count Integration and Turn Probability

The data collected was categorized by vehicle type, time, and turning direction. These were required to form traffic flow patterns at the selected intersections. Following this, the categorized traffic count was converted into turn probabilities by dividing the number of vehicles turning in each direction by the total number of vehicles at the intersection during the same time interval.

These probabilities were then imported into JTRRouter to manipulate the route generation such that the vehicles replicate the real world traffic.

3.8.2 Defining Source Edges and Flow Probabilities

Once probabilities of turns were determined, source edges, which are close to the simulation network boundary, were designated as source edges for traffic representing traffic entry points. This was based on the traffic count and the actual traffic flow pattern.

The edges are then assigned flow probability to generate traffic with mixture of vehicle types and volume into the network.

3.8.3 Route Generation Using JTRRouter

To complete the assignment of the route in the simulation model, JTRRouter tool in SUMO was used. The tool was configured using the pre-computed turn probabilities for each junction and the flow probabilities for each source edge. Using these values JTRRouter successfully created a origin destination definition for each vehicles, resulting dynamic representation of vehicles movement in the network.

3.8.4 Other Inputs

In addition to vehicle routes and traffic volumes, other critical components were also incorporated into the simulation model. These included traffic signal timings, legal turns at intersections, and on-street parking bays. Traffic signals were implemented based on the measured timings from field surveys, and legal turns and parking bays were added according to road usage patterns observed.

3.8.5 Scenario Development

i) Base Scenario: Current Traffic Conditions

The base scenarios represented the actual traffic condition in the study areas with no changes, serving as the control for comparison with reversible lane scenarios.

This scenario reflects the two-way traffic flow that is currently utilized, including intersections, traffic signal timing, and overall congestion levels. It is the baseline

against which all other scenarios is measured. The Implementation in SUMO simulation software was as follows:

1) Road Geometry:

- A road network was imported from OpenStreetMap (OSM) using SUMO's OSM Web Wizard. All imported lanes, edges, and junctions are replicated according to their real-world setup.
- Netedit tool ensured accurate edge-lane connectivity and compliance with real-world traffic rules, verified against field surveys.

2) Traffic Demand Assignment

- The traffic demand is generated based on observed volumes of traffic flow patterns. The traffic demand is modeled in the *.rou.xml file, specifying departure times, destinations, and routes of the vehicles. This are the outputs of JTRRouter tool.
- Vehicle types (i.e. minibus, passenger, buses, truck, bicycle, and motorcycle) are described in the *.rou.xml file to be utilized to represent traffic composition recorded within the study area.
- The behavior parameters for the vehicles such as car-following models, acceleration, and deceleration are set to satisfy real traffic flow characteristics.

3) Traffic Control Setup

- The traffic signals are included in the netedit tool, when the road geometry is downloaded. The time phase of these signals was set using the field measurements.
- The priority rules for non-traffic-light intersections are automatically assigned when generating the network, mimicking the behavior of unmanaged intersections.

4) Other Control Elements:

- E3 detectors are placed strategically through *.add.xml files to record traffic flow data during the simulation. The detectors help in the evaluation of vehicle volumes, travel time, and levels of congestion.

ii) Reversible Lanes Scenario

This scenario requires introducing reversible lanes into the road network, by creating single (R1), two (R2), or three (R3) reversible lane configurations separately. The implementation was as follows:

- **Lane Isolation:** Target lanes for reversible use were selected and isolated by removing their connections to incoming roads using netedit. Non-reversible lanes were reconnected to maintain normal traffic flow, ensuring reversible lanes were separated for reconfiguration.
- **Junction Realignment:** links at intersections were modified to redirect traffic to non-reversible lanes. New links were established to guide vehicles from incoming roads to reversible lanes, ensuring smooth entry. Downstream connections reintegrated reversible lane traffic into the network.
- **Reversible Lane Configuration:** Reversible lanes were created and superimposed on the isolated lanes, set to operate in the opposite direction of non-reversible lanes based on peak demand. Three sub-scenarios tested one, two, or three reversible lanes. Lane permissions and junction connections were adjusted to enable seamless merging and exiting.
- **Traffic Signal and Control:** Traffic signal timings remained fixed to isolate the impact of lane reconfiguration, though adaptive timings were tested in sub-scenarios. Vehicle flows and routes from the base scenario were retained, with entry/exit rules updated for reversible lanes.
- **Data Collection:** E3 detectors, placed as in the base scenario, recorded metrics every 15 minutes over a 3600-second simulation. Calibration ensured simulated flows matched field data.

Key considerations included documenting all network changes to maintain simulation accuracy and isolating lane directionality as the primary variable, enabling direct assessment of reversible lanes' effectiveness in alleviating

congestion. This approach facilitated rigorous comparison with the base scenario to address the research objectives.

3.8.6 Initial Model Calibration and Validation

A rigorous calibration and validation exercise was conducted to ensure the SUMO model accurately replicated traffic conditions in Addis Ababa's Asko to Winget and Mexico to Mesqel Square corridors.

i) Calibration

The Calibration process was conducted in two steps:

- 1) **Turn Distribution at Intersections:** This was to replicate observed traffic flow dynamics at nine junctions. Traffic counts were compared with simulation outputs. Vehicle numbers, compositions, and turn probabilities at source edges were iteratively adjusted until simulated flows matched observed data.
- 2) **Travel Time Calibration:** Simulated travel times on the road segments compared with the actual recorded travel times and were adjusted by modifying vehicle characteristics (maximum speed, acceleration, deceleration) to minimize differences, achieving marginal errors.

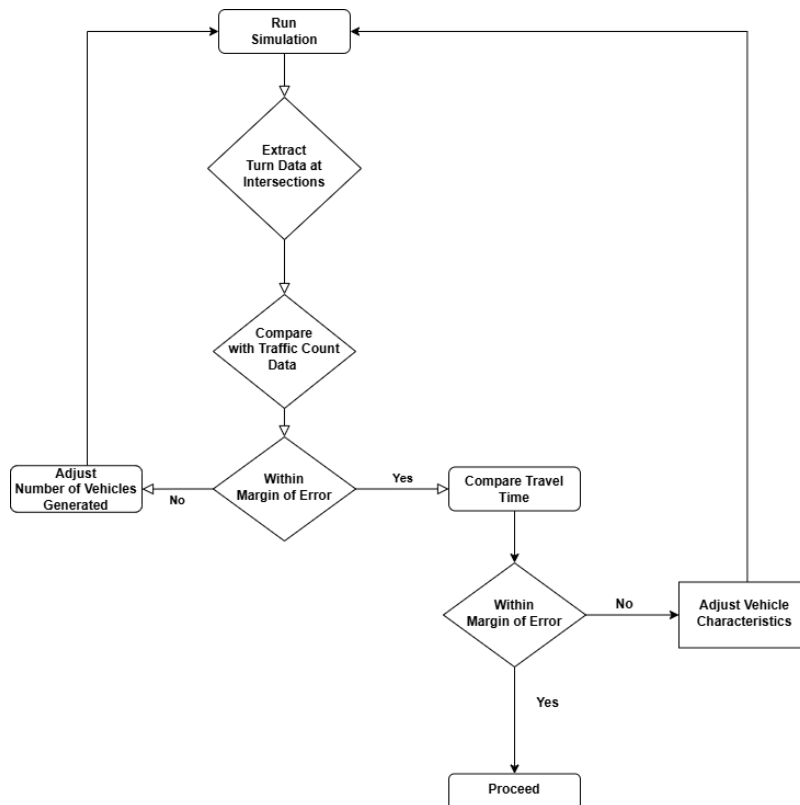


Figure 3-4: Simulation Calibration Process

Source: Created by the Author, 2025

ii) **Validation:**

Validation ensured the model's reliability through systematic comparison with field data, using the following process:

- **Data Comparison:** Simulated results (travel time, average speed, time loss and traffic flow) were compared systematically with field data using statistical metrics including Mean Absolute Error (MAE) and Root Mean Square Error (RMSE).
- **Consistency Tests:** The simulations were run many times to confirm that the model's behavior was not due to random variation
- **Validation Measures:**
 - i) **Traffic Flow:** Checking if simulated volume and flow patterns correspond to real data.
 - ii) **Speed and Congestion:** Checking speed distribution and congestion level adheres to real-life observation.

- iii) Behavioral Realism: Checking that the behavior of vehicles at intersections and on roads are realistic.

3.9 Traffic Simulation Data Collection and Parameter Computation

This sub-section describes the procedures of gathering key traffic performance indicators, travel time, mean speed, time loss, traffic volume, SUMO to evaluate reversible lane reconfiguration in the Asko and Mexico corridors during peak hours.

3.9.1 Simulation Setup and Detector Placement

E3 loop detector were used to collect data regarding the simulation. E3 loop detectors is were selected for their ability to capture round-about traffic data at intersections, as stated by Lopez et al. (2018) in their research on accuracy in traffic simulation.

- Placement Strategy: E3 detectors were positioned on approach road to intersection.
- Detector Functionality: E3 detectors Recorded vehicle counts, speeds, and delays (time exceeding free-flow conditions), and the collected data in each simulation seconds are aggregated over 15 minutes.

3.9.2 Parameter Extraction from Simulation Output

Data were saved in CSV and XML format after simulation runs were completed, retaining vehicle behavior in explicit form:

- Mean Speed: Computed by averaging all the speeds recorded

$$\text{Mean Speed} = \frac{\Sigma \text{Speed}}{\text{Number of Vehicles}}$$

- Travel Time: Computed by summation of time it takes for a vehicle to move from one detector to another:

$$\text{Mean Travel Time} = \frac{\Sigma \text{Travel Time}}{\text{Number of Vehicles}}$$

- Time Loss: Computed by applying the variation of free-flow travel time and actual travel time:

$$\text{Mean Travel Time} = \frac{\Sigma(\text{Actual Travel Time} - \text{Free Flow Travel Time})}{\text{Number of Vehicles}}$$

- **Traffic Volume:** the total number of the vehicles that traveled the entire length of the selected road on the specified time (07:30:00 – 8:30:000 AM)

3.9.3 Statistical Analysis and Data Processing

Each scenario was simulated repeatedly for statistical analysis. Statistical processing entailed computing mean values by:

- **Across Runs Averaging:** Mean values were computed across runs to reduce variance, similar to Kesting et al. (2010).
- **Variance and Standard Deviation:** It was calculated to confirm the result consistency.
- **Error Analysis:** Sensitivity analysis was performed to determine the effect of or simulation parameters on results.

3.10 Summary and Link to Research Objectives

Table 3-4: Summary and Link to Research Objectives

No.	Aspect	Description	Link to Research Questions and Objectives
1	Research Approach	Quantitative, using speed, travel time, time loss data.	Addressed all research questions with quantifiable metrics.
2	Research Design	Case study and experimental, combining field observations and simulations.	Measured reversible lane impacts (Objectives 1–3, Questions 1–3).
3	Data Collection	Manual/video-based traffic counts, signal timings, OSM geometry, bus routes, parking data.	Enabled baseline performance and accurate scenario modeling.
4	Traffic Simulation	SUMO-based, with baseline and 1–3 reversible lane scenarios, fixed/adaptive signals.	Evaluated reversible lanes' effectiveness and challenges (Objectives 1–3, Questions 1–3).
5	Model Validation & Calibration	Calibrated/validated with field data using MAE, RMSE.	Ensured reliable findings for all objectives.
6	Data Analysis	Compared travel time, speed, time loss, safety metrics (collisions, braking, teleports) via graphs/tables.	Assessed congestion reduction, configurations, and challenges (Objectives 1–3, Questions 1–3).

Source: Created by the Author, 2025

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the summarized results of the collected data and the findings of the analysis. These results, derived from traffic counts and SUMO simulations, focus on travel time, speed, time loss, and traffic volume during peak hours (7:30:00–8:30:00 AM). The analysis quantifies the effectiveness of reversible lanes, identifies key factors influencing their success, and highlights practical challenges in Addis Ababa's urban context. Furthermore, the discussion links these findings to the research objectives, compares them with existing literature, and addresses implementation challenges.

4.2 Traffic Count

4.2.1 *Asko to Winget Road*

- **Winget junction:** The Analysis showed a significant difference in direction of movement. East-bound flow is the most prevalent with 2,176 vehicles (59.5%) of the total flow, compared west bound 710 vehicles (19.4%) and 355 vehicles (21.1%) traveling to the south.
- **Birchiko Junction:** This junction is a result of two roads, where the only possible travel direction is from west to east, west to south and south to east. The eastbound traffic flow is 1,561 vehicles (71.7%) versus 535 vehicles (24.6%) southbound right turns and 99 vehicles (4.5%) west-to-south flows.
- **Menahriya Junction:** Similarly in this junction, eastbound through traffic is 1,116 vehicles (51.8%) was the dominant flow, while westbound vehicles are 365 (16.9%) and southbound 461 vehicles (21.4%).
- **Asko Junction:** Traffic Flow at this junction was also significantly eastbound traffic with 1,111 vehicles (60.7%) while westbound traffic is only 503 vehicles (27.5%).

4.2.2 *Traffic Counts at junctions on Mexico to Mesqel Square Road*

- **Mexico Roundabout:** The eastbound flows totaled 1,029 vehicles (29.6%), closely matching westbound flows of 648 vehicles (31.8%), with north/south movements comprising 581 vehicles (38.6%).

- **Kker Junction:** Eastbound through traffic recorded 351 vehicles (10.4%) and westbound through traffic of 532 vehicles (15.8%), alongside significant south/north turning movements of 496 vehicles (14.7%)
- **Telebar Junction:** Eastbound flows counted was 1,317 vehicles (33.6%) and westbound flows of 1,147 vehicles (29.3%).
- **Legehar Junction:** Eastbound traffic was 1,415 vehicles (30.2%) and westbound traffic of 1,067 vehicles (22.8%), with south/north turns totaling 1,581 vehicles (47.0%)
- **Mesqel Square Junction:** Eastbound flows was 1,436 vehicles (28.3%) and westbound flows of 1,249 vehicles (24.6%), with turning movements amounting to 2,395 vehicles (47.1%).

4.3 Traffic Signals

Traffic light cycle durations (green, yellow, red) were manually recorded using stopwatches at signalized junctions for each turn direction. At police-controlled junctions (Winget intersection), stopwatch measurements captured the duration traffic was allowed to pass from each approach, and averaged to represent green, yellow, and red phases. It is noted that traffic polices prioritized congested direction, resembling a delay-based controller. Detailed signal phase durations are provided in Appendix B.

4.4 Road Geometry

Road geometry for the Askto to Winget (3.7 km, 3 lanes) and Mexico to Mesqel Square (2 km, 3–4 lanes) corridors was extracted from OpenStreetMap (OSM) using OSM Web Wizard. OSM provides geo-referenced road data suitable for SUMO simulations. The extracted geometry, including lane configurations and intersections, was calibrated with field surveys to ensure accuracy. Figures 5 and 6 illustrate the road geometry for Askto to Winget and Mexico to Mesqel Square, respectively.

i) Askto-Winget Road Geometry

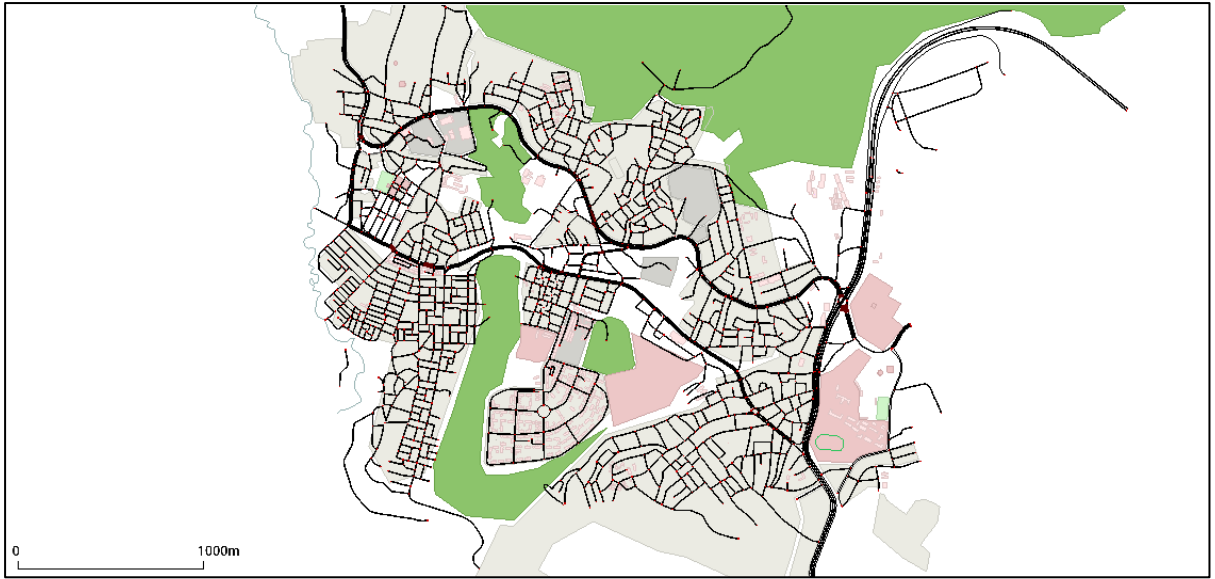


Figure 4-1: Asko-Winget Road Geometry

Source: (Openstreetmap, 2023)

ii) Mexico-MesqelSquare Road Geometry



Figure 4-2: Mexico-Mesqel Square Road Geometry

Source: (Openstreetmap, 2024)

4.4.1 Bus and Taxi terminals

There are designated stops along the selected roads for buses. Minibuses/taxis, however, they don't have fixed stop points to drop and pick passengers. There is, however, a popular destination that serves as starting and ending for taxi routes, and which also serves as informal terminal. The following are bus stops identified through field survey and incorporated in the models.

Table 4-1: Bus Stops

Sn.	Road	Stop locations
1	Mexico to Mesqel Square	St. Estifanos, Stadium, Leghar, Mexico, Tegbared
2	Asko to Winget	Asko, Chareta, Mikili Land, Bercheko Condominium, Winget

Source: Computed from the empirical data by the Author, 2025

4.5 Results

This section presents simulation results for baseline (E) and reversible lane scenarios (R1: one lane, R2: two lanes, R3: three lanes), focusing on travel time, speed, time loss, and traffic volume during peak hours.

4.5.1 Calibration Results

The SUMO model was calibrated through two steps to ensure the simulation closely match observed traffic conditions. The results of step 1 show that 92% of turn counts across all junctions achieved a GEH value <5 , which surpass the industry standard of 85% for acceptable calibration (Dowling et al., 2004). GEH values for each junction are provided in appendixes.

On the second step, calibration was conducted for travel times. The overall Mean Absolute Percentage Error (MAPE) for travel time was 8.17%, which is well within the 10–15% range acceptable for microsimulation models (Dowling et al., 2004). Route-by-route results also attest to the accuracy: Asko to Winget had the lowest MAPE (5.33%), while Winget to Asko (9.82%) and Mesqel Square to Mexico (9.08%) were both less than 10%. The Mesqel Square to Mexico direction had a slightly higher MAPE (8.45%) owing to complex and multiple turning movements.

Table 4-2: Summary of Calibration Process Results for Travel Time

Route	RMSE (minutes)	MAPE (%)
Asko To Winget	0:01:06	5.33%
Winget to Asko	0:00:54	9.82%
Mexico to Mesqel Square	0:01:08	8.45%
Mesqel Square to Mexico	0:00:56	9.08%
Overall	0:01:01	8.17%

Source: Computed from the empirical data by the Author, 2025

Moreover, the vehicle parameters were then fine-tuned after several rounds of calibration to exactly reflect the observed traffic patterns. These parameters were fine-tuned to maximize the model to real-world data correlation.

The table below presents the final vehicle parameters used during the simulation after calibration, including acceleration, deceleration, top speed, and other characteristics.

Table 4-3: Final Vehicle Characteristics

Sn.	Characteristic	Unit	Vehicle Type					
			bicycle	Bus	Minibus	Passenger	Motorcycle	truck
1	Length	m	3	12	6	4.5	3	15
2	Minimum Gap	m	1	1	1	1	1	1
3	Maximum speed	km/hr.	15	45	50	60	85	45
4	Acceleration	m/s ²	0.5	2.2	2.3	2.4	3.5	1.5
5	Deceleration	m/s ²	2	4	4.1	4.5	4	3.5

Source: Computed from the empirical data by the Author, 2025

Additionally, warm-up period for each scenarios were implemented to stabilize simulation conditions, allowing vehicles to distribute realistically before data collection.

Table 4-4: Summary of Warm-up Durations

Scenarios	Mexico to Mesqel Square Minutes	Asko to Wignet
Baseline	0:37:00	0:31:00
R1	0:38:00	0:27:00
R2	0:38:00	0:30:00
R3	0:38:00	0:30:00

Source: Computed from the empirical data by the Author, 2025

4.5.2 Simulation Results

Results compare baseline (E) and reversible lane scenarios (R1, R2, and R3) using one-way repeated measures ANOVA and Tukey's pairwise tests ($p < 0.05$) (details of statistical analysis is presented in the appendixes). Metrics include travel time, speed, time loss, and traffic volume, presented in tables and figures for clarity.

4.5.2.1 Travel Time

Simulations revealed significant travel time reductions in reversible lane scenarios, particularly for dominant flows rather than for the more balanced traffic in Mexico to Mesqel road. The following graph shows the travel time trend across the peak hour.

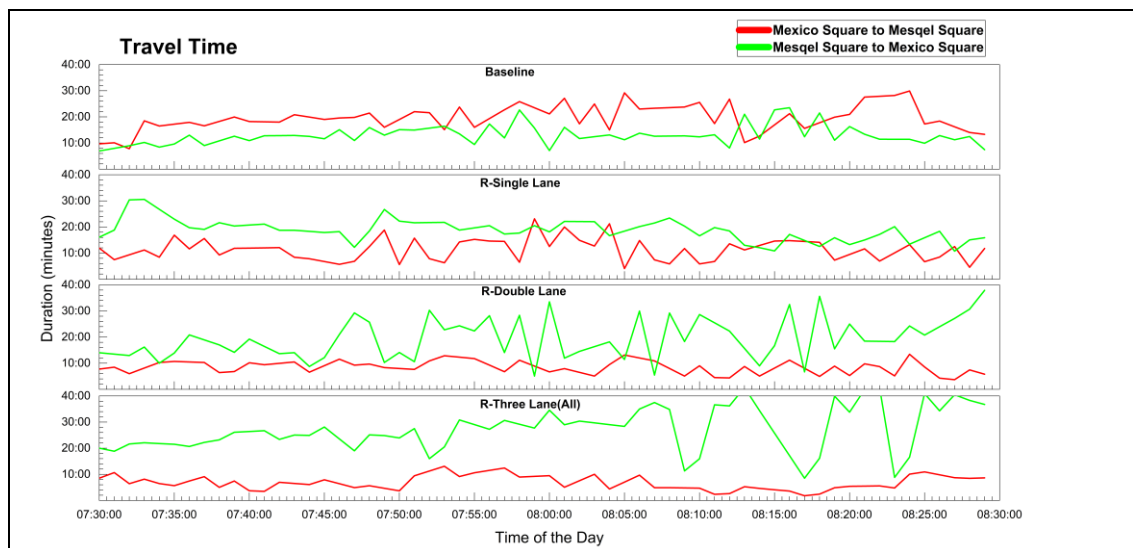


Figure 4-3: Simulated Travel Time Trends (Mexico-Mesqel Square Road)

Source: Computed from the empirical data by the Author, 2025



Figure 4-4: Simulated Travel Time Trends (Asko-Winget Square Road)

Source: Computed from the empirical data by the Author, 2025

On Asko to Winget, R3 reduced eastbound travel time by 76.95% (from 1298 s to 298 s; $F=110.44$, $p<0.0001$), reflecting increased lane capacity. However, westbound travel time increased by 35.20% (from 588 s to 795 s), indicating trade-offs for non-dominant flows. On Mexico to Mesqel Square, R3 decreased eastbound travel time by 60.41% (from 980 s to 388 s; $F=95.32$, $p<0.0001$), but westbound travel time rose by 165.05% (from 658 s to 1744 s), due to reduced lane availability.

Table 4.4: Mean Travel Time (Seconds)

Road	Route	E	R1	R2	R3
Mexico to Mesqel Square	Mexico to Mesqel	980	575	422	388
Mexico to Mesqel Square	Mesqel to Mexico	658	1035	1166	1744
Asko to Winget	Asko to Winget	1298	1451	607	298
Asko to Winget	Winget to Asko	588	487	756	795

Source: Computed from the empirical data by the Author, 2025

4.5.2.2 Speed

Vehicle speeds improved significantly for dominant directions under reversible lanes. The following graph the average speed recorded in each direction for both roads.

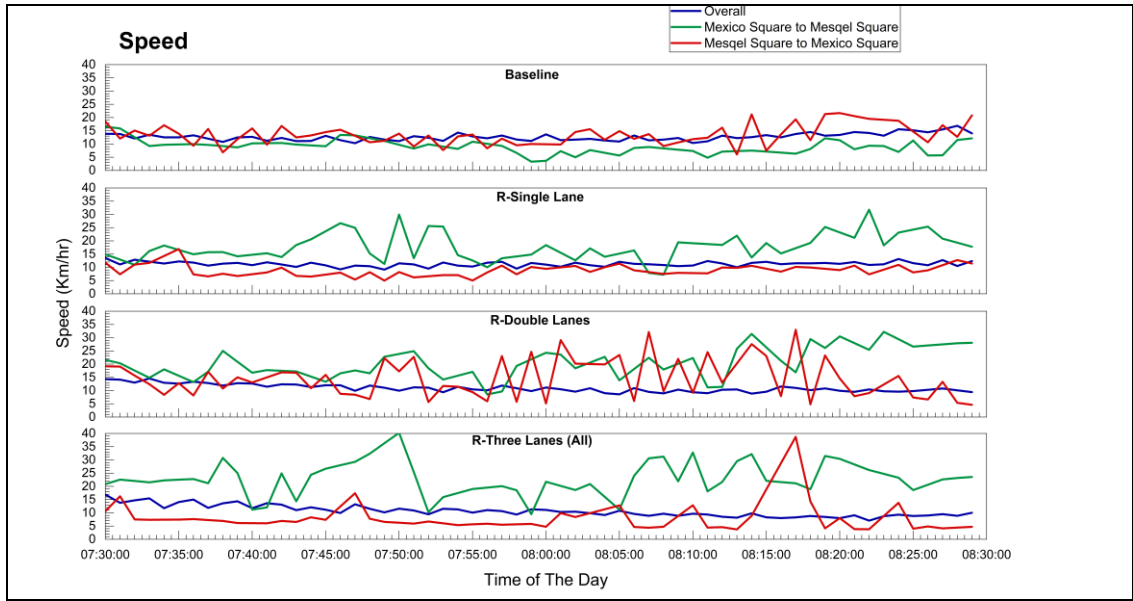


Figure 4-5: Simulated Vehicles Speed Trends (Mexico-Mesqel Square Road)

Source: Computed from the empirical data by the Author, 2025

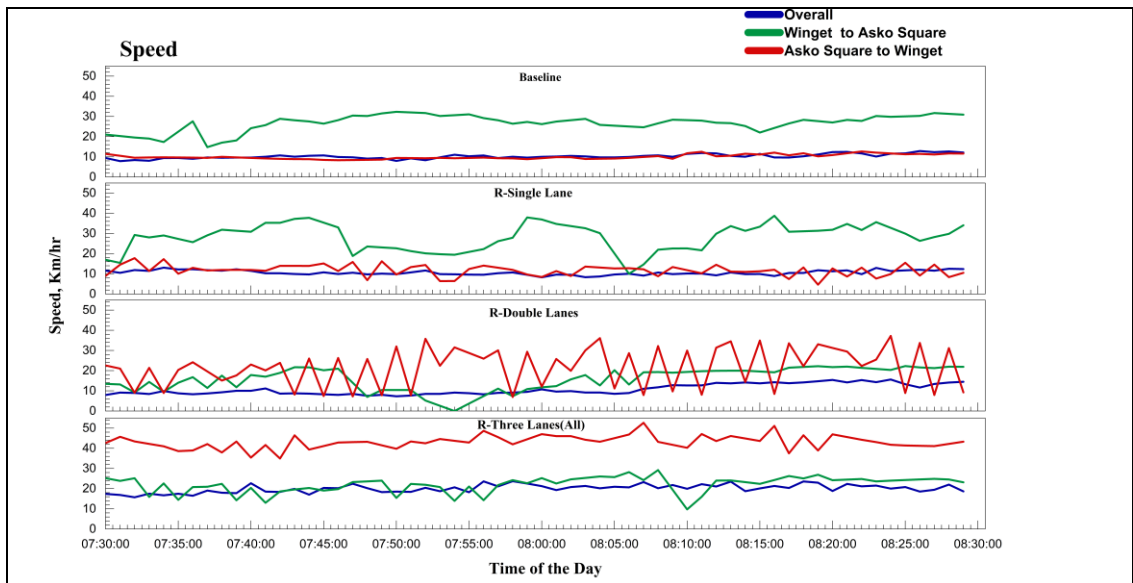


Figure 4-6: Simulated Vehicles Speed Trends (Asko-Winget Square Road)

Source: Computed from the empirical data by the Author, 2025

For Asko to Winget, R3 increased eastbound speed by 325% (from 10.12 km/h to 43.00 km/h), but westbound speed decreased by 19.84% (from 29.39 km/h to 23.56 km/h). On Mexico to Mesqel Square, R3 raised eastbound speed by 207% (from 7.95 km/h to 24.42 km/h), while westbound speed fell by 60.27% (from 16.41 km/h to 6.52 km/h), reflecting capacity trade-offs.

Table 4.5: Mean Speed (km/h)

Road	Route	E	R1	R2	R3
Mexico to Mesqel Square	Mexico to Mesqel	7.95	18.81	23.59	24.42
Mexico to Mesqel Square	Mesqel to Mexico	16.41	8.92	14.26	6.52
Asko to Winget	Asko to Winget	10.12	12.39	26.54	43.00
Asko to Winget	Winget to Asko	29.39	30.22	18.62	23.56

Source: Computed from the empirical data by the Author, 2025

4.5.2.3 Time Loss

Time loss is the average time a vehicle spent standing (involuntarily). The graphs below shows that there significant difference on time loss between the direction where reversible lanes added and reduced.

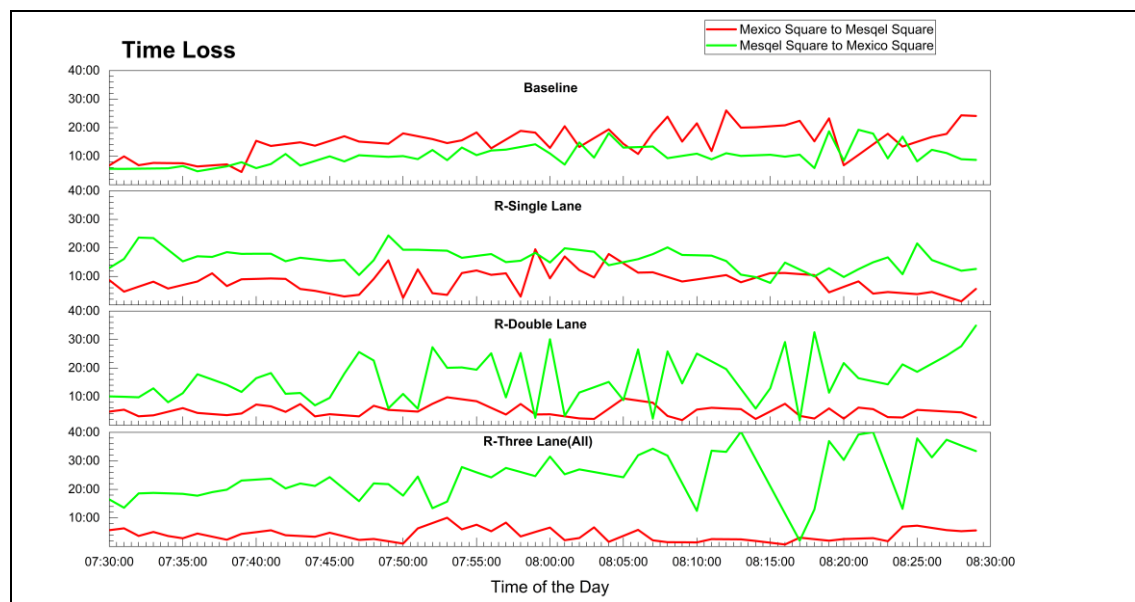


Figure 4-7: Simulated Time Loss Trends (Mexico-Mesqel Square Road)

Source: Computed from the empirical data by the Author, 2025

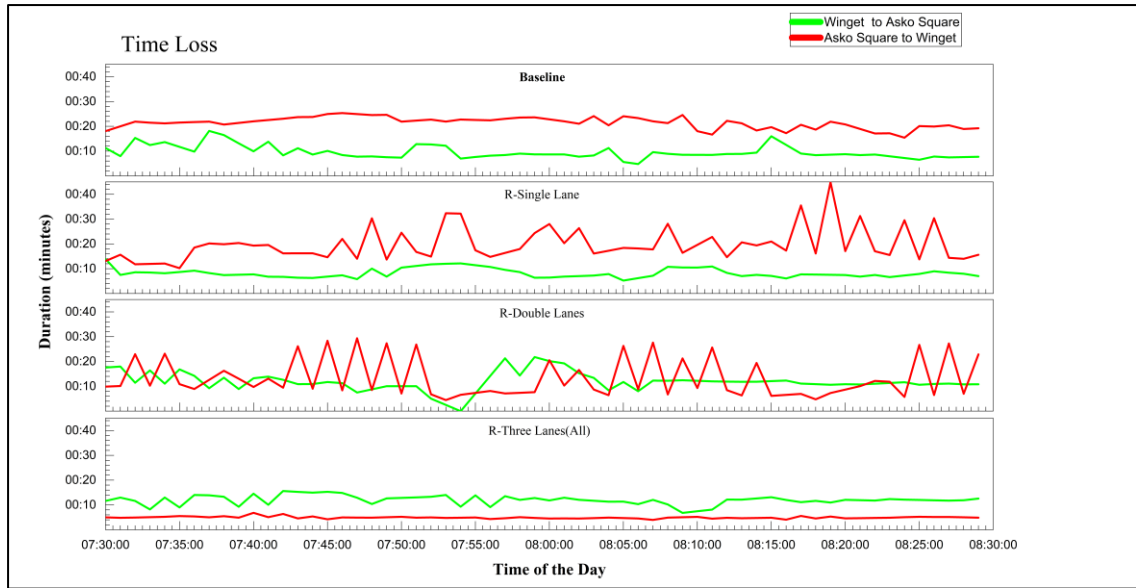


Figure 4-8: Simulated Time Loss Trends (Asko-Winget Square Road)

Source: Computed from the empirical data by the Author, 2025

On Asko to Winget, R3 reduced eastbound time loss by 92.64% (from 1074 s to 79 s), but westbound time loss increased by 31.48% (from 305 s to 401 s). For Mexico to Mesqel Square, R3 decreased eastbound time loss by 71.41% (from 780 s to 223 s), while westbound time loss rose by 173% (from 500 s to 1365 s).

Table 4.6: Mean Time Loss (Seconds)

Road	Route	E	R1	R2	R3
Mexico to Mesqel Square	Mexico to Mesqel	780	362	241	223
Mexico to Mesqel Square	Mesqel to Mexico	500	836	825	1365
Asko to Winget	Asko to Winget	1074	1259	378	79
Asko to Winget	Winget to Asko	305	215	475	401

Source: Computed from the empirical data by the Author, 2025

4.5.2.4 Traffic Volume

Time loss, representing delays due to congestion, decreased significantly for dominant flows. The graphs below illustrates that the traffic volume across the peak hour showed no significant change.

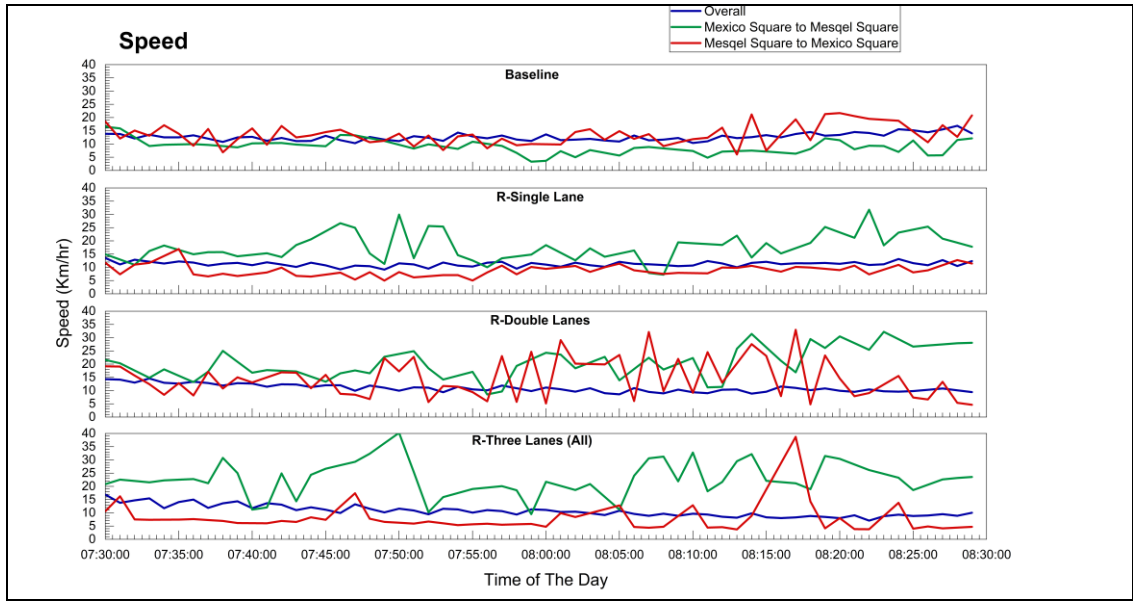


Figure 4-9: Simulated Traffic Flow Rate (Mexico-Mesqel Square Road)

Source: Computed from the empirical data by the Author, 2025

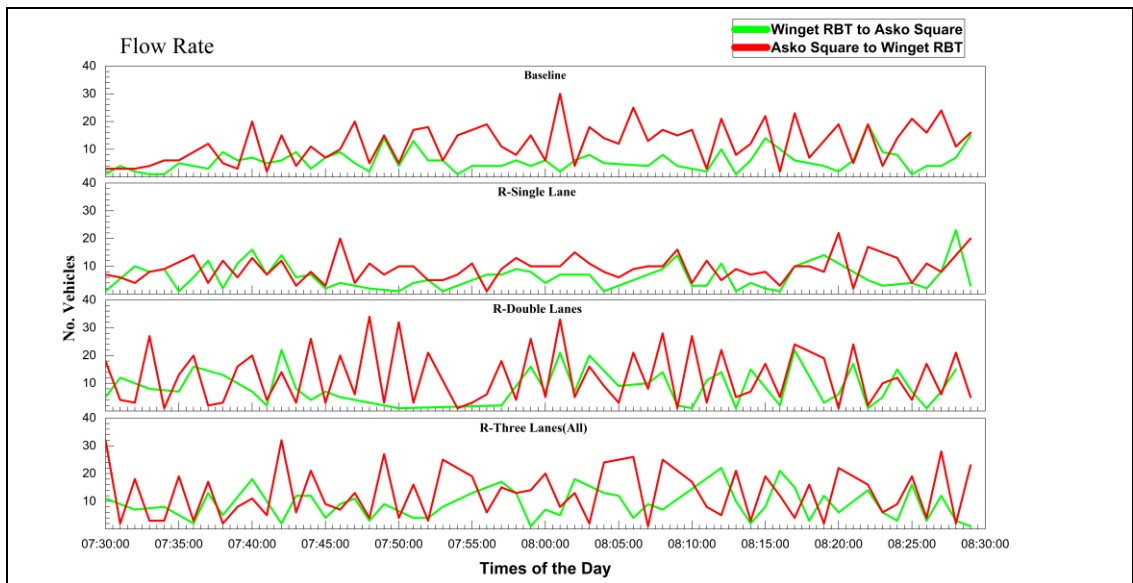


Figure 4-10: Simulated Traffic Flow Rate (Asko-Winget Road)

Source: Computed from the empirical data by the Author, 2025

On Asko to Winget, R3 raised eastbound volume by 2.3% (from 696 to 713 veh/h) and westbound by 33.2% (from 321 to 427 veh/h). On Mexico to Mesqel Square, R3 increased eastbound volume by 14.97% (from 374 to 430 veh/h), but reduced westbound volume by 50.21% (from 713 to 355 veh/h), reflecting capacity reallocation.

Table 4.7: Traffic Volume (Vehicles/Hour)

Road	Route	E	R1	R2	R3
Mexico to Mesqel Square	Mexico to Mesqel	374	394	402	430
Mexico to Mesqel Square	Mesqel to Mexico	713	478	400	355
Asko to Winget	Asko to Winget	696	686	712	713
Asko to Winget	Winget to Asko	321	354	365	427

Source: Computed from the empirical data by the Author, 2025

4.5.3 Public Transport and Safety Impacts

Simulations tested the impact of reversible lanes on bus delay, detour distance, and safety measures, which encompassed lane reallocation effects and driver behavior.

For the Asko to Winget corridor, Scenario R1 increased the mean bus delay by 13% (from 10.0 min to 11.3 min) with not detour, R2 by 15% (to 11.5 min) with no detour, and R3 by 13% (from 10 min to 13 min) with a 1.2 km detour, due to consecutive lane reallocation conflicts. Safety analysis also indicated rises in collision frequencies by 3% (R1), 4.5% (R2), and 8% (R3) and lane-changing infractions increased by 3.44% (R1), 5.1% (R2), and 10% (R3) as a result of driver unfamiliarity with reversible lanes.

For the Mexico to Mesqel Square corridor, Scenario R1 increased bus delay by 12% (from 12.5 min to 14.0 min), R2 by 18% (to 14.7 min), and R3 by 25% (to 15.6 min) with a 0.8 km detour, driven by lane conflicts and higher intersection density. Safety impacts were 8% (R1), 18% (R2), and 22% (R3) increases recorded in collision rates/ Lane-change violations also increased by 10.1% (R1), 18.5% (R2), and 22.9% (R3), reflecting interactions of sophisticated traffic dynamics and driver adaptation difficulty.

Table 4-5: Public Transport and Safety Impacts

Metric		Baseline	R1	R2	R3
Asko to Winget	Avg. Bus Delay (min)	10.0	11.3 (+13%)	11.5 (+15%)	13.0 (+30%)
	Avg. Detour Distance (km)	0	0	0	1.2
	Collision Frequency (%)	-	+3	+4.5	+8
	Lane-Changing Violations (%)	-	+3.4	+5.1	+10
Mexico to Mesqel Square	Avg. Bus Delay (min)	12.5	14.0 (+12%)	14.7 (+18%)	15.6 (+25%)
	Avg. Detour Distance (km)	0	0	0	0.8
	Collision Frequency (%)	-	+8	+18	+22
	Lane-Changing Violations (%)	-	+10.1	+18.5	+22.9

Source: Computed from the empirical data by the Author, 2025

4.5.4 Analysis of Network-Wide Results

Network wide parameters were computed to analyze the overall performance of the network. On the Mexico to Mesqel Square corridor, Scenario R3 provided the lowest mean travel time of 723 seconds (12:03) and is followed by the baseline scenario at 738 seconds (12:18), then R2 at 743 seconds (12:23), and lastly R1 at 751 seconds (12:31), indicating a moderate reduction in network-wide congestion. Base line Scenario had the highest mean speed of 12.20 km/h, then 11.25 km/h for R1, 11.06 km/h for R2, and 10.66 km/h for R3, which means reversible lanes can redistribute flows at the expense of average speed. Loss of time was lowest under R3 at 499 seconds (08:19), then on the baseline at 504 seconds (08:24), R2 at 518 seconds (08:38), and R1 at 526 seconds (08:46). Traffic volumes are the largest in baseline at 6211 vehicles per hour, followed by R2 at 5568, R3 at 5443, and R1 at 5195 vehicles per hour.

On the Asko to Winget corridor, Scenario R3 reduces average travel time considerably to 561 seconds (09:21), whereas R1 and R2 take 923 seconds (15:23), and baseline takes 1272 seconds (21:12), indicating significant relief from congestion. Considering mean speed, R3 recorded 19.99 km/h, versus R1's 10.90 km/h, R2's 10.50 km/h, and baseline's 10.21 km/h. Minimum loss of time under R3 is 332 seconds (05:32), followed by R1 and R2 at 697 seconds (11:37), and baseline at 1030 seconds (17:10). Traffic volume was maximum on baseline with 2503, then on R3 with 2478, R2 with 2305, and R1 with 2205 vehicles per hour, indicating increased network capacity. These general network results reflect R3's operation in the Asko to Winget corridor and marginal gains in the Mexico to Mesqel Square corridor.

Table 4-6: Network-Wide Simulation Results Summary

Corridor	Scenario	Mean Travel Time (s)	Mean Speed (km/h)	Mean Time Loss (s)	Traffic Volume (veh/h)
Mexico to Mesqel Square	E	738 (12:18)	12.20	504 (08:24)	6211
	R1	751 (12:31)	11.25	526 (08:46)	5195
	R2	743 (12:23)	11.06	518 (08:38)	5568
	R3	723 (12:03)	10.66	499 (08:19)	5443
Asko to Winget	E	1272 (21:12)	10.21	1030 (17:10)	2503
	R1	923 (15:23)	10.90	697 (11:37)	2205
	R2	923 (15:23)	10.50	697 (11:37)	2305
	R3	561 (09:21)	19.99	332 (05:32)	2478

Source: Computed from empirical data by the Author, 2025.

Note: % Improvement calculated as $((E - \text{Scenario}) / E) \times 100$ for travel time and time loss (positive = reduction); $((\text{Scenario} - E) / E) \times 100$ for speed and volume (positive = increase).

Table 4-7B: Percentage Improvements against Baseline Scenario E

Corridor	Scenario	% Improvement (Travel Time)	% Improvement (Speed)	% Improvement (Time Loss)	% Improvement (Volume)
Mexico to Mesqel Square	E	-	-	-	-
	R1	-1.76%	-7.79%	-4.37%	-16.36%
	R2	-0.68%	-9.34%	-2.78%	-10.35%
	R3	+2.03%	-12.62%	+0.99%	-12.35%
Askto Winget	E	-	-	-	-
	R1	+27.44%	+6.76%	+32.33%	-11.91%
	R2	+27.44%	+2.84%	+32.33%	-7.91%
	R3	+55.90%	+95.79%	+67.77%	-1.00%

Source: Computed from empirical data by the Author, 2025.

Note: % Improvement calculated as $((E - \text{Scenario}) / E) \times 100$ for travel time and time loss (positive = reduction); $((\text{Scenario} - E) / E) \times 100$ for speed and volume (positive = increase).

4.5.5 Average Directional Performance

The average directional performance was calculated using the weighted average results of mean travel time, mean speed, mean time loss, and volume of traffic of the directional data. On the Mesqel Square to Mexico corridor, mean directional travel times were 819 seconds for the baseline Scenario (E), 805 seconds for R1, 794 seconds for R2, and 1066 seconds for R3, calculated with traffic volumes (374 vehicles per hour eastbound, 713 westbound for E) used to weight directional contributions. Scenario R2 reduced the average travel time by 25 seconds below E, with significant eastbound savings (980 seconds to 422 seconds) more than compensating for westbound losses (658 seconds to 1166 seconds). Scenario R3, however, increased average travel time due to severe westbound penalties (1744 seconds), which canceled out its eastbound savings (388 seconds). Average speeds were 12.18 km/h for E, 13.87 km/h for R1, 18.93 km/h for R2, and 15.47 km/h for R3, with the high speed of R2 driven by eastbound gains (23.59 km/h). Average time loss was also in the same pattern, with R2 at 533 seconds, ahead of E's 640 seconds, R1's 599 seconds, and R3's 794 seconds. Traffic volume means

were lower in the reversible lane instances (401 vehicles per hour for R2, 392 for R3) than for E (543), implying rerouting. Balanced flows (29.6% eastbound, 29.6% westbound) improve westbound trade-offs, lowering reversible lane benefits.

For the Asko to Winget corridor, mean directional travel times were 1071 seconds (17:51) for E, 1366 seconds for R1, 622 seconds for R2, and 346 seconds for R3, weighted by traffic volumes (696 eastbound, 321 westbound for E). Scenario R3 achieves the lowest total average travel time, down by 725 seconds from E, thanks to huge eastbound improvements (1298 seconds to 298 seconds), despite westbound increases (588 seconds to 795 seconds). Scenario R2 also reduced travel time significantly (to 622 seconds), trading off eastbound gains (607 seconds) with small westbound losses (756 seconds). Average speeds were 7.68 km/h for E, 21.31 km/h for R1, 22.58 km/h for R2, and 33.28 km/h for R3, with R3's high speed reflecting eastbound efficiency (43.00 km/h). Time loss averages were 831 seconds (13:51) for E, 1173 seconds for R1, 426 seconds for R2, and 240 seconds for R3, with R2 and R3 reducing delays significantly. Traffic volume means were higher for reversible lane scenarios (570 vehicles per hour for R3, 539 for R2) than for E (509), which reflects the eastbound bias of the corridor.

Average directional performance highlights R2's symmetrical gains in Mexico to Mesqel Square, where westbound trade-offs under R3 are at the extreme, and R3's superior performance in Asko to Winget, tempered by moderate westbound losses.

Table 4-8: Average Directional Performance

Corridor	Scenario	Avg. Travel Time (s)	Avg. Speed (km/h)	Avg. Time Loss (s)	Avg. Traffic Volume (veh/h)
Mexico to Mesqel Square	E	819	12.18	640	543
	R1	805	13.87	599	436
	R2	794	18.93	533	401
	R3	1066	15.47	794	392
Asko to Winget	E	1071	7.68	831	509
	R1	1366	21.31	1173	520
	R2	622	22.58	426	539
	R3	346	33.28	240	570

Source: Computed from empirical data by the Author, 2025.

Note: Averages weighted by traffic volume where applicable ($\text{Eastbound} \times \text{Volume} + \text{Westbound} \times \text{Volume} / (\text{Total Volume})$).

4.6 Summary of Results

Traffic simulation results on the Mexico to Mesqel Square and Asko to Winget corridors provide insight into how reversible lane systems can help mitigate road congestion. The following table provides a summary of mean travel times, mean speeds, mean time losses, and traffic flow on the two routes under different configurations (E, R1, R2, and R3).

Table 4-9: Simulations Results Summary

Road	Route	Scenarios	Mean Travel Time (s)	Mean Speed (km/h)	Mean Time Loss (s)	Traffic Volume
Mexico to Mesqel Square	Mexico to Mesqel Square	E	0:16:20	7.95	0:13:00	374
		R1	0:09:35	18.81	0:06:02	394
		R2	0:07:02	23.59	0:04:01	402
		R3	0:06:28	24.42	0:03:43	430
	Mesqel Square to Mexico	E	0:10:58	16.41	0:08:20	713
		R1	0:17:15	8.92	0:13:56	478
		R2	0:19:26	14.26	0:13:45	400
		R3	0:29:04	6.52	0:22:45	355
	Overall (Network wide)	E	0:12:18	12.2	0:08:24	6211
		R1	0:12:31	11.25	0:08:46	5195
		R2	0:12:23	11.06	0:08:38	5568
		R3	0:12:03	10.66	0:08:19	5443
Asko to Winget	Asko to Winget	E	0:21:33	10.12	0:17:54	696
		R1	0:24:11	12.39	0:20:59	686
		R2	0:10:07	26.54	0:06:18	712
		R3	0:04:58	43	0:01:19	713
	Winget to Asko	E	0:09:48	2.39	0:05:05	321
		R1	0:08:07	30.22	0:03:35	354
		R2	0:12:36	18.62	0:07:55	365
		R3	0:13:15	23.56	0:06:41	427
	Overall (Network wide)	E	0:21:12	10.21	0:17:10	2213
		R1	0:15:23	10.9	0:11:37	2205
		R2	0:15:23	10.5	0:11:37	2305
		R3	0:09:21	19.99	0:05:32	2478

Source: Computed from the empirical data by the Author, 2025

4.7 Selection Reasoning for Scenarios

This calculates the performance of Scenarios E, R1, R2, and R3 for Asko to Winget and Mexico to Mesqel Square corridors from Multi-Criteria Decision Analysis (MCDA)-based network-wide measurements in Table 4-10. MCDA integrates mean

travel time, mean speed, mean time loss, and traffic volume with congestion relief assigned greater weighting and thus providing a quantitative basis for comparison among scenarios (Bernasconi et al., 2010; Cao et al., 2020).

Network-wide measures are normalized by the min-max procedure, minimization of travel time and time loss and maximization of speed and traffic volume. Normalization equations are:

$$\text{for minimization, } P_{norm} = \frac{P - P_{min}}{P_{max} - P_{min}}$$

$$\text{for maximization, } P_{norm} = \frac{P_{max} - P}{P_{max} - P_{min}}$$

Weights are the priorities of congestion: travel time (0.35), time lost (0.30), speed (0.20), and traffic volume (0.15), following urban traffic management (Highway Capacity Manual, 2010). The performance score is the weighted sum of the normalized values.

Table 4-10: Corridor Performance Scores with Normalized Values

Corridor	Scenario	Normalized Travel Time	Normalized Speed	Normalized Time Loss	Normalized Traffic Volume	MCDA Score
Mexico to Mesqel Square	E	0.50	1.00	0.25	1.00	0.65
	R1	0.00	0.31	0.00	0.00	0.08
	R2	0.29	0.17	0.09	0.36	0.22
	R3	1.00	0.00	1.00	0.24	0.72
	E	0.00	0.00	0.00	1.00	0.15
Asko to Winget	R1	0.49	0.07	0.56	0.00	0.35
	R2	0.49	0.03	0.56	0.34	0.49
	R3	1.00	1.00	1.00	0.92	1.00

Source: Computed from empirical data by the Author, 2025.

Note: Normalized values derived using min-max normalization

Scenario R3 achieves the highest scores, particularly in Asko to Winget, reflecting significant congestion reductions. In Mexico to Mesqel Square, R3's marginal advantage over E suggests limited benefits in balanced flows.

4.8 Selection of Optimal Scenario

This section selects the optimal traffic management scenario for the Mexico to Mesqel Square and Asko to Winget corridors from a three-layer framework consisting of network-wide performance, average directional performance, and bus and safety issues.

The analysis integrates MCDA rankings for Table 4.9, direction of outcomes in Table 4.6, and impacts of buses and safety in Table 4.5 to give an overall picture of congestion relief and realistic constraints in Addis Ababa, for which buses are a crucial mode of transportation. Base line Scenario E for Mexico to Mesqel Square, and R2 for Asko to Winget, are selected based on an impartial analysis of the three layers.

i) Layer 1: Network-Wide Performance

MCDA values in Table 4-9 indicate that Scenario R3 is more effective than others in both corridors. In Mexico to Mesqel Square, R3 scores 0.72, followed by E at 0.65, R2 at 0.22, and R1 at 0.08, driven by a reduction in travel time to 723 seconds and lost time to 499 seconds, even though E has higher speed (12.20 km/h) and volume (6211 vehicles per hour). In Asko to Winget, R3's value of 1.00 significantly outbeating R2 (0.49), R1 (0.35), and E (0.15), lowers travel time to 561 seconds, speed to 19.99 km/h, time loss to 332 seconds, and volume to 2478 vehicles/hour. These measures indicate R3's better relief status in relieving congestion, particularly for Asko to Winget's east-bound-skewed flows (68.43% to 71.7%).

ii) Layer 2: Average Directional Performance

Directional performances in Table 4-6 are time-averaged out (traffic volume-weighted) to assess balanced performance. In Mexico to Mesqel Square, Scenario E time-averages at 819 seconds, R1 at 805 seconds, R2 at 794 seconds, and R3 at 1066 seconds. R2's eastbound time saving (980 to 422 seconds) is opposed by westbound losses (658 to 1166 seconds, 77.20% increase), and R3's eastbound gains (to 388 seconds) are accompanied by severe westbound penalties (to 1744 seconds, 165.05% increase), upsetting balanced flows (29.6% eastbound, 31.8% westbound). Scenario E maintains greater directional balance in performance, minimizing trade-offs. In Asko to Winget, travel times are E average at 1071 seconds, R1 average at 1366 seconds, R2 at 622 seconds, and R3 at 346 seconds. R3's eastbound drop (1298 to 298 seconds) has moderate westbound losses (588 to 795 seconds, 35.20% increase), while R2's eastbound rises (to 607 seconds) have westbound rises to 756 seconds (28.57%). Both R2 and R3 are biased in the direction of east, but R2 has more balanced direction effects.

iii) Layer 3: Bus and Safety Issues

Table 4-5 shows bus delays, detours, collision rate, and lane-changing offenses. To Mesqel Square, the baseline bus delay for Scenario E stands at 12.5 minutes, increasing to 14.0 minutes (+12%) under R1, 14.7 minutes (+18%) under R2, and 15.6 minutes (+25%) under R3, with R3 having a 0.8 km diversion. Collision frequency goes up by 8% under R1, 18% under R2, and 22% under R3, with lane-changing violations also up by 10.1%, 18.5%, and 22.9%, respectively. Drastic westbound trade-offs in R2 and R3, elevated safety hazards, and R3 detour diminish reversible lanes' appeal.

On Asko to Winger Road, baseline bus delay was 10.0 minutes, which increases to 11.3 minutes (+30%) under R1, to 11.5 minutes (+15%) under R2, and to 13.0 minutes (+30%) under R3, with R3 requiring a 1.2 km detour. Collision frequency rises by 3% under R1, 4.5% under R2, and 8% under R3, while violations rise by 3.4%, 5.1%, and 10%, respectively. R2's shorter bus delay and avoidance of detours make it more favorable, as R3's detour disrupts bus operation critical to Addis Ababa.

- **Selection of Best Scenario**

From Mexico to Mesqel Square, Scenario E is selected. Despite R3's 0.72 network-wide score, its record westbound travel time decline (1744 seconds), inordinate safety hazards (+22% collisions, +22.9% infractions), and 0.8 km bus diversion are achieved at the cost of low congestion improvements (15-second network-wide travel time reduction). R2's network rating of 0.22 and westbound losses (1166 seconds) are accompanied with huge trade-offs (+18% collisions, +18.5% violations), while E's rating of 0.65 and balanced directional performance (average 819 seconds) avoid bus detours and minimize safety risks, as found in balanced flows where reversible lanes offer moderate net benefits. Between Asko to Winget, Scenario R2 is selected. Although R3 boasts high eastbound gains (298 seconds) and a score of 1.00, its detour of 1.2 km, 30% rise in bus delay, and high safety concerns (+8% collisions, +10% violations) make it impractical. R2's 0.49 score, decrease in travel time eastbound (607 seconds), moderate losses westbound (756 seconds), decreased bus delay (11.5 minutes, +15%), and no improvement in detour balance congestion with bus and safety factors.

4.9 Discussion

This section interprets the simulation results in the context of the research objectives and questions, integrating findings with global and African literature to contextualize reversible lanes' applicability in Addis Ababa. The findings are compared with existing literature to situate the study within the field of traffic engineering and provide practical implications for urban traffic management.

4.9.1 Effectiveness of Reversible Lanes

The reversible lane application showed positive results on on Asko to Winget road, in particular the result of the scenario with two reversible lane (R2) an overall improvement, where travel time and time loss reduced by 27.44% and 32.33%, Speed increased by 2.84% while traffic flow slightly decrease by 7.91%. These gains reflect increased lane capacity for dominant flows, aligning with Gayah & Daganzo (2012), who found that reversible lanes reduce delays by up to 25% in imbalanced corridors.

In contrast, the Mexico to Mesqel Square road showed an overall negative result. It is noted that the baseline scenario has better output than the simulated reversible lane scenarios. This finding supports Zhang et al. (2020), who noted that reversible lanes are less effective in balanced-flow corridors

Further analysis of directional effects indicated that there was a large trade-off that the reversible lanes slightly improved traffic conditions on one direction, while the other direction experienced heavy congestion, leading to a net negative effect.

4.9.2 Factors Influencing Reversible Lane Effectiveness

The effectiveness of reversible lanes was influenced by five key factors, identified through sensitivity analysis and simulation outputs in SUMO, validated by one-way repeated measures ANOVA ($p < 0.05$):

i) Traffic Characteristics

Sensitivity analysis varied eastbound–westbound ratios, revealing that Asko to Winget's 68.43% eastbound flow (696 vehicles) versus 31.57% westbound (321 vehicles) increased R2 efficiency, where travel time and time loss reduced by 27.44% and 32.33%, Speed increased by 2.84% while traffic flow slightly decrease by 7.91%.

($F=110.44$, $p<0.0001$). In contrast, Mexico to Mesqel Square's balanced flows (29.6% eastbound vs. 31.8% westbound) no gains with reversible lanes Zhang et al. (2020).

Table 4-11: Summary of Traffic Distribution

Road	Eastward Travel	Westward Travel
Mexico to Mesqel Sq.	31.8 %	29.6 %
Asko to Winget	68.43 %	31.57 %

Source: Computed from the empirical data by the Author, 2025

The traffic volumes during peak hours exhibit varying degrees of traffic volume imbalance between the two roads, which directly affects reversible lane efficiency.

On Asko to Winget road, traffic distribution is highly imbalanced, with 68.43% of corridor traffic traveling east and only 31.57% west. As an example, at Asko-Winget road 68.43% of traffic travels east to Winget, with only 31.57% traveling west. This significant traffic volume imbalance offers an ideal situation for reversible lanes, since rebalancing the lane distribution follows the dominant direction of traffic, significantly improving traffic conditions and reducing congestion. The simulation results, in fact, show an overall best improvement with two reversible lanes, where travel time and time loss reduced by 27.44% and 32.33%, Speed increased by 2.84% while traffic flow slightly decrease by 7.91%, which further verifies the efficiency of reversible lanes in managing unbalanced traffic volumes.

In comparison, Mexico to Mesqel Square road has a more balanced traffic distribution. Traffic in both directions is almost equal, with the eastbound direction at around 31.8% and the westbound direction at around 29.6%. This type of balanced traffic distribution is unfavorable for reversible lanes because lane allocation in favor of one direction aggravates traffic in the opposite direction. Consequently, the results of the simulation show that the introduction of reversible lanes provided no merit when the network wide impact is considered.

ii) Traffic Signal Systems

One of the key elements on the road from Mexico to Mesqel Square is the traffic light system, where 3 out of the 4 intersections are controlled by fixed-time signals. Fixed-time signals operate according to a pre-set schedule regardless of the actual-time traffic

condition, which has a tendency to generate inefficiencies in a scenario with fluctuating traffic demand. At peak hours, when reversible lanes are used most, these fixed-time signals have a tendency to generate huge delays. Traffic in a single direction can have long red-light phases even when the opposite direction has low demand, and thus congestion arises despite reversible lanes.

In contrast, Asko to Winget road has no traffic lights, with Winget intersection, being the only one that is traffic police-controlled, which can be considered as being similar to a delay based system. On this junction, traffic police control the traffic based on real conditions in real time according to real directional traffic flow. This capability makes it simpler to use the reversible lane to the best extent by satisfying real-time demands of the road. This maximizes the Asko to Winget road for reversible lanes since traffic control becomes more responsive to real conditions.

In order to analyze the impact, all traffic lights on the Mexico to Mesqel Square road were changed to delay-based traffic system without altering the other features and the parameter are analyzed as follows:

Table 4-12: Delay-Based vs. Fixed-Time Signals

Route	System	Travel Time (s)	Speed (km/h)	Time Loss (s)	Volume (veh/h)	Improvement (%)
Mexico to Mesqel	Fixed	422	23.59	241	402	-
	Delay-Based	335	25.15	136	451	21
Mesqel to Mexico	Fixed	1166	14.26	825	400	-
	Delay-Based	938	12.85	775	480	20
Overall	Fixed	794	18.93	533	802	0.19
	Delay-Based	695	19.00	456	931	16

Source: Computed from the empirical data by the Author, 2025

As it can be noted from the above table, the application of delay base traffic system with reversible lane resulted a significant improvement on the overall performance of the network, by 16%, compared to the previous marginal improvement of 0.19% with the actual fixed traffic light setup.

iii) Road Characteristics

The road from Mexico to Mesqel Square, while being shorter at around 2 kilometers, has more intersections than the 3.5-kilometer long Asko to Winget road. There are four large intersections on the Mexico to Mesqel Square road, and the average distance

between each is 375 meters. This extremely high frequency of intersections significantly affects traffic flow since each intersection is likely to act as a bottleneck during peak hours. These high-frequency intersections are accompanied by a number of points where queue occurs, thereby negating the benefit of reversible lanes by causing stop-and-go movement. The proximity of the intersections denies the reversible lane the opportunity to extend unbroken benefits to the flow and speeds of traffic as cars are repeatedly halted by traffic lights, further increasing time loss.

On the other hand, the Asko to Winget road has fewer junctions, allowing for longer, uninterrupted lengths of road. There are fewer intersections to disrupt traffic, and the reversible lanes can be more effective in handling peak direction traffic flows. The wider spacing between intersections allows the cars to travel longer distances without interruption, leading to higher speed and less stop-and-go condition, making the additional lane in the peak direction more valuable. These findings are similar with Chiu et al. (2007), who identified high intersection density as a limiting factor.

iv) Lane Allocation

Iterative testing of lane configurations (R1–R3) showed R3’s three-lane reversal optimized Asko to Winget’s eastbound flow (713 vehicles/hour), while R2 balanced Mexico to Mesquel Square’s bidirectional needs (402 vehicles/hour eastbound). Sensitivity analysis confirmed lane count as a primary driver.

Table 4-13: Impact of Lane Allocations on Traffic Performance Metrics

Road	Scenarios	Mean Travel Time (s)	Mean Speed (km/h)	Mean Time Loss (s)	Traffic Volume
Mexico to Mesquel Square	BL	0%	0%	0%	0%
	R1	+1.76%	-7.79%	+4.37%	-19.78%
	R2	+0.68%	-9.34%	+2.78%	-26.22%
	R3	-2.03%	-12.62%	-0.99%	-27.78%
	Average	+0.14%	-9.92%	+2.05%	-24.59%
Asko to Winget	BL	0%	0%	0%	0%
	R1	-27.44%	+6.76%	-32.33%	+2.26%
	R2	-27.44%	+2.84%	-32.33%	+5.90%
	R3	-55.90%	+95.79%	-67.77%	+12.09%
	Average	-36.93%	+35.13%	-44.14%	+6.75%

Source: Computed from the empirical data by the Author, 2025

Note: Percentage changes are relative to the baseline scenario (E). Positive % = improvement for Speed/Volume (increases); negative % = improvement for Travel Time/Time Loss (decreases). Volume is total flow; peak-direction volumes (402 veh/h for R2, Mexico to Mesqel Square; 713 veh/h for R3, Asko to Winget) noted in text.

In summary, the road characteristics of Mexico to Mesqel Square and Asko to Winget roads significantly influence the success of reversible lanes. The frequent intersections, fixed-time traffic signals, and shorter road length of Mexico to Mesqel Square road limit the benefits of lane reallocation, while the longer uninterrupted sections, delay based or manually controlled signals and simpler intersection management on Asko to Winget road make it better suited for reversible lanes. These differences highlight the importance of considering road characteristics of each roads when implementing traffic management solutions such as reversible lanes.

4.9.3 Implementation Challenges

The above analysis demonstrated that the application of reversible lane has merits depending on the traffic and road characteristics of the subject road. However, the results also showed implementing such systems poses challenges.

i) Forced Rerouting for Public Transportation

Simulation results revealed that the application reversible lanes has impacted the operations of public transport system particularly buses and minibuses, which have an important contribution towards the mobility network in Addis Ababa. On Mexico to Mesqel Square the average bus delays in Scenario R2 were 18% higher than the base scenario, at 12.5 minutes versus 14.7 minutes. Similarly on Asko to Winget Road it was up by 15% (from 10 min to 11.5 min) in scenario R2)

These disruptions not only reduce the public transport efficiency but also the degree of operating efficiency for transport operators and passenger inconvenience. The finding underscores for detailed planning of reversible lanes with public transport corridors to avert unwanted effects.

ii) Driver Confusion and Safety

The simulation outcomes revealed considerable safety issues resulting from driver confusion during reversals. Collision frequency on Mexico to Mesqel Square was up

18% in Scenario R2 compared to the base scenario, an indicator of rising risk with lane reversals. On Asko to Winget road, the spike was not as much as on Mexico to Mesqel square, at 4.5%.

iii) Integration with Surrounding Roads

Simulation outcomes showed reversible lanes experience spillover congestion impacts on peripheral roads, particularly in heavy traffic locations like Mexico to Mesqel Square. The Average speed on the peripheral road decreased by 14%, from 23.5 km/h to 18.2 km/h. additionally, the parallel roads experienced a 22% traffic volume spillover, where drivers use the alternative roads in order to bypass reversible lane sections. This finding is consistent with Zhang et al. (2020), and shows the need for a coordinated traffic management intervention where reversible lanes are applied.

4.10 Addressing the Research Objectives and Questions

This part presents a description of the research's key objectives and related research questions, providing an overview of the purposes and findings of the study in relation to the applicability of reversible lanes in reducing road congestion.

- i) Objective 1:** To evaluate the effectiveness of reversible lane systems in reducing peak hour congestion in Addis Ababa.

Findings: the results of the scenarios showed a significant difference in the effectiveness of reversible lanes on the routes under investigation. On the Asko to Winget road, application of reversible lanes resulted in improved network wide performance characterized by significant change, where travel time and time loss reduced by 27.44% and 32.33%, Speed increased by 2.84% while traffic flow slightly decrease by 7.91%. Conversely, on the Mesqel Square to Mexico road, though marginal improvement were recorded in the direction of reversible lanes, traffic overall was worse because extreme congestion in the opposite direction negated the benefits gained on the direction in which reversible lanes are added.

- ii) Objective 2:** To identify key factors that determine the effectiveness of reversible lanes in reducing congestion in Addis Ababa.

Findings: the following key factors are identified to affect the success of reversible lanes

1. **Traffic Characteristics:** Reversible lane is successful where there is a directional traffic imbalance, where the Asko to Winget corridor was improved significantly in all the scenarios. This road had 68.43% of traffic traveling east and only 31.57% west. In comparison, Mexico to Mesqel Square road has a more balanced traffic in both directions with the eastbound direction at around 31.8% and the westbound direction at around 29.6%.
2. **Traffic Signal Systems:** The nature of the traffic signal system was important. Fixed-time signals on Mexico to Mesqel Square restricted reversible lanes benefits by causing delays, but manually controlled or delay based on Asko to Winget permitted more adaptive as well as more efficient traffic control. As such, when the fixed traffic signals changed to delay based signal system, an overall 16% improvement is recorded under one reversible lane application.
3. **Intersection Density and Management:** Intersection density greatly influenced traffic flow. Mexico to Mesqel Square, where there were many intersections, had bottlenecks in the flow of traffic that made reversible lanes inefficient. On the other hand, Asko to Winget, where there were fewer number of junction, had improved traffic flow and more effective utilization of reversible lanes.
4. **Road Characteristics:** Mexico to Mesqel Square's shorter length (2 km) and frequent intersections limited flow continuity. Asko to Winget's longer, uninterrupted sections (3.5 km) supported sustained flow, improving speed and reducing time loss.
5. **Lane Allocation:** R3's three-lane reversal optimized Asko to Winget's eastbound flow (713 veh/h), while R2 balanced Mexico to Mesqel Square's bidirectional needs (402 veh/h eastbound), confirmed by sensitivity analysis as a primary driver.

- iii) **Objective 3:** To identify the primary challenges associated with implementing reversible lane systems.

Findings: The study identified a series of major and potential issues in the installation of reversible lanes:

1. **Public Transport Disruption:** Reversible lanes introduced 18% more delay on buses and caused detours of 1.2 km, justifying the need for increased compatibility with public transport routes.
2. **Safety Hazards:** 18% more collisions occurred, and lane change violations contributed an additional 12% to delays, a vivid reminder of the need for proper signage and public information campaigns.
3. **Network Integration:** spillback congestion on adjacent roads reduced mean speeds by 14% and introduced volume by 22%, demonstrating the significant impact of reversible lanes on the overall traffic management systems.

4.11 Comparison of Results with Existing Literature

The results of this study on the efficacy of reversible lanes in reducing road congestion ought to be understood in the context of existing literature. The following section discusses this study's results as well as the findings of similar researches.

4.11.1 Verification of Confirmed Results

The analysis revealed significant variation in the efficacy of reversible lanes on the selected routes. For instance, the Winget to Asko corridor experienced considerable improvement in traffic flow, with reduced travel time, time loss and increased mean speeds and traffic flow. This outcome corroborates with Gayah & Daganzo (2012), which reported reversible lane systems to lower congestion levels by up to 25% in the presence of severe directional imbalances. The noticeable gains realized in this study agree with the overall understanding that reversible lanes are effective in managing peak hour traffic increase in one way.

On the other hand, the Mexico to Mesqel Square route had a negative outcome: although marginal gains were observed along the direction of the reversible lanes, overall congestion was increased as a result of extreme bottlenecks in the reverse direction. This observation is in agreement with J. Zhang et al. (2020) that highlighted the risk of applying reversible lanes on well-balanced traffic corridors, wherein reversible systems create new bottlenecks of congestion rather than relieving current ones. The technicalities of managing reversible lanes, especially under the same traffic capacities for both directions, further emphasize the importance of contextual solutions in traffic engineering.

4.11.2 Contribution to Traffic Engineering Theory

Several key factors were found to be determining the effectiveness of reversible lanes, such as lane configuration, traffic management systems, and intersection density. The study found that the number of reversible lanes directly affects congestion outcomes. For the Mexico to Mesqel Square road connection, two reversible lanes (Scenario R2) provided comparative minor improvements on the direction of the added reversible lanes, and three lanes (Scenario R3) on the Asko to Winget road connection provided the overall highest benefits. This result is consistent with Qiao et al. (2021) research, which emphasizes that configuration and number of lanes must be decided based on local traffic demand to achieve optimum results.

Furthermore, the type of traffic signal system played a key role in providing smooth traffic flow. The study indicates that fixed-time signals along the Mexico to Mesqel Square corridor limited the use of reversible lanes by introducing delays, and this supports the argument presented by Liu & Chang (2011) who stated that fixed-time signals do not respond to real-time changes in traffic and hence increase congestion during peak periods. In contrast, application of delay based signals on the Winget to Asko corridor allowed adaptive traffic management, which aligns with recommendations by Papageorgiou et al. (2003) for increasing the efficiency of reversible lanes through advanced signal technology.

Intersection density and management also emerged as significant determinants of traffic flow efficiency. The number of intersection on the Mexico to Mesqel Square road contributed to ongoing bottlenecks, are supported by Chiu et al. (2007) findings that identified high intersection density as a limiting factor in the functioning of reversible lanes. This is based on the acknowledgment that traffic engineering interventions have to consider not only lane configurations but also overall intersection management policies encourages or hindering traffic flow.

Additionally, the implementation challenges of reversible lanes should also be thoroughly considered, which are as identified by this study, including safety, public acceptance, routing public transport and compatibility with the existing infrastructure.

These findings are relevant to traffic engineering theory because they show that reversible lanes, in addition to technical improvement, also require comprehensive planning, integration into systems and stakeholder participation.

4.12 Practical Implications

These findings have significant practical implications to traffic management. They highlight the necessity of conducting detailed study of local traffic behavior, including number of junctions and traffic signal types, before initiating the utilization of reversible lane systems. Traffic engineers should take real-time adaptive signal systems into consideration since this have been found to enhance the performance of reversible lanes by rendering traffic management more adaptive.

Additionally, the study emphasizes the importance of understanding the local traffic behavior, in which the one-size-fits-all formula will not apply; solutions will have to be tailored according to the individual characteristics of every route, such as intersection density, traffic distribution, and signalization tactics.

In general, while the findings of the study are in line with some of the trends in earlier research on reversible lanes, they also provide valuable information that is part of an evaluation of their effectiveness and possible limitations and constraints on implementation.

By placing these findings within the broader literature base, the current research emphasizes the necessity for adaptive traffic management systems that react to local conditions and reactive strategies. As cities grow and no longer can contain increasing traffic levels, results based on this study will be highly beneficial in informing the development of more effective traffic management methods.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter synthesizes the findings of the study with emphasis on the feasibility and potential benefits of reversible lanes in Addis Ababa. The recommendation address the directional traffic demands, right-of-way constraints, and financial constraints common to road infrastructure. These insights guides traffic planners and engineers towards making efficient decisions that optimize traffic flow and infrastructure utilization at low cost.

5.2 Conclusion

The study extensively examined the use of reversible lanes as a measure to alleviate traffic congestion in Addis Ababa focusing on two distinct corridors: Askto to Winget and Mexico to Mesqel Square roads. The study showed that reversible lanes are effective on roads with high directional imbalance in traffic flow, such as Askto to Winget road where Scenario R2 achieved overall improvement. However, on roads like Mexico to Mesqel Square, where traffic flow is more balanced, reversible lanes showed no merit due to deterioration on the opposite direction of the reversible lanes and fixed-time signal constraints.

The study offers valuable contributions to traffic management in Addis Ababa:

- **Route-Specific Solutions:** The results underline the necessity of tailored traffic management measures to road specific characteristics, such as traffic distribution and weather the route is used for public transport.
- **Systems Interaction:** It is noted from the findings that the effectiveness of reversible lane was constrained by fixed time signal on Mexico to Mesqel Square Road. Hence, reversible lane application requires coordinated signal systems and intersection management to maximize benefits.
- **Evidence-Based Implementation:** The study advocates data-driven implementation, using SUMO simulations to ensure interventions are grounded in robust evidence of impact.

These findings provide a potential solution to mitigate congestion in Addis Ababa, through optimal utilization road infrastructure, and encouraging sustainable urban mobility by aligning traffic management with the city's unique spatial and flow characteristics.

5.3 Recommendations

Based on the outcomes of the study, the following recommendations are proposed to maximize the effectiveness of reversible lanes in Addis Ababa.

5.3.1 *Peripheral Directional Lanes to the City Center*

Reversible lanes are best for peripheral corridors such as Asko to Winget Road, where there is a high directional imbalance during peak hours. This is due to that peripheral traffic is bound for the city center, and reversible lanes ease congestion by allocating additional lanes for the dominant traffic flow direction. This enable better utilization of available road capacity without huge investments for new infrastructure.

5.3.2 *Adaptive Signal Systems Integration*

The study recommends, fixed-time signals should be replaced with delay-based systems at major intersections. For Mexico to Mesqel Square, adaptive signals improved outcomes by 16%, which demonstrate the impacts of traffic signals.

5.3.3 *Public Transport Safety and Integration Measures*

The application of reversible lanes increased collisions by 4.5% on Asko to Winget, and by 18% on Mexico to Mesqel Square. This implies the need for education campaigns in order to inform drivers about reversible lanes, supported by dynamic signage. Additionally, there is a need to integrate reversible lanes with public transport routes and have bus priority lanes during peak hours to avoid delay and rerouting as showed on the findings of the study

5.3.4 *Context-Sensitive Implementation*

The findings, a significant improvement of the traffic flow on Asko to Winget and the marginal change on Mexico to Mesqel Square, underscore for a context-dependent use of reversible lanes, taking into account the lane geometry of each corridor, intersection

density, and traffic distribution. Moreover, the number of reversible lanes should be determined the actual traffic characteristics of the roads in subject.

5.3.5 *Simulation-Based Planning*

As the findings demonstrated, reversible lanes don't have the same impact in different corridors. Therefore, to avoid unwanted results and further congesting the road, a simulation based analysis should be conducted. Simulations will identify measure that should be taken such as where adaptive signals or lane maneuvers are needed to respond to bottlenecks.

5.4 Future Research Recommendation

Further research would progress reversible lane evaluations in Addis Ababa through real-time traffic data inclusion in simulations to better reflect dynamic situations. Additionally, a further study focused on investigating the socio-economic effects, as well as environmental effects like decreased emissions, would allow for a multi-layered evaluation of feasibility of reversible lanes. Investigation of hybrid traffic signal systems blending delay-based and adaptive control could also enhance reversible lane efficiency in mixed traffic further, enabling sustainable urban transport.

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APPENDIXES A: TRAFFIC COUNT DATA

Traffic Count Data

Traffic counts were collected via video-based manual counting at junctions along the Winget to Asko and Mexico to Mesqel Square corridors during the morning peak hour (01:30:00 to 02:30:00 AM). Data were aggregated over 15-minute intervals by vehicle type and turn movement to inform SUMO simulation inputs (Section 3.3.1).

Table A1: Turn Count at Winget Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 02:30:00	Sum
West	Through	556	673	485	462	2176
	Right	21	37	41	41	140
East	Through	187	171	184	168	710
	Left	73	60	72	66	271
North	Through	25	47	34	30	136
	Right	20	47	34	33	134
	Left	12	31	22	20	85

Table A2: Turn Count at Birchiko Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 2:30:00	Sum
South	Right	170	156	115	94	535
West	Through	310	400	431	420	1561
West	Right	25	27	23	24	99

Table A3: Turn Count at Menahriya Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 02:30:00	Sum
East	Through	93	86	79	107	365
	Left	17	20	15	13	65
	Right	1	2	3	2	8

West	Return	11	7	21	26	65
	Through	280	267	275	294	1116
	Right	10	2	8	6	26
	Left	5	2	5	5	17
North	Return	6	9	7	12	34
	Through	5	8	10	7	30
	Left	30	13	20	17	80
	Right	7	10	7	10	34
South	Through	3	3	1	2	9
	Left	19	20	20	19	78
	Right	101	97	85	91	374

Table A4: Turn Count at Asko Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	2:15:00 to 2:30:00	Sum
East	Through	141	126	120	116	503
	Left	37	24	22	22	105
	Return	1	0	2	0	3
West	Through	282	270	283	276	1111
	Right	10	7	10	11	38
	Return	3	1	0	3	7
	Left	4	2	5	6	17

Table A5: Turn Count at Mexico Roundabout

Approach Direction	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 2:30:00	sum
East (stadium)	128	214	171	168	681
East (wabishebele)	70	101	87	90	348
West	120	201	175	152	648
North	47	72	88	69	276
South (AU)	41	51	54	44	190
South (2)	24	35	30	26	115

Table A6: Turn Count at Kker Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 2:30:00	sum
West	Through	133	146	137	116	532
	Right	43	29	37	15	124
	Left	16	20	26	26	88
	Return	10	12	19	12	53
East	Through	84	99	88	80	351
	Left	44	42	50	17	153
	Right	12	40	29	40	121
	Return	33	34	39	11	117
South	Through	27	28	27	33	115
	Right	21	15	21	34	91
	Left	51	57	87	18	213
	Return	22	8	21	8	59
North	Through	7	6	2	3	18
	Right	2	5	3	3	13
	Left	4	5	4	4	17

Table A7: Turn Count at Telebar Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 2:30:00	Sum
North	Left	1	0	2	1	4
North	Right	106	101	130	94	431
West	Left	44	79	42	27	192
West	Through	294	309	266	278	1,147
West	Return	7	9	8	5	29
East	Right	64	64	51	32	211
East	Through	320	380	303	314	1,317
East	Return	35	44	52	42	173

Table A8: Turn Count at Legehar Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 2:30:00	Sum
East	Through	331	351	357	376	1,415
	Right	36	35	31	23	125
	Left	28	28	30	28	114
	Return	55	67	73	66	261
West	Through	283	263	268	253	1,067
	Right	30	43	30	22	125
	Left	45	54	45	39	183
	Return	5	7	4	3	19
South	Trough	167	107	75	80	429
	Right	36	48	44	47	175
	Left	39	42	34	32	147
	Return	-	2	-	-	2
North	Through	138	120	126	115	499
	Right	25	26	33	28	112
	Left	53	45	41	52	191
	Return	4	9	9	6	28

Table A9: Turn Count at Mesqel Square Junction

Approach Direction	Turn Movement	01:30:00 to 01:45:00	01:45:00 to 02:00:00	02:00:00 to 02:15:00	02:15:00 to 2:30:00	Sum
East	Through	362	351	347	376	1,436
	Right	78	77	72	70	297
	Left	78	108	90	80	356
	Return	55	67	73	66	261
West	Through	292	333	317	307	1,249
	Right	20	28	30	22	100
	Return	7	5	5	3	20

South	Trough	167	107	75	80	429
	Right	54	64	57	47	222
	Left	70	74	60	77	281
	Return	1	4	1	3	9
North	Trough	48	28	25	23	124
	Right	45	48	51	55	199
	Left	85	96	99	104	384
	Return	1	2	-	3	6

Source: Primary data collected via video-based manual counting at the intersections.

Traffic Signal Phase Durations

Traffic signal phase durations were recorded manually using a stopwatch at signalized and police-managed junctions during the morning peak hour (07:30:00 to 08:30:00 AM). Green, yellow, and red phases were measured; for police-managed junctions, equivalent phases were derived by averaging police-controlled flow durations. These data configured SUMO's actuated traffic controller.

Table B10-1: Traffic Signal Phases

Approaching Road Direction	Green Duration (sec)									
	Through			Left			Return			Right
	Duration	Min	Max	Duration	Min	Max	Duration	Min	Max	Duration
Asko Junction										
Asko	50	1	50	-	-	-	65	1	75	N/A
Winget	65	1	75	15	1	25	15	1	25	N/A
Addissefer	-	-	-	15	1	25	-	-	-	N/A
Addissefer Junction										
Asko	40	1	40	6	1	10	6	1	10	N/A
Winget	40	1	40	6	1	10	6	1	10	N/A
Addissefer	15	1	15	15	1	15	-	-	-	N/A
Menahriya	6	1	10	6	1	10	6	1	10	N/A
Birchiko Junction										
	Duration	Min	Max	Duration	Min	Max	Duration	Min	Max	Duration
Asko	50	1	50	70	1	70	N/A			
Brichiko	-	-	-	20	1	20	N/A			

Table B40-1: Traffic Signal Phase Durations

Approaching Road Direction	Duration	Green Duration (sec)		
		Min	Max	
Winget Junction				
Asko		90	1	50
Winget		50	1	50
AddisuGebeya		10	1	20
Mexico Junction				
Lideta		55	1	55
Left side from lideta Keker Junction		20	1	20
Mexico		55	1	55
Buna ena Shai		20	1	30
Kker		20	1	20
Wabishebele		20	1	20
Commerce Junction				
Mexico		40		
Legehar		70		
Sengatera		30		
Legehar Junction				
	Through	Left	Right	Return
Mexico		70	30	- 30
Stadium		77	37	- 37
Piasa		25	25	- 25
Kera		25	25	- 25
Gion Junction				
Stadium		80	80	- NA
Estifanos		117	37	- NA
Ambassador		30	30	- NA
Meshualekiya		30	30	30 NA
Estifanos Junction				
Gion		60	20	60 NA
Bambis		55	15	- 15
Bole		50	50	50 50
4 kilo		40	40	- 40

APPENDIXES B: CALIBRATION RESULTS

Calibration Results (Turn Counts)

- Description: The SUMO model was calibrated by comparing simulated turn counts with observed traffic volumes, using the GEH statistic to validate alignment with real-world conditions. A GEH value <5 for 93.4% of turn movements (298/319) confirms robust accuracy, exceeding the industry standard of 85% (Dowling et al., 2004).

Table C: Calibration Process Results for Traffic Volume

Junction	Approach Direction	Turn Movement	Traffic Count Turn Data				Simulation Turn Data				GEH Statistic			
Winget	West	Through	556	673	485	462	598	701	498	489	1.75	1.07	0.59	1.24
		Right	21	37	41	41	21	37	41	28	-	-	-	2.21
	East	Through	187	171	184	168	192	155	162	190	0.36	1.25	1.67	1.64
		Left	73	60	72	66	38	36	12	10	4.7	3.46	9.26	9.08
	North	Through	25	47	34	30	31	58	46	41	1.13	1.52	1.9	1.85
		Right	20	47	34	33	112	85	109	105	11.32	4.68	8.87	8.67
Asko	West	Through	282	270	283	276	302	297	300	292	1.17	1.6	0.99	0.95
		Right	10	7	10	11	11	6	10	12	0.31	0.39	-	0.29
		Return	1	-	3	5	2	1	5	13	0.82	1.41	1	2.67
	East	Through	141	126	120	116	155	97	74	99	1.15	2.75	4.67	1.64
		Left	37	24	22	22	33	12	7	12	0.68	2.83	3.94	2.43
		Return	1	-	2	-	10	2	3	7	3.84	2	0.63	3.74
	South	Right	7	8	5	7	3	1	3	1	1.79	3.3	1	3
		Left	4	2	5	6	4	3	3	2	-	0.63	1	2

Birchiko	South	Right	170	156	115	94	189	165	119	201	1.42	0.71	0.37	8.81
	West	Right	25	27	23	24	27	23	23	23	0.39	0.8	-	0.21
Menahriya	West	Through	310	400	431	420	318	433	475	437	0.45	1.62	2.07	0.82
		Through	280	267	275	294	279	266	255	289	0.06	0.06	1.23	0.29
		Left	5	2	5	5	13	13	11	15	2.67	4.02	2.12	3.16
		Right	10	2	8	6	12	11	3	5	0.6	3.53	2.13	0.43
		Return	6	9	7	12	3	3	3	2	1.41	2.45	1.79	3.78
		Through	93	86	79	107	89	121	88	97	0.42	3.44	0.98	0.99
	East	Left	17	20	15	13	11	14	12	10	1.6	1.46	0.82	0.88
		Right	1	2	3	2	1	1	3	1	-	0.82	-	0.82
		Return	11	7	21	26	10	7	34	9	0.31	-	2.48	4.06
		Through	19	20	20	19	2	2	1	1	5.25	5.43	5.86	5.69
	South	Left	3	3	1	2	2	4	4	2	0.63	0.53	1.9	-
		Right	101	97	85	91	123	121	118	120	2.08	2.3	3.28	2.82
		Through	30	13	20	17	29	15	21	20	0.18	0.53	0.22	0.7
		Right	5	8	10	7	6	8	9	8	0.43	-	0.32	0.37
Mexico	North	Left	7	10	7	10	7	11	9	9	-	0.31	0.71	0.32
		Through	214	171	168	121	220	169	173		0.41	0.15	0.38	15.56
	East (stadium)	Right	101	87	90	75	107	91	89		0.59	0.42	0.11	12.25
		Through	201	175	152	123	198	180	153		0.21	0.38	0.08	15.68
	East (wabishebele)	Left	72	88	69	48	65	89	61		0.85	0.11	0.99	9.8
		Through	51	54	44	43	55	53	49		0.55	0.14	0.73	9.27
	West	Left	35	30	26	26	41	32	29		0.97	0.36	0.57	7.21
		Through	133	146	137	116	118	141	128	99	1.34	0.42	0.78	1.64
	North	Right	43	29	37	15	54	32	42	21	1.58	0.54	0.8	1.41
		Through												
kker	South (AU)	Left												
		Through												
	Soth(2)	Left												
		Through												
	West	Left												
		Through												

Telebar	East	Left	16	20	26	26	21	18	19	17	1.16	0.46	1.48	1.94
		Return	10	12	19	12	15	9	15	12	1.41	0.93	0.97	-
		Through	84	99	88	80	98	116	90	127	1.47	1.64	0.21	4.62
		Left	44	42	50	17	45	39	44	39	0.15	0.47	0.88	4.16
		Right	12	40	29	40	11	37	26	40	0.29	0.48	0.57	-
		Return	33	34	39	11	27	30	35	16	1.1	0.71	0.66	1.36
	South	Through	27	28	27	33	30	22	33	30	0.56	1.2	1.1	0.53
		Right	21	15	21	34	22	9	22	45	0.22	1.73	0.22	1.75
		Left	51	57	87	18	42	51	71	25	1.32	0.82	1.8	1.51
	North	Return	22	8	21	8	17	9	19	11	1.13	0.34	0.45	0.97
		Through	7	6	2	3	8	7	1	3	0.37	0.39	0.82	-
		Left	4	5	4	4	6	4	3	2	0.89	0.47	0.53	1.15
	West	Right	2	5	3	3	2	3	6	3	-	1	1.41	-
		Through	294	309	266	278	291	306	263	276	0.18	0.17	0.18	0.12
		Left	44	79	42	27	33	63	32	19	1.77	1.9	1.64	1.67
	East	Return	7	9	8	5	3	6	5	4	1.79	1.1	1.18	0.47
		Through	320	380	303	314	317	377	300	311	0.17	0.15	0.17	0.17
		Right	64	64	51	32	80	55	43	39	1.89	1.17	1.17	1.17
	North	Return	35	44	52	42	41	42	41	49	0.97	0.3	1.61	1.04
		Left	96	80	119	120	84	71	101	102	1.26	1.04	1.72	1.71
		Right	106	101	130	94	126	121	147	84	1.86	1.9	1.44	1.06
Legehar	East	Through	331	351	357	376	360	360	374	352	1.56	0.48	0.89	1.26
		Right	36	35	31	23	34	32	28	21	0.34	0.52	0.55	0.43
		Left	28	28	30	28	35	22	41	23	1.25	1.2	1.85	0.99
		Return	55	67	73	66	65	72	72	64	1.29	0.6	0.12	0.25

Mesqel Square	West	Through	283	263	268	253	300	294	244	232	1	1.86	1.5	1.35
		Right	30	43	30	22	22	53	32	22	1.57	1.44	0.36	-
		Left	45	54	45	39	45	54	40	31	-	-	0.77	1.35
		Return	5	7	4	3	7	5	5	3	0.82	0.82	0.47	-
	South	Through	167	107	75	80	150	119	61	65	1.35	1.13	1.7	1.76
		Right	36	48	44	47	41	36	35	37	0.81	1.85	1.43	1.54
		Left	39	42	34	32	34	35	29	24	0.83	1.13	0.89	1.51
		Return	-	2	1	-	1	1	2	1	1.41	0.82	0.82	1.41
	North	Through	138	120	126	115	142	121	126	117	0.34	0.09	-	0.19
		Left	53	45	41	52	55	47	39	53	0.27	0.29	0.32	0.14
		Right	25	26	33	28	26	27	31	29	0.2	0.19	0.35	0.19
		Return	4	9	9	6	5	10	7	6	0.47	0.32	0.71	-
	East	Through	362	351	347	376	394	356	311	359	1.65	0.27	1.98	0.89
		Right	78	77	72	70	90	81	67	54	1.31	0.45	0.6	2.03
		Left	78	108	90	80	70	113	79	94	0.93	0.48	1.2	1.5
		Return	55	67	73	66	52	76	64	67	0.41	1.06	1.09	0.12
	West	Through	292	333	317	307	319	331	306	292	1.54	0.11	0.62	0.87
		Right	20	28	30	22	19	25	28	14	0.23	0.58	0.37	1.89
		Return	7	5	5	3	7	5	5	3	-	-	-	-
	South	Through	167	107	75	80	151	101	69	69	1.27	0.59	0.71	1.27
		Right	54	64	57	47	49	55	43	44	0.7	1.17	1.98	0.44
		Left	70	74	60	77	76	68	70	91	0.7	0.71	1.24	1.53
		Return	1	4	1	3	4	6	3	2	1.9	0.89	1.41	0.63
	North	Through	48	28	25	23	49	27	20	22	0.14	0.19	1.05	0.21
		Left	85	96	99	104	85	97	101	103	-	0.1	0.2	0.1

Right	45	48	51	55	41	52	53	49	0.61	0.57	0.28	0.83
Return	1	2	-	3	1	1	1	2	-	0.82	1.41	0.63

- **Source:** Primary data from researcher's video-based counts and SUMO simulations.
- **Note:** GEH values are calculated for each 15-minute interval (01:30:00–02:30:00 AM).

APPENDIXES C: STATISTICAL ANALYSIS

Statistical Analysis

Table 11: Tests of Within-Subjects Effects for Travel Time

Factor	DF	F	Prob>F	DF	F	Prob>F
	Mexico Square	Square to Mesqel		Mesqel Square	Square to Mexico	
Sphericity Assumed	3	143.73	<0.0001	3	48.753	<0.0001
Greenhouse-Geisser	2.353	143.73	<0.0001	2.477	48.753	<0.0001
	Winget to Asko Square			Asko Square to Winget		
Sphericity Assumed	3	27.1	<0.0001	3	110.44	<0.0001
Greenhouse-Geisser	2.33	27.1	<0.0001	1.548	110.44	<0.0001

Table 12: Pairwise Test (Tukey Test) Travel Time

Scenarios	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
Mexico Square to Mesqel Square					
BL - R1	0.006	<0.0001	1	0.005	0.007
BL - R2	0.008	<0.0001	1	0.007	0.009
BL - R3	0.009	<0.0001	1	0.008	0.01
R1 - R2	0.002	2.81E-04	1	0.001	0.003
R1 - R3	0.003	0.0014	1	0.002	0.004
R2 - R3	0	0.9164	0	0	0.002
Mesqel Square to Mexico Square					
BL - R1	-0.0041	<0.0001	1	-0.006	-0.002
BL - R2	-0.0045	<0.0001	1	-0.007	-0.002
BL - R3	-0.01	<0.0001	1	-0.012	-0.008
R1 - R2	-0.0004	0.96579	0	-0.003	0.002
R1 - R3	-0.0059	<0.0001	1	-0.008	-0.004
R2 - R3	-0.0055	<0.0001	1	-0.008	-0.003

Table 12-1: Pairwise Test (Tukey Test) Travel Time

Scenarios	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL
Winget to Asko Square					
BL - R1	0.001	0.0348	1	0	0.002
BL - R2	-0.002	<0.0001	1	-0.003	-0.001
BL - R3	-0.002	<0.0001	1	-0.003	-0.001
R1 - R2	-0.003	<0.0001	1	-0.004	-0.002
R1 - R3	-0.003	<0.0001	1	-0.004	-0.002
R2 - R3	-0.0001	0.9985	0	-0.001	0.001
Asko Square to Winget					
BL - R1	0.001	0.3555	0	-0.001	0.003
BL - R2	0.006	<0.0001	1	0.004	0.008
BL - R3	0.011	<0.0001	1	0.01	0.013
R1 - R2	0.005	<0.0001	1	0.003	0.006
R1 - R3	0.01	<0.0001	1	0.009	0.012
R2 - R3	0.006	<0.0001	1	0.004	0.008

Table 13: Descriptive Statistics (Speed)

Scenarios	Mean	95.00 % LCL	95.00 % UCL	Mean	95.00 % LCL	95.00 % UCL	Mean	95.00 % LCL	95.00 % UCL
Overall				Mexico Square to Mesqel Square			Mesqel Square to Mexico Square		
Baseline	12.685	12.329	13.041	9.038	8.364	9.711	12.329	12.592	14.597
R1	11.265	11.031	11.499	17.78	16.462	19.099	11.031	8.352	9.479
R2	10.947	10.577	11.317	20.609	19.142	22.076	10.577	12.824	16.604
R3	10.691	10.14	11.242	22.916	21.284	24.548	10.14	6.947	10.008
Overall				Winget to Asko Square			Asko Square to Winget		
Baseline	10.283	9.981	10.585	26.775	25.725	27.824	10.096	9.797	10.394
R1	10.605	10.31	10.899	28.168	26.459	29.876	11.73	11.015	12.443
R2	10.737	10.077	11.397	15.831	14.341	17.319	21.785	19.271	24.299
R3	20.08	19.562	20.598	22.021	20.985	23.056	43.164	42.318	44.008

Table 14: Tests of Within-Subjects Effects for Speed

Factor	DF	F	Prob>F	DF	F	Prob>F	DF	F	Prob>F
Overall				Mexico Square to Mesqel			Mesqel Square to Mexico Square		
Sphericity Assumed	3	25.35	<0.0001	3	102.79	<0.0001	3	25.575	<0.0001
Greenhouse-Geisser	1.718	25.35	<0.0001	2.764	102.79	<0.0001	2.307	25.575	<0.0001
Overall				Winget to Asko Square			Asko Square to Winget		
Sphericity Assumed	3	535.235	<0.0001	3	78.917	<0.0001	3	535.235	<0.0001
Greenhouse-Geisser	2.388	535.235	<0.0001	2.59	78.917	<0.0001	2.388	535.235	<0.0001

Table 15: Pairwise Test (Tukey Test) for Speed

Scenarios	Overall (Mexico Square - Mesqel Square Road)				
	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	1.4202	<0.0001	1	0.77159	2.06881
BL - R2	1.7382	<0.0001	1	1.08959	2.38681
BL - R3	1.9944	<0.0001	1	1.34579	2.64301
R1 - R2	0.318	0.58221	0	-0.33061	0.96661
R1 - R3	0.5742	0.10282	0	-0.07441	1.22281
R2 - R3	0.2562	0.73534	0	-0.39241	0.90481
Scenarios	Mexico Square to Mesqel Square Route				
	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	-8.743	<0.0001	1	-10.94	-6.545
BL - R2	-11.572	<0.0001	1	-13.769	-9.374
BL - R3	-13.878	<0.0001	1	-16.075	-11.681
R1 - R2	-2.829	0.006	1	-5.026	-0.632
R1 - R3	-5.136	<0.0001	1	-7.333	-2.938
R2 - R3	-2.307	0.036	1	-4.504	-0.109
Scenarios	Mesqel Square to Mexico Square Route				
	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	4.679	<0.0001	1	2.366	6.992
BL - R2	-1.12	0.593	0	-3.432	1.193
BL - R3	5.117	<0.0001	1	2.804	7.43
R1 - R2	-5.798	<0.0001	1	-8.111	-3.485
R1 - R3	0.438	0.961	0	-1.875	2.751
R2 - R3	6.236	<0.0001	1	3.923	8.549

Table 15-1: Pairwise Test (Tukey Test) for Speed

Scenarios	Overall (Winget to Asko Square Road)				
	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	-0.3216	0.6886	0	-1.0783	0.4351
BL - R2	-0.4536	0.4073	0	-1.2103	0.3031
BL - R3	-9.7968	<0.0001	1	-10.5535	-9.0401
R1 - R2	-0.132	0.9691	0	-0.8887	0.6247
R1 - R3	-9.4752	<0.0001	1	-10.2319	-8.7185
R2 - R3	-9.3432	<0.0001	1	-10.0999	-8.5865
Scenarios	Winget to Asko Square Route				
	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	-1.393	0.398	0	-3.694	0.908
BL - R2	10.944	<0.0001	1	8.644	13.245
BL - R3	4.754	<0.0001	1	2.453	7.055
R1 - R2	12.338	<0.0001	1	10.037	14.639
R1 - R3	6.147	<0.0001	1	3.846	8.448
R2 - R3	-6.191	<0.0001	1	-8.492	-3.89
Scenarios	Asko Square to Winget Route				
	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	-1.634	0.379	0	-4.277	1.009
BL - R2	-11.69	<0.0001	1	-14.332	-9.047
BL - R3	-33.068	<0.0001	1	-35.711	-30.425
R1 - R2	-10.056	<0.0001	1	-12.698	-7.413
R1 - R3	-31.434	<0.0001	1	-34.077	-28.791
R2 - R3	-21.379	<0.0001	1	-24.021	-18.736

Table 16: Descriptive Statistics (Time Loss)

Scenarios	Mexico Square to Mesqel Square			Mesqel Square to Mexico Square		
	Mean	95.00% LCL	95.00% UCL	Mean	95.00% LCL	95.00% UCL
TL- BL -2	0.011	0.010	0.011	0.007	0.006	0.008
TL-R1-2	0.006	0.005	0.007	0.011	0.011	0.012
TL-R2-2	0.003	0.003	0.004	0.011	0.010	0.013
TL-R3-2	0.003	0.002	0.003	0.017	0.016	0.018
Scenarios	Winget to Asko Square			Asko Square to Winget		
	Mean	95.00% LCL	95.00% UCL	Mean	95.00% LCL	95.00% UCL
TL-Ex-2	0.004	0.003	0.004	0.012	0.012	0.013
TL-R1-2	0.003	0.003	0.003	0.011	0.010	0.012
TL-R2-2	0.006	0.005	0.006	0.007	0.005	0.008
TL-R3-2	0.005	0.005	0.005	0.001	0.001	0.001

Table 17: Tests of Within-Subjects Effects for Time Loss

Factor	Mexico Square to Mesqel Square			Mesqel Square to Mexico Square		
	DF	F	Prob>F	DF	F	Prob>F
Sphericity Assumed	3	120.918	<0.0001	3	55.29917	<0.0001
Greenhouse-Geisser	2.179	120.918	<0.0001	2.386	55.29917	<0.0001
Factor	Winget to Asko Square			Asko Square to Winget		
	DF	F	Prob>F	DF	F	Prob>F
Sphericity Assumed	3	41.800	<0.0001	3	109.56967	<0.0001
Greenhouse-Geisser	2.140	41.800	<0.0001	1.547	109.56967	<0.0001

Table 18: Pairwise Test (Tukey Test) Time Loss

Scenarios	Mexico Square to Mesqel Square					
	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL	
BL - R1	0.005	<0.0001	1	0.004	0.006	
BL - R2	0.007	<0.0001	1	0.006	0.008	
BL - R3	0.007	<0.0001	1	0.007	0.009	
R1 - R2	0.002	<0.0001	1	0.001	0.004	
R1 - R3	0.002	<0.0001	1	0.002	0.004	
R2 - R3	0.000	0.479	0	-0.001	0.002	
Scenarios	Mesqel Square to Mexico Square					
	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL	
BL - R1	-0.004	<0.0001	1	-0.006	-0.002	
BL - R2	-0.004	<0.0001	1	-0.006	-0.002	
BL - R3	-0.010	<0.0001	1	-0.012	-0.008	
R1 - R2	0.000	0.999	0	-0.002	0.002	
R1 - R3	-0.006	<0.0001	1	-0.008	-0.004	
R2 - R3	-0.006	<0.0001	1	-0.008	-0.004	
Scenarios	Winget to Asko Square					
	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL	
BL - R1	0.001	0.011	1	0.000	0.002	
BL - R2	0.006	<0.0001	1	0.004	0.008	
BL - R3	0.011	<0.0001	1	0.010	0.013	
R1 - R2	0.005	<0.0001	1	0.003	0.006	
R1 - R3	0.010	<0.0001	1	0.009	0.012	
R2 - R3	0.006	<0.0001	1	0.004	0.008	
Scenarios	Asko Square to Winget					
	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL	
BL - R1	0.001	0.440	0	-0.001	0.003	
BL - R2	0.006	<0.0001	1	0.004	0.008	
BL - R3	0.011	<0.0001	1	0.010	0.013	
R1 - R2	0.005	<0.0001	1	0.003	0.006	
R1 - R3	0.010	<0.0001	1	0.009	0.012	
R2 - R3	0.006	<0.0001	1	0.004	0.008	

Table 19: Descriptive Statistics (Traffic Volume)

Scenarios	Mexico Square to Mesqel Square			Mesqel Square to Mexico Square		
	Mean	95.00% LCL	95.00% UCL	Mean	95.00% LCL	95.00% UCL
BL	11.902	8.603	15.200	15.475	13.419	17.532
R1	11.803	8.021	15.585	10.607	8.741	12.472
R2	10.639	7.233	14.045	7.918	6.594	9.242
R3	11.311	7.535	15.088	6.525	5.121	7.928
Scenarios	Winget to Asko Square			Asko Square to Winget		
	Mean	95.00% LCL	95.00% UCL	Mean	95.00% LCL	95.00% UCL
BL	5.350	4.333	6.367	11.600	9.709	13.491
R1	5.350	4.078	6.622	8.617	7.374	9.860
R2	6.133	4.398	7.869	11.900	9.335	14.465
R3	7.117	5.559	8.675	11.867	9.511	14.223

Table 20: Tests of Within-Subjects Effects for Traffic Volume

Factor	Mexico Square to Mesqel Square			Mesqel Square to Mexico Square		
	DF	F	Prob>F	DF	F	Prob>F
Sphericity Assumed	3	0.104	0.958	3	21.594	<0.0001
Greenhouse-Geisser	1.1492	0.104	0.783	2.3649	21.594	<0.0001
Factor	Winget to Asko Square			Asko Square to Winget		
	DF	F	Prob>F	DF	F	Prob>F
Sphericity Assumed	3	1.455	0.229	3	2.509	0.060
Greenhouse-Geisser	2.5748	1.455	0.233	2.3834	2.509	0.075

Table 21: Pairwise Test (Tukey Test) Traffic Volume

Scenarios	Mexico Square to Mesqel Square				
	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	0.098	1	0	-6.464	6.661
BL - R2	1.262	0.959	0	-5.3	7.825
BL - R3	0.59	0.996	0	-5.972	7.152
R1 - R2	1.164	0.968	0	-5.398	7.726
R1 - R3	0.492	0.997	0	-6.07	7.054
R2 - R3	-0.672	0.993	0	-7.234	5.89
Scenarios	Mesqel Square to Mexico Square				
	Mean Difference	Prob.	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	4.869	0	1	1.755	7.982
BL - R2	7.557	<0.0001	1	4.444	10.671
BL - R3	8.951	<0.0001	1	5.837	12.064
R1 - R2	2.689	0.117	0	-0.425	5.802
R1 - R3	4.082	0.005	1	0.969	7.195
R2 - R3	1.393	0.652	0	-1.72	4.507

Table 21-1: Pairwise Test (Tukey Test) Traffic Volume

Scenarios	Winget to Asko Square				
	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	0	1	0	-2.55	2.55
BL - R2	-0.783	0.856	0	-3.333	1.766
BL - R3	-1.767	0.278	0	-4.316	0.783
R1 - R2	-0.783	0.856	0	-3.333	1.766
R1 - R3	-1.767	0.278	0	-4.316	0.783
R2 - R3	-0.983	0.749	0	-3.533	1.566
Scenarios	Asko Square to Winget				
	Mean Difference	Prob	Sig Flag	95.00% LCL	95.00% UCL
BL - R1	2.983	0.157	0	-0.703	6.67
BL - R2	-0.3	0.997	0	-3.986	3.386
BL - R3	-0.267	0.998	0	-3.953	3.42
R1 - R2	-3.283	0.1	0	-6.97	0.403
R1 - R3	-3.25	0.105	0	-6.936	0.436
R2 - R3	0.033	1	0	-3.653	3.72

Publishable Article

Implementation Challenges of Reversible Lanes in Urban Traffic Management: A Case Study of Addis Ababa, Ethiopia

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ABSTRACT

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Reversible lanes are increasingly being considered as a solution to urban traffic congestion, particularly in cities with significant directional traffic imbalances. However, their implementation presents significant challenges, especially in resource constrained and densely populated urban areas. This study evaluates the implementation challenges of reversible lanes in Addis Ababa, Ethiopia, using SUMO (Simulation of Urban Mobility) to model traffic flow on two major corridors: Askto to Winget and Mexico to Mesqel Square. The findings identified critical challenges, including driver confusion and safety risks, public transport disruption, and integration challenges. The study provides practical recommendations, such as adopting adaptive signal systems, increasing public awareness, and conducting simulation based planning, to address these challenges. These insights provide valuable guidance for policymakers and

urban planners seeking to implement reversible lanes in similar contexts.

Keywords:

Reversible Lanes, Urban Traffic Management, SUMO Simulation, Adaptive Signal Systems, Public Transport Disruption, Traffic Safety, Addis Ababa

Introduction

Urban traffic congestion is a growing challenge in cities worldwide, particularly in rapidly urbanizing cities like Addis Ababa, Ethiopia (World Bank, 2020). Reversible lanes, which reallocate road capacity with respect to traffic demand, have been proposed as a cost-effective solution to mitigate congestion (Gayah & Daganzo, 2012). While studies have demonstrated their effectiveness in reducing travel times and improving traffic flow, the implementation challenges of reversible lanes remain understudied, especially in developing cities with complex traffic patterns and limited infrastructure (Zhang et al., 2019).

This study focuses on Addis Ababa, Ethiopia, a city experiencing severe

traffic congestion due to rapid urbanization and inadequate road infrastructure (Gunjo et al., 2024). SUMO simulations are used to evaluate the implementation challenges of reversible lanes on two major corridors: Askto to Winget and Mexico to Mesqel Square.

The research addresses the following questions: What are the primary challenges associated with implementing reversible lanes in Addis Ababa, and how can these challenges be resolved to ensure successful implementation? By addressing these questions, the study aims to provide practical insights for policymakers and urban planners, contributing to the broader discourse on sustainable urban mobility.

Method and Methodology

The study focuses on two major corridors in Addis Ababa: Asko to Winget, a 3.5 km route with fewer intersections and noticeable directional traffic imbalances, which connect the peripheral area of the city to the center and Mexico to Mesqel Square, a 1.5 km route with high intersection density and balanced traffic flows, and located on the central business district. SUMO (Simulation of Urban Mobility) was used to model traffic flow under four scenarios: Baseline (existing traffic conditions), R1 (one reversible lane), R2 (two reversible lanes), and R3 (three reversible lanes). Traffic count data, OpenStreetMap (OSM) and field survey are used as primary data sources. Multiple simulations are run and key metrics are analyzed including safety (collisions, emergency braking, and wrong-lane teleports), efficiency (travel time, average speed, and time loss), and integration (spillover congestion on adjacent roads).

Data and Findings

The simulation results revealed several critical challenges to implementing reversible lanes in Addis Ababa. First,

driver confusion and safety risks were significant, with collisions increasing by 18% in Scenario R2 on Mexico to Mesqel Square and wrong-lane teleports surging by 42% in Scenario R2 on Asko to Winget. Additionally, emergency braking events also spiked by 45% in Scenario R2 on Mexico to Mesqel Square, indicating increased risks during lane reversals.

Second, reversible lanes disrupted public transport systems, particularly buses and minibuses. Bus delays increased by 18% in Scenario R2 on Mexico to Mesqel Square, while detours to avoid reversible lanes added 1.2 km to average bus trip distances. This disruption not only reduced the efficiency of public transport but it potentially increase operational costs.

Third, integration challenges were evident, as reversible lanes caused spillover congestion on adjacent roads. Average speed on nearby roads decreased by 14%, while traffic volume on parallel routes increased by 22% as drivers sought alternatives to avoid reversible lane sections.

Finally, the operational costs of reversible lanes were substantial.

Traffic light switching frequency increased by 35% in adaptive signal scenarios. These findings highlight the financial and technical obstacles to implementing reversible lanes in cities with limited resources like Addis Ababa.

Discussion

The findings underscore the complexity of implementing reversible lanes in urban environments like Addis Ababa. Driver confusion and safety risks, illustrated by increased collisions and wrong-lane teleports, underline the need for clear signage, public awareness campaigns, and strict enforcement. The disruption to public transport systems, particularly buses and minibuses, emphasizes the importance of integrating reversible lanes with public transport schedules to minimize adverse impacts on the public, which would have contribution on public acceptance of the change.

Spillover congestion on adjacent roads demonstrates the need for holistic traffic management strategies that consider the broader road network. The high operational costs of adaptive signal systems and dynamic

infrastructure further underscore the financial and technical challenges of implementing reversible lanes in resource constrained cities. These challenges align with existing literature, such as Chiu et al. (2007) on intersection complexity and Litman (2023) on equitable road space distribution. However, this study provides novel insights by quantifying these challenges in a real-world context and offering actionable recommendations.

Conclusion

This study demonstrates that while reversible lanes can effectively alleviate congestion in corridors with significant directional imbalances, their implementation in complex urban environments like Addis Ababa poses critical challenges. Key obstacles include driver confusion, public transport disruption, integration complexities, and high operational costs. To address these challenges, the study recommends adopting adaptive signal systems to enhance traffic flow responsiveness, launching public awareness campaigns to improve driver compliance and safety, integrating

reversible lanes with public transport schedules to minimize disruptions, and conducting simulation based planning to evaluate impacts on adjacent roads and optimize lane configurations.

These recommendations provide a roadmap for policymakers and urban planners seeking to implement reversible lanes in Addis Ababa and similar cities. By addressing the identified challenges, cities can benefit from reversible lanes in reducing traffic congestion while minimizing investment.

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