MEKELLE UNIVERSITY
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SCHOOL OF COMPUTING
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LEVERAGING INTERNET OF THINGS (IOT) TO ENHANCE TRAFFIC MANAGEMENT SYSTEMS IN MEKELLE CITY

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BY

HAFTAMU HAILU

ADVISOR LETTER

E-mail letters to:

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To whom it may concern:

I have read the thesis of ________________________ and it is complete and ready to defend.

Sincerely,

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Advisor

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DECLARATION

I, the undersigned, hereby declare that this work is based on the results found by myself. Where other sources of information have been used, they have been acknowledged by reference. This work, neither in whole nor in part, has been previously submitted for any degree in any universities.

Haftamu Hailu ________________________

Name (Student) ***Signature***

Place: Mekelle

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This thesis has been submitted with my approval as a university advisor.

Fitusm* Gebreegziabher *(PhD) ________________________

Advisor Name ***Signature***

Dedicated to

My beloved Family

Abstract

Rapid urbanization and motorization in Mekelle City have created significant traffic management challenges, including recurrent congestion, road safety concerns, and inefficient manual control systems. Conventional traffic management approaches, which rely on fixed signal timing and limited real-time monitoring, have proven inadequate in addressing these issues. This study investigates the potential of leveraging the Internet of Things (IoT) to enhance traffic management systems in Mekelle City.

A mixed-methods research design was employed, combining surveys, interviews, and simulation experiments. Primary data were collected from 102 road users and key stakeholders such as traffic police and urban planners, while secondary data were obtained from government reports and existing literature. A synthetic simulation was conducted to compare the performance of traditional fixed-time traffic signals with IoT-enabled adaptive signal control.

The results demonstrate that the IoT-adaptive control strategy significantly reduces average queue length and vehicle delay while increasing throughput compared to the baseline fixed-time model. Specifically, average delays decreased by over 13 seconds per vehicle, while overall throughput improved. Survey findings further revealed strong public support for IoT-based traffic monitoring and violation detection systems, though opinions were divided on broader integration with cloud-based platforms and navigation services.

The study concludes that IoT-enabled adaptive traffic management systems offer a feasible and impactful solution for Mekelle City, capable of improving mobility, reducing environmental impacts, and enhancing commuter safety. However, challenges remain, including infrastructure readiness, cost implications, and the need for comprehensive policy support. The research recommends a pilot deployment at major intersections, followed by phased city-wide implementation, integration with public transport systems, and further microscopic simulation using locally calibrated data.

This work contributes to the growing field of smart city research in low-resource settings by providing an evidence-based framework for IoT-driven traffic management in Ethiopia.

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First and foremost, I would like to express my deepest gratitude to my advisor, **Dr. Fitsum** Gebreegziabher, for his invaluable guidance, unwavering patience, and insightful feedback throughout the entire process of this research. His expertise and encouragement were instrumental in shaping this thesis.

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Haftamu Hailu Chekole
Mekelle, Ethiopia
August 2025

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List of Acronyms and Abbreviations

AI - Artificial Intelligence

ANPR - Automatic Number Plate Recognition

ATM - Adaptive Traffic Management System

ATCSs - Adaptive Traffic Control Systems

CCTV - Closed-Circuit Television

DBSCAN - Density-Based Spatial Clustering of Applications with Noise

ERA - Ethiopian Roads Authority (used in the context of your study)

GDP - Gross Domestic Product

GPS - Global Positioning System

IoE - Internet of Everything

IoV - Internet of Vehicles

IoT - Internet of Things

IRB - Institutional Review Board (Implied by "ethical research standards")

ITS - Intelligent Transportation System

Li-Fi - Light Fidelity

LSTM - Long Short-Term Memory (a type of AI model)

M2M - Machine-to-Machine

PSV - Public Service Vehicle (used in the context of your study)

RFID - Radio Frequency Identification

SCOOT - Split, Cycle, and Offset Optimization Technique

STMS - Smart Traffic Management System

SVM - Support Vector Machine (a type of AI model)

SUMO - Simulation of Urban MObility (a traffic simulation software)

UTMC - Urban Traffic Management and Control

VISSIM - A traffic simulation software package (proprietary name)

VLC - Visible Light Communication

WSN - Wireless Sensor Network

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Consider a city where all of the utilities, traffic signals, and streetlights are smoothly integrated to improve everyday living and cutting-edge technologies. Through the integration of digital solutions and smart infrastruc. This is the essence of a smart city: a livable, sustainable, and efficient urban environment made possible by the use of data ture, these cities want to produce an urban environment that is more efficient and responsive.

This revolution is centered on the Internet of effects (IoT), a network of networked bias that gathers, partake, and use ambient data. IoT links the physical and digital worlds, enabling bias like smart business signals that acclimate to changing business circumstances and environmental quality detectors to record data.

The Internet of Things (IoT) presents an opportunity to revolutionize traffic management by enabling real-time data collection, smart traffic signal control, predictive analytics, and automated incident detection. IoT-based solutions can optimize traffic flow, reduce delays, enhance road safety, and minimize environmental impacts.

Mekelle City, the capital of the Tigray Regional State in Ethiopia, has seen rapid urbanization and motorization over the past decade. With increasing population density, vehicle ownership, and infrastructural constraints, the city faces serious transportation challenges including traffic congestion, high accident rates, and inadequate pedestrian safety measures. Traditional traffic management systems, which are largely manual and reactive, have proven insufficient.

Meanwhile, the emergence of the Internet of Things (IoT) has introduced powerful capabilities for real-time monitoring and intelligent control across various sectors. In traffic systems, IoT enables data collection through sensors and smart devices, decentralized decision-making, and real-time interventions. Cities like Barcelona and Singapore have successfully adopted IoT-based traffic systems, resulting in measurable reductions in congestion and environmental impact. Mekelle, though currently lacking such infrastructure, presents a valuable opportunity for implementation of a pilot smart traffic system.

1.2. Problem Statement

The current traffic management system in Mekelle is characterized by inefficient signal timing, absence of real-time monitoring, uncoordinated public transport, and poor pedestrian infrastructure. These limitations have led to increased commute times, frequent traffic violations, and road accidents. There is a clear need for a modern, intelligent system that can adapt dynamically to traffic conditions and provide data for future planning. There the above mentioned problems in Mekelle town have initiated me to solve the problem

1.3 Objectives

1.3.1 General Objective:

To design and evaluate an IoT-based traffic management system aimed at improving urban mobility and safety in Mekelle City.

1.3.2 Specific Objectives:

- To assess existing traffic patterns and infrastructure in Mekelle.
- To analyze current traffic conditions and challenges in Mekelle
- To design an IoT-based framework incorporating sensors, edge devices, and cloud analytics.
- To implement a pilot system at selected intersections.
- To evaluate the system's effectiveness in terms of reduced congestion and improved safety.
- To provide policy recommendations for city-wide adoption.

1.4 Research Questions

- What are the major contributors to traffic congestion in Mekelle?
- How can IoT technology be applied to traffic management in Mekelle City?
- What are the key challenges in implementing an IoT traffic management system locally?
- How can IoT technologies be leveraged to monitor and control traffic more effectively?
- What infrastructure is required to implement such a system in Mekelle?
- What are the expected impacts on travel time, safety, and traffic violations?

- Will the IoT-based Systems improve traffic flow and reduce congestion compared to current methods?

1.5 Significance of the Study

This research will contributes to the growing field of smart urban mobility by proposing a localized solution tailored to the needs of an Ethiopian city. It also offers insights for policymakers, urban planners, and technologists interested in scalable smart city solutions in low-resource settings.

1.6 Scope and Limitations

1.6.1 Scope

The study focuses on vehicular and pedestrian traffic within Mekelle's core commercial districts. The proposed solution includes only basic public transport integration and does not address freight or intercity traffic.

1.6.2 Limitation

Budgetary constraints and limited internet connectivity may restrict the scale of implementation.

1.7 Research Methodology

This study employed a pragmatic research philosophy, utilizing a mixed-methods approach to comprehensively address the research objectives. This design was chosen to triangulate findings, thereby enhancing the validity and reliability of the results by combining quantitative traffic performance data with qualitative insights from stakeholders.

1.7.1 Research Conceptual Framework

The conceptual framework for this research is built upon the input-process-output model, guided by the principles of IoT-driven smart city solutions.

These included the existing traffic infrastructure of Mekelle City, real-time and historical traffic data (vehicle volume, queue length, delay times), and stakeholder perceptions (commuters, traffic police, urban planners). The core process involved the design and simulation of an IoT-based adaptive traffic control system. This system processes real-time data from sensors, applies optimization algorithms (inspired by systems like SCOOT), and outputs dynamic traffic signal timings. The expected outputs were measurable improvements in key performance indicators (KPIs) such as reduced average vehicle delay, shorter queue lengths, increased throughput, and enhanced stakeholder satisfaction with the traffic management system.

This framework posits that integrating IoT sensors, edge computing, and cloud analytics into Mekelle's traffic infrastructure will directly lead to more efficient and adaptive traffic management outcomes.

1.7.2 Research Process

The research was executed in a sequential, phased process:

A comprehensive review of existing literature on IoT, conventional traffic systems, and smart traffic solutions was conducted to identify the knowledge gap and define the specific problem for Mekelle City. The study area (key intersections in Mekelle) was identified. Sampling strategies for surveys and interviews were designed, and data collection instruments were developed. Quantitative data was gathered through manual traffic counting at selected intersections. Qualitative data was collected via surveys from commuters and structured interviews with traffic police and urban planners. A simulation model replicating Mekelle's traffic conditions was built. A baseline scenario (current fixed-time system) and an intervention scenario (IoT-adaptive system) were defined. Quantitative data from simulations and surveys were analyzed using descriptive and comparative statistics. Qualitative data from interviews were analyzed using thematic analysis. The results from the quantitative and qualitative analyses were interpreted together to draw conclusions and validate the proposed IoT framework's effectiveness and feasibility. The findings, conclusions, and recommendations were compiled into this thesis document.

1.7.3 Data Collection Methods

Data were gathered from multiple sources to ensure a holistic understanding:

- **Primary Data:**

Structured questionnaires were administered to 102 road users (private and public transport drivers) to capture their experiences, perceptions of congestion causes, and acceptance of IoT-based solutions. Semi-structured interviews were conducted with key informants, including traffic police officers and city urban planners, to gain expert insights into operational challenges and implementation barriers. Manual traffic counting was performed at peak and off-peak hours at major intersections to establish baseline traffic volumes and pattern Performance data (delay, queue length, throughput) was generated from the simulation models for both the baseline and IoT scenarios.

Secondary Data: Traffic volume reports and city planning documents were obtained from the Ethiopian Roads Authority (ERA) and the Mekelle City Administration to support the analysis of existing conditions.

1.7.4 Tools

The following tools and software were utilized in this research:

- **Simulation Software:** SUMO (Simulation of Urban MObility) was used to model traffic flow and test the performance of the adaptive signal control algorithm.
- **Data Analysis:** Microsoft Excel were used for statistical analysis and visualization of survey and traffic data.
- **Design:** Diagrams and conceptual frameworks were created using Microsoft Visio

1.8 Thesis Outline

This thesis is organized into five main chapters:

- **Chapter One: Introduction** presents the background, problem statement, research objectives, questions, significance, scope, and limitations of the study.
- **Chapter Two: Literature Review** critically examines existing scholarly work on IoT, conventional traffic systems, smart traffic solutions, and identifies the knowledge gap this research aims to fill.
- **Chapter Three: Research Methodology** details the research design, study area, population and sampling techniques, data sources, collection methods, simulation setup, and data analysis techniques employed.
- **Chapter Four: Data Analysis, Results, and Discussion** presents the findings from the surveys, interviews, and traffic simulations, providing an interpretation and discussion of the results in relation to the research objectives.
- **Chapter Five: Conclusion and Recommendation** summarizes the key findings, states the conclusions drawn from the study, acknowledges its limitations, and provides practical recommendations for implementation and suggestions for future research.

CHAPTER TWO: LITRATURE REVIEW

2.1 Concept of IoT

The Internet of Things (IoT), also sometimes referred to as the Internet of Everything (IoE), consists of all the web-enabled devices that collect, send, and act on data they acquire from their surrounding environments using embedded sensors, processors, and communication hardware. These devices, often called "connected or smart" devices, can sometimes talk to other related devices, a process called machine-to-machine (M2M) communication, and act on the information they get from one an- other (Hegde & Deekshith 2019, 154). Humans can interact with the gadgets to set them up, give them instructions, or access the data, but the devices do most of the work on their own without human intervention.

Smart traffic systems worldwide showcase the transformative power of IoT and AI integration. Alibaba's City Brain, deployed first in Hangzhou, China (2016), uses AI-driven analytics and camera feeds to control traffic lights and detect accidents, yielding a 15% increase in traffic speed in pilot districts before scaling citywide—and expanding to cities like Kuala Lumpur Wikipedia.

Europe also leads with integrated solutions. The UK's Urban Traffic Management and Control (UTMC) framework enables diverse systems—such as ANPR cameras, traffic signals, and air quality sensors—to communicate via shared platforms for centralized control Wikipedia. In Amsterdam, the Smart City initiative (since 2009) links real-time traffic monitoring, flexible lighting, and parking solutions to optimize urban flow Wikipedia.

Cities in the U.S. and beyond are leveraging machine learning at the edge for efficient traffic forecasting. For instance, Aimsun Live, used in San Diego and France, combines real-time data with simulations to forecast future network patterns and guide control decisions Wikipedia. Additionally, research like "Enhancing Urban Mobility: Integration of IoT Road Traffic Data and AI" (2023) demonstrates the efficacy of machine learning techniques—such as SVMs and LSTM networks—for short- and long-term traffic prediction ResearchGateijeecs.iaescore.com.

Across Africa, the rush toward smart urban systems is gaining traction. Telecom operators are integral, deploying 4G/5G infrastructure that enables IoT connectivity for applications like traffic monitoring, smart parking, and public safety—seen in innovations across Cairo, Lagos, Kigali, and Abidjan telecomreviewafrica.com.

Kenya's Nairobi Urban Transport Improvement Programme introduced a real-time ITS using IoT and machine learning to adapt signal timing and disseminate traffic updates, successfully reducing congestion ResearchGate.

Similarly, other Kenyan research frameworks propose IoT-based traffic systems to address parking scarcity, congestion, and accident detection, recommending integrations like RFID, Wi-Fi, and cloud management repository.anu.ac.ke.

A practical deployment named IBM Street Sense installed smartphone sensors in Nairobi's waste vehicles, using real-time analytics to uncover traffic slowdowns and hazards like potholes, demonstrating the benefits of IoT for urban mobility beyond traditional traffic systems Asia Growth Partners.

Specific Ethiopia-focused studies remain sparse in the literature. However, broader smart city initiatives—like IoT-enhanced security systems and pilot smart traffic lights in Addis Ababa—highlight growing exploratory applications telecomreviewafrica.com. As such, Mekelle offers a prime setting to advance Ethiopia's smart mobility research by adapting global and regional best practices to local infrastructure conditions.

Moreover, research on data sourcing challenges in Accra underscores the importance of integrating varied datasets (OpenStreetMap, private providers) to overcome road network data gaps—providing relevant methodological guidance for Mekelle Cambridge University Press & Assessment

Congestion falls into three categories, which include: recurring, non-recurring, and pre-congestion (Chow et al., 2013). Recurring congestion is when congestion occurs at a specific time and location, and a motorist is privy and finds ways on how to avoid it. Non-recurring congestion happens at a particular time when the circumstances are not definite. The congestion is not anticipated and makes it worse than recurring congestion as it adds up to the existing congestion without a solution. Pre-congestion occurs where a motorist who uses a given route understands that there is congestion and re-routes to a less congested road (Popoola & Adeniji, 2013). The result is the formation of 'new' congestion on existing road congestion.

Costs of congestion involve increased travel time and reduced speeds, which impose a fee on commuters (Popoola & Adeniji, 2013). The costs of congestion exist in two categories. Direct cost results are easily observable when there are delays when the road network is congested. The vehicles idling longer than usual will increase the running and maintenance costs of the car. Indirect cost occurs when there is increased commodity price due to fuel price or death due to road accidents (Abdul-Wahab, 2013). The purchase of vehicles as a result of a rise in social income leads to less development as a result of traffic build up on the roads.

Efficient traffic management requires quantifiable ways to ascertain the condition and status of the road network (Chaple & Paygude, 2013). Values used in the measurement of traffic congestion exists in two categories: Basic measures and ratio measures. Basic measures estimate the delay time where the delay is the extra time taken for a given route, which is the additional time a commuter takes in a given road network.

This measure shows the effects on the entire transportation system when the delay time is reduced (Takyi et al., 2013). The calculation gives the real-time status of the road. The estimate of total vehicle delay is calculated as follows: -

The assumption made is that there is a definite time stamp required to traverse through a given road. The problem with total delay is that there must be a specific measurement for an acceptable time, and the measure will only be known when the delay occurs. Individuals who are stuck in traffic congestion makes it inefficient for them.

The derivation of ratio measures is from two factors of road congestion. The most popular ratio is the buffer index, which is calculated as follows: - The buffer index calculates the extra time in percentage a traveller is allowed to travel to make it on time. The 95th percentile travel rate and average travel rate is used rather than average travel time to mitigate the issue with trips (Francke & Kaniok, 2013). The buffers index is predictive, and it is crucial for people undertaking a journey whose calculation is as follows:

Traffic congestion solutions in western countries may not solve the causes of traffic congestion in Africa (EL-Kadi, 2013). Making money is the primary concern among transport operators than transporting the public. Buses and taxis break down as a result of overloading leading to traffic congestion. Implementation of extra charge for congestion systems necessitated the need for people whose preference was to cycle and walk to use a particular road network (Alvanides, 2014). Africa has not implemented such measures which incline pedestrians and cyclists to use the road (Alvanides, 2014). A motorist drives at a lower speed to avoid hitting the cyclist who cycles on the leading road network, eventually leads to congestion.

The African roads are in a dilapidated state due to financial constraints (Popoola & Adeniji, 2013). Motorists drive at a lower velocity, which leads to congestion. The poor road infrastructure makes motorists drive in inappropriate routes when avoiding potholes, which results in accidents and eventually leads to traffic congestion (Gachanja, 2015).

Below are examples of African cities that have addressed Traffic congestion.

Lagos: The former capital city of Nigeria, with a 3.9% annual population growth with the expectation of rising to 24 million in 2020 (Obia, 2016). Lagos is the third most in the list of popular cities in the world (Obia, 2016). 57% of commuters in Lagos spend 30 to 60 minutes stuck in a traffic jam (Popoola & Adeniji, 2013). Research has been done in Lagos to determine the causes of traffic congestion. The findings revealed that traffic congestion was as a result of an increase in the number of vehicles without an upgrade of the existing infrastructure of the road network (EL-Kadi, 2013). The findings also revealed that the use of smart traffic control system to monitor vehicles have a significant impact in reducing traffic congestion. It cautioned that the system should not be used in isolation but should complement the native traffic management system, such as the construction of flyovers and underpass.

Cairo: The government's initiative to subsidize fuel makes the city unique (EL-Kadi, 2013). The result is an increased number of vehicles as people can afford to maintain the cars and fuel them, which leads to an increase in travel time, which leads to traffic congestion (Abdul- Wahab, 2013). Cairo has a 4% GDP level as a result of the cost of congestion (EL-Kadi, 2013). A research conducted in Cairo reveals that the main problem of traffic congestion is an increase in vehicle ownership, mismanagement of traffic, and expansion of cities. A recommendation of the monorail was to replace micro-buses which traverses within the town.

Nairobi: Estimation of the Nairobi population will reach 5 million by the end of 2025. The estimations reveal that Nairobi will end up congested as the infrastructure remains unchanged (Budde, 2014). Over the past five years, the number of vehicles in Nairobi has increased steadily (Kinai et al., 2014). The cheap Japanese models have accelerated the importation of cars into the country. It has led to an increase in city cubs, which have increased the demand for the road network. Traffic congestion is made worse by careless drivers who are not privy to traffic rules and regulations. The existing traffic infrastructure remains the same, but the number of vehicles increases every day. Nairobi is a small city with buildings alongside major roads that make road expansion impossible (Gachanja, 2015). More innovative ways are required to deal with traffic congestion than the construction of road infrastructure (Raje et al., 2018).

The table shows the congestion statistics of African cities

Table 1: Congestion in Africa Citites

World Rank	Africa Rank	City, Country	Traffic Index	Time Index (minutes)
2	3	Nairobi, Kenya	313.11	71.05
5	7	Pretoria, South Africa	275.67	52.71
11	10	Cairo, Egypt	264.87	53.34
23	18	Johannesburg, South Africa	227.53	46.13
38	35	Cape Town, South Africa	198.69	41.60
97	71	Durban, South Africa	146.24	34.43

2.2 Conventional Traffic Management System

According to Elango et al. (2024), conventional traffic management systems refer to a traditional method of controlling traffic flow on roads, typically relying on static traffic signal timings, fixed signage, and limited data collection, with minimal ability to adapt to changing traffic conditions in real-time, unlike more advanced "Intelligent Transportation Systems" (ITS) that utilize real-time data and dynamic adjustments to optimize traffic flow (Elango et al. 2024, 150). In response to the limitations associated with conventional traffic systems, smart traffic light systems have emerged as a transformative solution. Through the use of advanced technologies and real-time data analytics, smart traffic light systems offer dynamic traffic monitoring, adaptive signal control, and integration with smart infra- structure to improve traffic flow, enhance safety, and reduce congestion.

Smart traffic lights have made management and monitoring of vehicle a necessity in many countries (Budde, 2014). Two strategies used in the management of traffic include Fixed and real- time. Fixed traffic lights work with a definite time where the duration of the signal does not consider current status. Real-time traffic lights are adaptive to the real-time situation of the road. Specific variables, such as the count of cars, speed, and direction, determine the decision on how to manage traffic lights (Adunya, 2015).

Smart traffic management is a system that uses sensors and traffic signals to monitor and control traffic (Rizwan et al., 2016). Centrally managed sensors and traffic signals exist on the city's major roads. Smart traffic management improves traffic flow by giving priority to traffic according to real-time changes in traffic conditions. The system prioritizes vehicles that enter intersections and uses green split phasing to ensure the efficient flow of cars through the city. Nairobi city employs fixed traffic lights signals that are not responsive to the queue length of traffic (Gachanja, 2015).

Smart traffic control systems use a centralized system with the aid of cameras to determine the number of vehicles. The images captured by the systems inform the intelligent traffic control system of real-time traffic conditions on major highways. The system calculates the timing every two seconds to determine whether to adjust traffic lights activity. The system adapts and changes to improve the arrival time of buses and reduce the number of vehicles in slip lanes (Roy, et al., 2016).

Smart traffic signals reduced the inefficiency of traffic jams or vehicles waiting at an empty intersection. Interconnected intelligent traffic lights can use IoT devices to identify patterns in traffic conditions and thereby update the traffic signals in real-time. Smart traffic lights enhance traffic flow where sensors collect data and communicate with the centralized traffic systems, which generate traffic patterns. The timing of traffic lights is adjusted per real-time traffic Conditions and, therefore, not limited to constant timing traffic conditions (Javed & Pandey, 2014). Smart traffic signals assist drivers by providing the required driving speed to arrive at a particular road intersection when the light is green. It assists in traffic regulation and creates a concept of "always green traffic lights" (Javed & Pandey, 2014).

Nairobi city, as part of a smart traffic system, should leverage the use of big data and the internet of things. IoT in traffic management refers to intelligent connected devices that communicate with portable gadgets such as mobile phones which have a connection with either Bluetooth or WIFI (Bull et al., 2016. The transmitted data is via the internet to a central system for analysis. Big data analyses this data and uses it to improve traffic management and flow.

Smart cities embed IoT devices, which include sensors and detectors in their infrastructure throughout the city (Rizwan et al., 2016). IoT and Big data impact traffic management in many ways. IoT devices mounted in major roads collect data and conveys it to a massive data management center for analysis. The analysis presents optimal lighting patterns to the smart traffic control lights, which adapts to the changing traffic situations. Sensors mounted on the road guide the emergency team to the site of the accident, in the form of alerts (Francke & Kaniok, 2013).

Data collected through sensors ensure the efficiency of public transport. The effectiveness of public transport is slowed down by a variety of factors, which include weather conditions or accidents that occur along the bus route (Popoola & Adeniji, 2013). Real-time traffic data along the given routes assists traffic officials in identifying issues and taking the necessary measures to ensure smooth traffic flow. In the 20th century, the only way of traffic improvement and traffic congestion reduction was through physical infrastructure (Harriet et al., 2016). Improving on the existing road infrastructure is a complex, expensive and only offers a partial solution to the current problem.

Smart traffic systems can have a significant effect on traffic flow than the high cost of building a new road. The root problem of traffic congestion is addressed by analyzing traffic patterns and provide responsive feedback. They enhance the quality of life reduction of pollution and eventually save lives. Real-time information to drivers helps cities regulate traffic on a major road intersection.

One of the most significant infrastructure problems experienced by developing countries is traffic management (Abdul, 2013). Developed countries and smart cities are using IoT and big data to address the issue of traffic congestion (Budde, 2014). The preference for owning a

vehicle is rampant in major cities as commuters prefer using their means without taking consideration of the stature of public transportation. Commuters in developed cities overlook the element of money and prefer reaching their destination with the required comfort (Popoola & Adeniji, 2013).

Traffic congestion as a result of the increased number of vehicles is rampant in developing cities. Several countries are addressing this through the extraction of information from CCTV feeds and transmitting data to the city traffic management centres. Efficient traffic management results in a better flow of vehicles with fewer vehicles idling on the roads in the traffic jam. All this eventually leads to lower run time, less pollution, and efficient utilization of natural resources.

2.3 IoT-Based Smart Traffic Light Systems

Developed countries and smart cities are already using IoT to their advantage to minimize issues related to traffic. The culture of the car has been cultivated speedily among people in all types of nations where residents prefer to drive their own vehicle rather than public transport.

2.3.1 IoT in Adaptive Traffic Control

Researchers will developed an IoT-based intelligent traffic strategy to supervise significant congestion through centralized and decentralized domain controllers (Majumdar et al. 2021). The information- gathering component uses sensing devices, camera systems, and radiofrequency identification. Also, the application layer for the IoT allows management of the traffic lights and notifications based on on-road vehicle frequency and offers a routine update through a software system. In their study, Arshad et al. (2017) described an inspection for reducing false projections based on the “Rankine-Hugoniot” circumstance and an origin-destination traffic facility. In order to authenticate the effectiveness of the suggested framework, a model was established. The testing results prove that the suggested method can successfully supervise precision and framework latency traffic congestion (Arshad et al. 2017).

Studies have also used IoT-based linked vehicles to gather real-time data. The vehicle-to-vehicle con- nection supports individual vehicle surveillance, allowing precise collision-avoidance planning. A study on transportation systems in smart cities developed a perfected system for recognizing traffic patterns to configure on busy roads. The visual signal unit exhibits the ongoing traffic patterns and occurrences via notifications, indications, or color combinations (Priyanka et al. 2021, 571). In addition, studieshave suggested an expressive Internet of Vehicles (IoV) routing protocol, recognizing complex rela- tionships between automobiles, roadways, ecosystems, and pedestrian crossings (Hussein et al., 2018).

2.3.2 Cloud-Based Traffic Monitoring and Management

A cloud-based traffic monitoring and management system refers to a system that uses cloud computing to collect, analyze, and manage real-time traffic data from various sources like sensors, cameras, and GPS devices (Shashank et al. 2021, 185). This allows for efficient traffic flow optimization and control through data analysis and decision-making using algorithms. All these are then hosted on a remote cloud infrastructure instead of on-premise servers, essentially to enable intelligent traffic management using the scalability and processing power of the cloud.

2.3.3 Comparison Between Fixed-Timer and IoT-Integrated Traffic Lights

Conventional traffic management systems primarily rely on fixed-timer traffic lights, which operate based on preconfigured time intervals (Ariffin et al. 2021). These systems use a static control logic, meaning that the duration of each traffic signal phase remains constant regardless of actual traffic conditions. In contrast, IoT-integrated traffic lights use a dynamic control mechanism that adjusts signal timing based on real-time traffic data. Unlike fixed-timer traffic lights, which operate on predetermined schedules, IoT-based systems are designed to prioritize traffic lanes with higher congestion (Qasim et al. 2024).

Fixed-timer traffic lights cannot detect or react to unexpected changes, such as the arrival of emergency vehicles or sudden increases in traffic volume due to road incidents (Dimri et al. 2024, 102). This lack of adaptability often exacerbates congestion during peak hours and causes unnecessary delays during off-peak periods when traffic is minimal. IoT-integrated traffic lights, on the other hand, can be programmed to respond dynamically by detecting real-time changes in traffic patterns and adjusting the signal phases accordingly (Damadam et al. 2022). Fixed-timer traffic lights are relatively inexpensive to install and require minimal technological expertise for deployment. Conversely, IoT- integrated traffic lights involve a higher upfront investment, as they require microcontrollers, sensors, cloud infrastructure, and wireless communication technologies (Ramadhan et al. 2021, 542). Despite this initial cost, they are more cost-effective in the long term, community-wise.

2.4 Review of Existing Literature on Smart Traffic Light Solutions

As research on sustainable traffic solutions keeps increasing, studies on several aspects of smart traffic have been conducted. A study on image processing proposed an adaptive traffic light control system that uses image processing and image matching techniques to control the traffic in an effective manner by taking images of each lane at a junction. The density of traffic in the images at each junction is compared. The results showed that more time is allocated for the vehicles on the densest road to pass compared to other less dense roads (Meng et al. 2021). An edge operation detector is used to detect the density of traffic at each lane. A study conducted by Lilhore et al. (2022) presented the design and implementation of an adaptive traffic management system (ATM) based on ML and IoT. The design of the proposed system is based on three essential entities: vehicles, infrastructure, and events. The design utilizes various scenarios to cover all the possible issues of the transport system. The proposed ATM system also utilizes the machine-learning-based DBSCAN clustering method to detect any accidental anomaly (Lilhore et al. 2022). An Internet-of-Things (IoT)-based system has also been proposed for health care services to organize and to establish the traffic signaling and pick up a route under which road congestion.

The existing traffic control strategies include vehicle stop, average delay, travel time, queuing length, traffic volume, and vehicle speed. The traditional traffic signal collects data at predefined locations which are not deployable in a large scale of urban road networks (Santani, et al., 2015). The use of IoT enabled devices enhances traffic control management in significant road intersections controlled by traffic lights. The development of IoT computing systems requires a combination of several technologies. The following relevant technologies will assist in the development of IoT applications.

2.4.1 Radio Frequency Identification (RFID)

RFID is the primary technology for identifying objects uniquely. It makes integration into any purpose easy as a result of reduced size and cost. The transceiver microchip could be either passive or active, depending on its application. Active tags have an inbuilt battery since they have a continuous data signals emission while passive tags get activated when they are triggered (Karakostas, 2013). Active tags are usually costlier than passive tags and have a wide range of applications. An RFID system comprises of readers and associated RFID tags that emit specific identifying information such as location when it gets triggered by a signal. The emitted data signals are transmitted to the readers using radio frequencies, which passes to the processors for analyses.

2.4.2 Wireless Sensor Network (WSN)

A wireless sensor network is a connection of devices that have sensors that can identify the surroundings and use wireless links to convey information (Kumar et al., 2014). Multiple hops forward data to a sink that is available locally or connected to other networks through a gateway. The nodes can either be stationary, movable which are aware of their current location. WSN, combined with other technologies, can be used to alter the environment in which they operate.

2.4.3 Cloud Computing

Cloud computing is an intelligent computing technology that converges several servers into one cloud platform to allow sharing of resources between each other. The resources can be accessed remotely at any time and in any place (Aazamet al., 2014). Cloud computing is the most critical technology in IoT devices, which converges servers and increases the processing power of objects. The cloud computing technology provides adequate storage capacity for collected data. Combining IoT and cloud computing offer a significant advantage when deploying objects to large scale development

2.4.4 Networking Technologies

These technologies are responsible for the connection between different objects; therefore, they require a fast and effective network to handle many potential devices. For a wide range of transmission networks, 3G and 4G networks are the most popular networks. For short-range networks, Bluetooth and WIFI technologies are the most efficient technologies.

2.4.5 Nano Technologies

Nanotechnology is a small improved version of the things that are connected. It enables the development of devices by decreasing the consumption of a system where the nanometer scale is used as a sensor and an actuator just like a standard device. Nano components made from Nano devices define a new networking paradigm, which is the internet of Nano-things.

2.4.5 Optical Technologies

The development of IoT devices is a result of drastic developments in optical technologies such as Li-Fi and Cisco's Bidi optical technology (Omina, 2015). Li-Fi, an epoch-making Visible Light Communication (VLC) technology, provides excellent connectivity on high bandwidth for IoT connected objects.

2.4.6 IoT solutions for Smart Traffic control

The Adaptive Traffic Control Systems (ATCSs) is the third generation of urban signal control systems after the fixed time coordinated signal systems (Misbahuddin, et al., 2015). ATCSs use real-time traffic data collected from IoT devices, unlike the centralized signal control system. The significant difference between ATCSs and constant timing of traffic lights is the adaptive nature of ATCSs to the real traffic flow.

Arrival time for vehicles at a road intersection is stochastic. Vehicles arrive one at a time or in batches. Inter arrival time varies between the different times of the day with various traffic conditions and the physical layout of the road and lanes (Kiunsi, 2013). For efficiency of traffic flow, real-time traffic signals must proactively respond to arrival streams to minimize vehicle stops and delays as much as possible. The SCOOT model will be discussed in detail and justify the proposed solution.

2.4.7 SCOOT (Split Cycle Offset Optimization Technique)

It is the most popular adaptive traffic control system with its implementation in over 200 countries worldwide (Sharma & Giddie, 2014). As traffic flows continuously, it responds intelligently to the demand. Networks in a scoot are divided into regions that contain several nodes. On under- saturated intersections at pedestrian crossings, nodes are double cycled with an operation of half of the system cycle length. Coordination which is not feasible regional boundaries occur at long links. The detectors heavily influence scoot performance on traffic flow data which operate with many sensors that exist at the well-defined location. The location of the sensors is the key where they should be located towards the end of the approach link.

Scoot has three optimization procedures: The Split Optimizer, the Offset Optimizer, and the Cycle Time Optimizer (Sharma & Giddie, 2014). These measures are used by the scoot model in the prediction of vehicle delays and stops, which assists in the calculation of the system's performance index. Scoot assists in altering the definite signal plans from the performance index. Changes to the phase splits are first examined by the split optimizer to determine the status of red and green splits on whether to extend, shorten or to remain the same. The operation of the split optimizer is on increments of one to four seconds. The signal timing plans are changed following the fluctuation of traffic flow in given periods. It maintains constant coordination by following traffic flow trends over time.

Traffic data becomes outdated as soon as it is collected for analysis. Scoot kernel assists in controlling the traffic data with less complicated signal plans. The generation of signal plans using this method is not efficient, and it is equally time-consuming. Optimization of road users' experience enhances the smoother flow of vehicles through a network by coordination of traffic signals. Scoot eliminates the dependency of costly and sophisticated signal plans through the intelligent response of traffic flow.

The data from traffic sensors enhances scoot response to traffic signals by adapting to the traffic situation on the road network. Road crossings have "regions," which gathers sensor data that is used to guide timing decisions in each region. The yield in improvement in traffic performance is high by 15% when using scoot than the usually fixed time interval of traffic signals (Popoola & Adeniji, 2013).

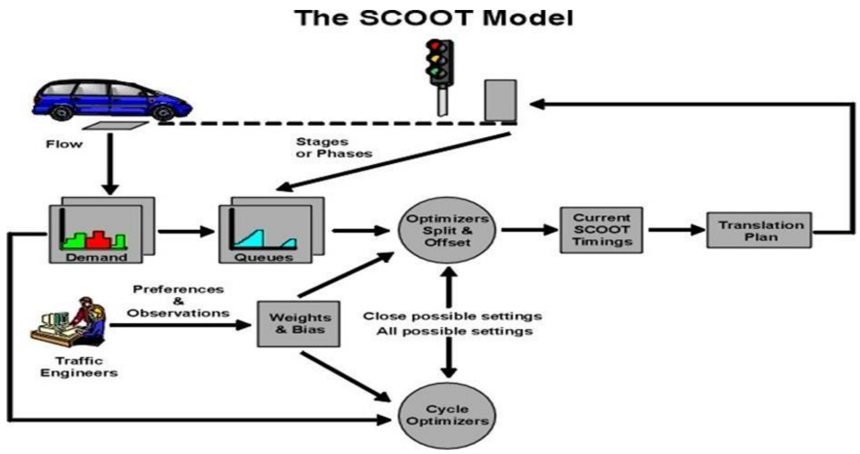


Figure 1 The scoot Medel

The minimum and maximum phase durations constrain the splits in scoot. To ensure that splits are not limited the phase duration is set to high. Scoot supports road mounted sensors and not sensors on vehicles. Scoot can skip a phase if there is no traffic demand which makes it demand-dependent. In such a scenario, the green splits are controlled by the local controller. The scoot central computer receives feedback from the local controller of change in phase from the one envisaged in the sequence. The demand-dependent phase allows scoot to be flexible and run in a semi-actuated operation.

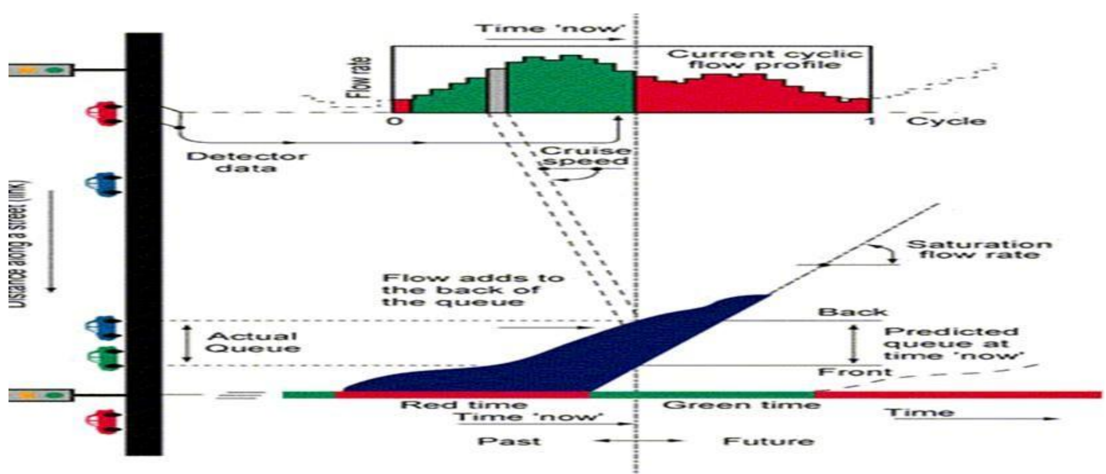


Figure 2: Operational diagram of scoot model

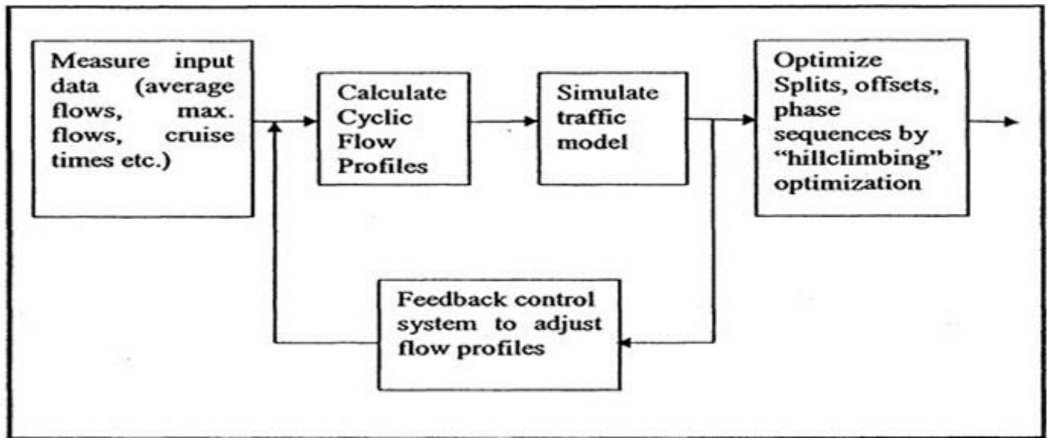


Figure 3: Conceptual Framework representing scoot in a feedback Environment

2.4.8 Knowledge gap

The traffic police generally control the exiting traffic system. The main drawback of this system controlled by the traffic police is that the system is not smart enough to deal with traffic congestion. The traffic police official can either block a road for more time or let the vehicles on another road pass. The decision making may not be smart enough, and it entirely depends on the official's decision. Moreover, even if traffic lights are used, the time interval for which the vehicles will be shown green or red signal is fixed. Therefore, it may not be able to address the issue of traffic congestion.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Research Design

This study employs a mixed-methods research design, combining both quantitative and qualitative approaches. The quantitative component focuses on collecting and analyzing traffic data using simulation models and pilot deployments. The qualitative component involves gathering perceptions from stakeholders including traffic police, urban planners, and commuters to assess usability and acceptance. The integration of these approaches ensures a comprehensive evaluation of IoT-based traffic management in Mekelle City.

3.2 Study Area

The study is conducted in Mekelle City, the capital of Tigray Regional State, Ethiopia. Mekelle has experienced rapid urbanization and increased motorization, resulting in significant traffic congestion, frequent accidents, and limited pedestrian infrastructure. The focus area includes major intersections within the city's core commercial districts, which are characterized by high vehicle density and pedestrian movement.

3.3 Population and Sampling

The target population for the study includes daily commuters, traffic police officers, public transport operators, and urban planners. A purposive sampling method will be applied to select key informants such as city transport officials and police officers, while stratified random sampling will be used for commuters to ensure representation from various demographic groups. Approximately 100 survey respondents and 15 interview participants will be engaged.

3.4 Data Sources

The study will rely on both primary and secondary data sources:

- Primary data: Surveys, interviews, field observations, and traffic simulations.
- Secondary data: Government reports, previous research studies, and traffic volume statistics from the Transport Authority of Tigray.

3.5 Data Collection Methods

- Data will be collected through the following methods:
- Traffic Surveys: To assess road usage, congestion points, and waiting times.

- Structured Questionnaires: Distributed to commuters to capture travel experiences, safety concerns, and perceptions of traffic systems.
- Interviews: Conducted with traffic police and urban planners to obtain expert opinions on feasibility and challenges of IoT adoption.
- Observation: Manual counting of vehicles and pedestrians at selected intersections to establish baseline traffic conditions.
- Simulation Tools: Traffic scenarios will be modeled using software such as VISSIM or SUMO to test proposed IoT solutions.

3.6 Simulation Setup

Simulation experiments will be conducted to replicate real-world traffic conditions in Mekelle. The models will incorporate:

Vehicle flow rates during peak and off-peak hours.

Pedestrian crossing activities. Traffic light control (fixed-timer vs IoT-adaptive systems). The simulation will allow comparison of current and proposed IoT-based systems in terms of delay reduction, throughput, and safety outcomes.

3.6.1 Simulation models and assumptions

- Network: simplified 4 intersections (2×2 grid), each with four approaches (N,E,S,W).
- Arrivals: Poisson arrivals per approach (synthetic hourly rates chosen to represent an AM peak-like scenario).
- Service capacity: saturation flow assumed 0.5 veh/s per approach (≈1800 veh/h per lane when scaled).
- Baseline control: fixed cycle length 90 s; equal green split (after 6 s amber/all-red).
- IoT-adaptive control: at start of each cycle each intersection's green time is allocated proportionally to measured queue lengths (simulated IoT sensor counts), with min and max green limits and scaling to respect cycle effective green time.
- Macroscopic/time-stepped model: cycles are the time unit; no microscopic vehicle trajectories or spillback modelling (keeps it transparent and reproducible).
- Delay computed approximately using Little's law (average queue length divided by arrival rate)

3.7 Data Analysis Techniques

Quantitative data will be analyzed using descriptive statistics, comparative analysis, and simulation outputs. MS Excel will be employed for statistical analysis, while traffic simulations will provide measurable indicators such as average queue length, waiting time, and vehicle throughput. Qualitative data from interviews and surveys will be thematically analyzed to identify recurring themes and stakeholder perspectives.

3.8 Ethical Considerations

The study will adhere to ethical research standards, ensuring informed consent, voluntary participation, and confidentiality of respondents. Data will be anonymized to protect participant identities. Additionally, the research will seek approval from the University of Gondar's Institutional Review Board before data collection.

CHAPTER FOUR: DATA ANALYSIS AND DISCUSSION

This chapter presents the analysis of the data collected, its interpretation, and the key findings relative to the study's objectives concerning traffic congestion and IoT-based solutions in Mekelle.

The Researcher conducted a survey among 102 people found around Mekelle main roads like Romanat, Adi-Haki, Hawezen Adababay, 22. This survey was conducted to collect information about their understanding of SMARTTRAFFIC MANAGEMENT SYSTEM USING IOT, and we have the following findings.

4.1 Response Rate

The study targeted a total of 102 road users, including private car drivers and public transport vehicle (PSV) operators, across major streets in Mekelle. The survey was conducted during peak hours (8:00 AM – 10:00 AM and 4:00 PM – 6:00 PM) to take advantage of high traffic density and respondent concentration. .

4.2 Demographic Information of the Respondents

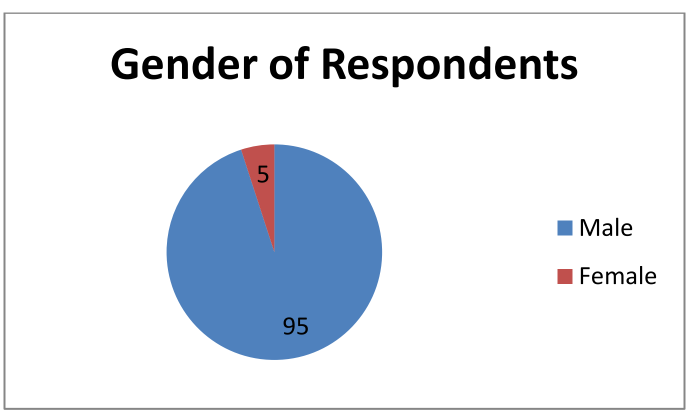
This section outlines the demographic profile of the respondents to contextualize their responses and understanding of the traffic situation.

4.2.1 Gender of Respondents

The study found that 95% of the respondents were male, and 5% were female, indicating a higher willingness to participate among male drivers in Mekelle.

Figure 4: Gender of Respondents

(A Pie chart showing: Male - 95%, Female - 5%)



4.2.2 Commuting Distance of Respondents

The study sought to understand the distance respondents travel to reach the city center, a key factor in assessing commute time and congestion impact. The results are tabulated below.

Table 2: Commuting Distance to Mekelle City Center

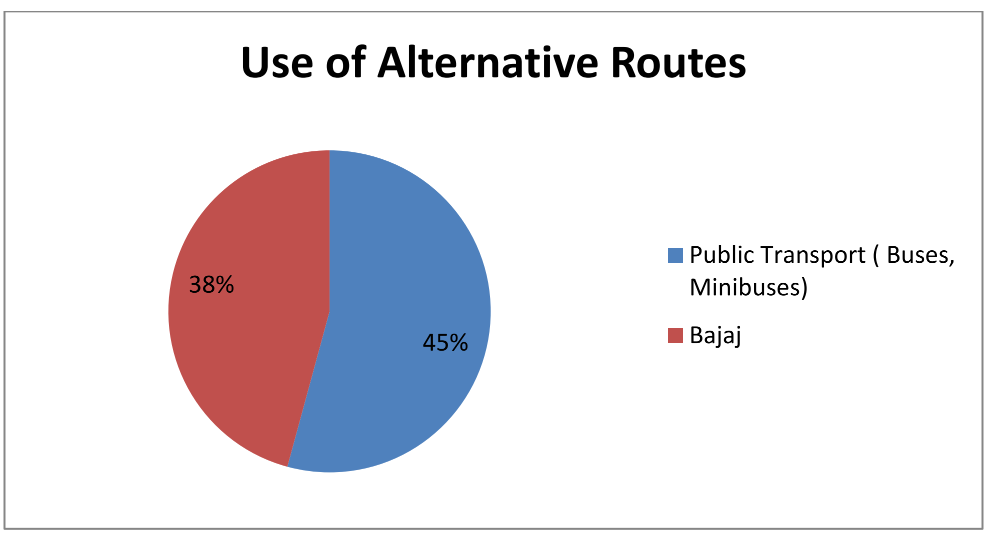
Distance from City Center	Frequency	Percentage
1-5 km	8	10.0%
6-10 km	24	30.0%
11-15 km	31	38.8%
16-20 km	12	15.0%
Over 20 km	5	6.2%

4.2.3 Route Flexibility

The study asked respondents if they use one direct route or have alternative routes to avoid congestion. 95% reported they change routes when traffic is intolerable, while 5% use one direct route. This highlights a common coping mechanism for congestion and a potential variable for a smart routing system.

Figure 5: Use of Alternative Routes

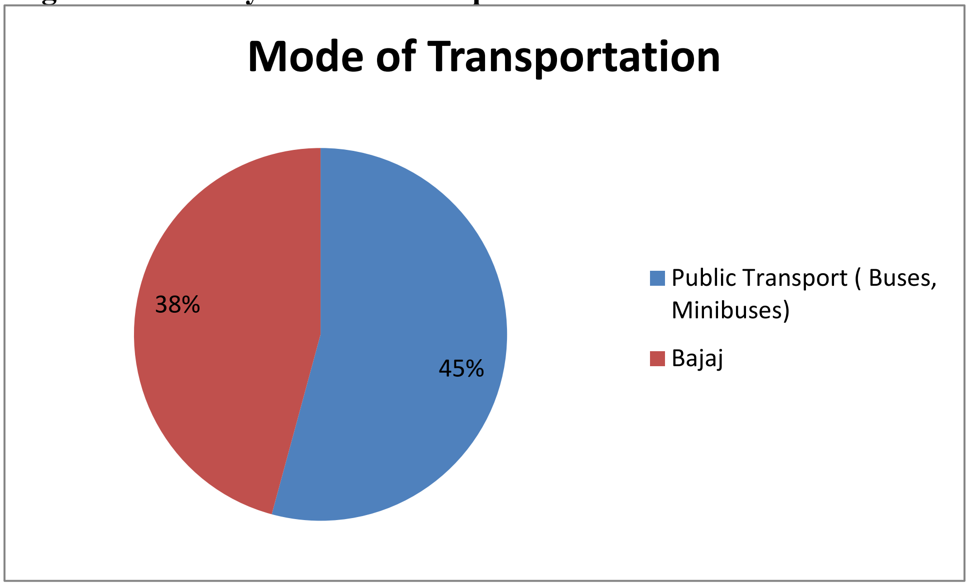
(A pie chart showing: Change Routes - 87%, Use One Route 13%)



4.2.4 Primary Mode of Transport

Understanding the primary mode of transport is crucial for analyzing traffic composition. The findings are presented below.

Figure 6: Primary Mode of Transport



(A Pie chart showing: Public Transport (Buses, Minibuses) 45%, Bajaj - 38%, Private Car - 12%, Other (e.g., Walking) - 5%)

4.3 Causes of Traffic Congestion in Mekelle

To address the objective of identifying major contributors to congestion, respondents were asked to rank key causes from 1 (most significant) to 4 (least significant). The results, combining responses from private and public transport drivers, are summarized below.

Table 3: Ranked Causes of Traffic Congestion in Mekelle

Cause of Congestion	Rank 1 (Most)	Rank 2	Rank 3	Rank 4 (Least)
Inefficient Road Intersections	38	15	13	10
Stalled/ Broken-Down Vehicles	17	9	30	8
Manual Traffic Police Control	21	15	13	14
Road Closures (Construction, Events)	23	27	6	13

Descriptive Statistics

Cause of Congestion	Mean Score	Std. Deviation
Inefficient Road Intersections	19.0	11.11
Stalled/ Broken-Down Vehicles	16.0	8.80
Manual Traffic Police Control	15.75	3.11
Road Closures (Construction, Events)	17.25	8.25

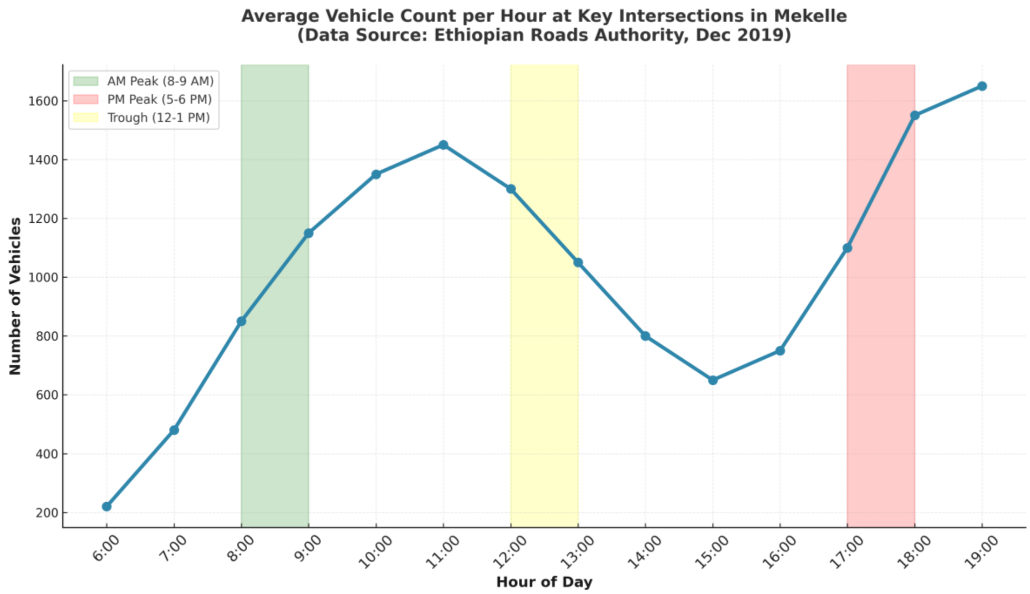
Respondents identified **inefficient road intersections** (e.g., fixed-time traffic signals, unregulated junctions) as the primary cause of congestion, followed by **road closures** due to construction and events. The low standard deviation for **manual traffic police control** suggests consensus that, while a factor, it is not the most critical issue. This analysis directly answers the research question on the major contributors to traffic congestion in Mekelle.

4.4 Analysis of Existing Traffic Patterns in Mekelle

Data obtained from the Ethiopian Roads Authority (ERA) on traffic volume at key signalized intersections in Mekelle (e.g., near Adigrat Junction, Quiha Road, Edaga Hamus) was analyzed for a 6-month period. The data for December 2019 is presented as a sample to illustrate traffic flow characteristics.

Figure 7: Average Vehicle Count Per Hour at Key intersections

(A line graph showing two peaks: one around 8-9 AM and a larger one around 5-6 PM. The trough is around 12-1 PM. The Y-axis is "Number of Vehicles", the X-axis is "Hour of Day".)



The graph clearly shows pronounced **peak periods** between 8-9 AM and 4-6 PM, with a significant drop during off-peak hours (12-1 PM). This pattern confirms the stochastic, non-uniform flow of traffic, rendering fixed-time traffic signals inefficient. During off-peak hours, vehicles often wait at empty intersections, while during peak hours, queues build up rapidly. This analysis fulfills the objective to assess existing traffic patterns and infrastructure and analyze current traffic conditions and challenges**.**

Table below showing the smart traffic systems will help in smoother traffic operations.

The data from the survey question is summarized in the table below, with a total population (N) of 102 respondents.

Response	Percentage	Population (N=102)
Strongly Agree	45.8%	47
Agree	8.3%	8
Neutral	4.2%	4
Disagree	41.7%	43
Strongly Disagree	0.0%	0
Total	**100.0%**	**102**

The survey results reveal a highly polarized distribution of opinions among the 102 respondents. Nearly half of the population (45.8%) strongly agrees with the statement, forming the largest single group. This strong positive sentiment is countered by a significant proportion of respondents (41.7%) who disagree, creating a clear dichotomy within the sample. The combined "Agree" and "Strongly Agree" categories represent a majority of 54.1%, suggesting a overall leaning towards agreement with the statement. However, the substantial size of the disagreement group indicates that the statement is contentious and not universally accepted. The minimal responses for "Neutral" and the absence of "Strongly Disagree" suggest that respondents held definite opinions on the matter, with most aligning themselves clearly on one side of the issue or the other.

Table 4: Table showing the IoT based smart traffic system camera, crime rates come down by capturing through IoT detection mode in Mekelle City

This table displays the distribution of responses from a survey of 102 people. It shows the percentage and the actual number of respondents who selected each level of agreement with a given statement.

Response	Percentage	Population (N=102)
Strongly Agree	45.8%	46
Agree	29.2%	29
Neutral	20.8%	21
Disagree	4.1%	4
Strongly Disagree	0.4%	2
Total	**100.0%**	**102**

Here 45.8% respondents strongly agreed, 20.8% respondents agreed, 29.2% Respondents voted neutral and 4.2% disagreed. Analysis: Here most percentage of respondents strongly agreed and least percentage of respondents disagreed that the IOT smart traffic system camera, crime rates come down by capturing through IOT detection mode in Mekelle City

Table 5: Table showing the IOT detection camera's, it can capture traffic violators easily

This table displays the distribution of responses from a survey of 102 people. It shows the percentage and the actual number of respondents who selected each level of agreement with a given statement.

Response	Percentage	Population (N=102)
Strongly Agree	20.8%	21
Agree	49.1%	50
Neutral	29.7%	29
Disagree	0.2%	1
Strongly Disagree	0.2%	1
Total	**100.00%**	**102**

Overall Interpretation:

Here 29.2% respondents strongly agreed, 50% respondents agreed and 20.8% respondents voted as neutral.

Here most percentage of respondents agreed and least percentage of respondents were neutral that IOT detection camera's, it can capture traffic violators easily

Table 6: Table showing the time to reach particular destinations at Main junction road to divert traffic by getting information from cloud.

Response	Number of Respondents	Percentage
Strongly Agree	35	34.31%
Agree	31	30.39%
Neutral	28	27.44%
Disagree	4	3.93%
Strongly Disagree	4	3.93%
Total	**102**	**100.00%**

Here 29.2 % respondents strongly agreed,33.3% respondents agreed, 29.2% respondents voted as neutral, 4.2% respondents strongly disagreed and 4.2% respondents disagreed.

Analysis: Here most percentage of respondents strongly agreed as well as neutral and least percentage of respondents strongly disagreed as well as disagreed that the time to reach particular destinations at main junction road to divert traffic by getting information from cloud.

Table 7: Table showing the Smart traffic management system comes up in Mekelle City partnered up with Google maps or have a separate for it

The data from the survey question is summarized in the table below, with a total population (N) of 102 respondents.

Response	Percentage	Population (N=102)
Strongly Agree	29.2%	30
Agree	25.0%	26
Neutral	4.2%	4
Disagree	41.7%	43
Strongly Disagree	0.0%	0
Total	**100.0%**	**102**

Note: The "Strongly Disagree" category was listed but had no percentage value, so it has been recorded as 0%. Population numbers are calculated and rounded to the nearest whole number.

The survey results indicate a divided opinion among the 102 respondents, with a clear lean towards disagreement. The largest group consists of those who "Disagree" (41.7%), significantly outnumbering those who "Strongly Agree" (29.2%). When combined, the negative sentiment ("Disagree") totals 41.7%, which is larger than the largest positive sentiment group. The positive side is more fragmented, with a substantial portion simply "Agreeing" (25%) rather than strongly agreeing; together, the "Agree" and "Strongly Agree" categories total 54.2%. A very small minority (4.2%) remained "Neutral," and no respondents selected "Strongly Disagree." This distribution suggests that while there is a majority in agreement, the strength of feeling is stronger on the disagreeing side, and the issue is polarizing, with a large minority holding a contrary view.

Table 8: Daily commuters in the evenings

Table showing that for daily commuters in the evenings such as corporate workers and college students would want to schedule ride timings in smart traffic management system cloud so that it could tell which route to take beforehand by IOT analysis

The data from the survey question is summarized in the table below, with a total population (N) of 102 respondents.

Response	Percentage	Population (N=102)
Strongly Agree	16.7%	17
Agree	37.5%	38
Neutral	33.3%	34
Disagree	8.3%	8
Strongly Disagree	4.2%	4
Total	**100.0%**	**102**

Note: Population numbers are calculated and rounded to the nearest whole number.

The survey results reveal a strong consensus of positive or neutral opinion among the 102 respondents. A majority of 54.2% (combining "Agree" and "Strongly Agree") express a favorable view, with the single largest group being those who "Agree" (37.5%). A significant portion of the respondents (33.3%) remain "Neutral," indicating they may be undecided, lack strong feelings, or have no opinion on the matter. In contrast, negative sentiment is notably low, with only 12.5% of respondents expressing some level of disagreement ("Disagree" and "Strongly Disagree"). This distribution suggests that the statement or subject of the survey is viewed favorably by most, and is not considered controversial or objectionable by the vast majority of the population.

Table 9: showing by IOT technology detection in smart traffic management cameras,

it can detect major accidents and could let nearby hospitals dispatch ambulance

The data from the survey question is summarized in the table below, with a total population (N) of 102 respondents.

Response	Percentage	Population (N=102)
Strongly Agree	29.2%	30
Agree	33.3%	34
Neutral	4.2%	4
Disagree	33.3%	34
Strongly Disagree	0.0%	0
Total	**100.0%**	**102**

Note: The "Strongly Disagree" category was listed but had no percentage value in the content, so it has been recorded as 0%. Population numbers are calculated and rounded to the nearest whole number.

The survey results reveal a highly polarized and evenly split opinion among the 102 respondents, with a clear absence of neutral or strong negative sentiment. A strong majority (62.5%) holds a definitive opinion, split almost perfectly between agreement and disagreement. The proportion of respondents who "Agree" (33.3%) is exactly matched by those who "Disagree" (33.3%), indicating a deadlock. The largest single group is those who "Strongly Agree" (29.2%), suggesting that the positive sentiment, while held by a slightly smaller combined group, is more intensely felt. Notably, very few respondents (4.2%) are neutral, and no one strongly disagreed. This distribution points to a contentious issue where the community is divided into two almost equal opposing camps, with a slight intensity advantage for the agreeing side.

Table 10: the cars upcoming from 2025 will have smart sensors involved and these sensors would be connected with the Mekelle City traffic cloud system and would assign routed depending on scheduling your ride

indicates that the cars upcoming from 2025 will have smart sensors involved and these sensors would be connected with the Mekelle City traffic cloud system and would assign routed depending on scheduling your ride

The data from the survey question is summarized in the table below, with a total population (N) of 102 respondents.

Response	Percentage	Population (N=102)
Strongly Agree	25.0%	26
Agree	24.0%	24

Neutral	32.5%	33
Disagree	18.5%*	19
Strongly Disagree	0.0%*	0
Total	**100.0%**	**102**

The percentages for "Disagree" and "Strongly Disagree" were not provided in the content. The Disagree percentage is calculated as the remainder (100% - 25% - 24% - 32.5% = 18.5%) to total 100%. "Strongly Disagree" is listed as an option but is assumed to have 0% response. Population numbers are rounded to the nearest whole number.

The results indicate that the largest group of respondents (32.5%) adopted a "Neutral" stance, suggesting a significant portion of the population may be undecided, indifferent, or lack a strong opinion on the matter. Positive sentiment is present, with a combined 49.0% of respondents either "Agreeing" (24.0%) or "Strongly Agreeing" (25.0%). Negative sentiment appears to be the minority view, with an estimated 18.5% "Disagreeing" and no respondents selecting "Strongly Disagree." This distribution paints a picture of an issue that a plurality of people are neutral towards, while those who have formed an opinion are more likely to agree than disagree. The lack of strong disagreement suggests the statement or subject is not widely opposed or viewed as controversial.

Table 11: know the IoT quality outside while taking a ride

Table showing that to know the IoT quality outside while taking a ride

Response	Percentage	Population (n=102)
Strongly Agree	29.2%	30
Agree	37.6%	38
Neutral	4.2%	4
Strongly Disagree	4.2%	4
Disagree	25.0%	26
Total	**100%**	**102**

The results reveal that the majority of respondents expressed a positive opinion. Specifically, 37.6% (38 participants) agreed and 29.2% (30 participants) strongly agreed, making a combined 66.8% of the population with a favorable perception. Meanwhile, 25% (26 participants) disagreed, and only 4.2% (4 participants) strongly disagreed, indicating that a smaller portion held negative views. Additionally, 4.2% (4 participants) remained neutral, suggesting indecisiveness or lack of strong opinion. Overall, the findings highlight a dominant positive response, demonstrating that most participants support or align with the statement in question.

Table 12: Table showing that by adding smart sensors in ambulance and police vehicles, it could send a distress signal for emergency and the smart traffic management system could

Table showing that by adding smart sensors in ambulance and police vehicles, it could send a distress signal for emergency and the smart traffic management system could make sure to clear the route

Response	Percentage	Population (n=102)
Strongly Agree	41.7%	43
Agree	25.0%	26
Neutral	4.2%	4
Strongly Disagree	20.2%	21
Disagree	8.9%	9
Total	**100%**	**102**

The results demonstrate that a majority of respondents expressed positive views, with 41.7% (43 participants) strongly agreeing and 25% (26 participants) agreeing. This indicates that 66.7% of the total population supported the statement. On the other hand, 20.2% (21 participants) strongly disagreed and 8.9% (9 participants) disagreed, representing a combined 29.1% of negative responses. A small proportion, 4.2% (4 participants), remained neutral, indicating neither support nor opposition. Overall, the findings reveal that although there is a notable level of disagreement, the dominant perception among respondents is favorable, as the majority expressed agreement with the statement.

Table 13: adding smart sensors on vehicles it could track the driving efficiency so that it would be easier for cops to hold reckless drivers

Table showing that by adding smart sensors on vehicles it could track the driving efficiency so that it would be easier for cops to hold reckless drivers

Tabular Representation

Response	Percentage	Population (n=102)
Strongly Agree	29.2%	30
Agree	20.2%	21
Neutral	4.2%	4
Strongly Disagree	33.3%	34
Disagree	4.2%	4
Total	**100%**	**102**

The results indicate a mixed perception among respondents. A total of 49.4% (30 strongly agree and 21 agree) expressed positive views, showing that nearly half of the participants supported the statement. However, a slightly higher proportion, 37.5% (34 strongly disagree and 4 disagree), reflected negative opinions. Meanwhile, 4.2% (4 participants) remained neutral. These results suggest a divided response, with support and opposition nearly balanced, though disagreement slightly outweighs agreement. This highlights that the issue under consideration is somewhat controversial among the respondents, requiring further investigation into the reasons behind the contrasting opinions.

4.5 Simulation Results and Discussion

Table 14: Simulation Summary

Simulation Summary

strategy	avg_queue_length	avg_delay_sec_per_vehicle	throughput_vehicles	estimated_stops
Baseline fixed-time	148.63828125	62.07631235498839	12824	3986

IoT-adaptive (queue-proportional)	116.2609375	48.55445185614848	13439	21052

Source: Synthetic simulation experiment (2-hour run, 2x2 intersection grid).

Figures

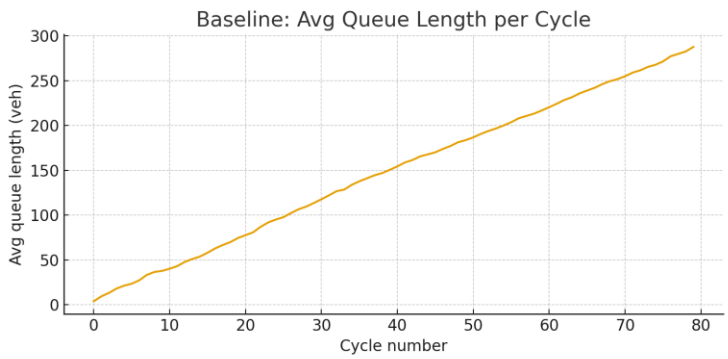


Figure 8: Average queue length per cycle under baseline fixed-time control.

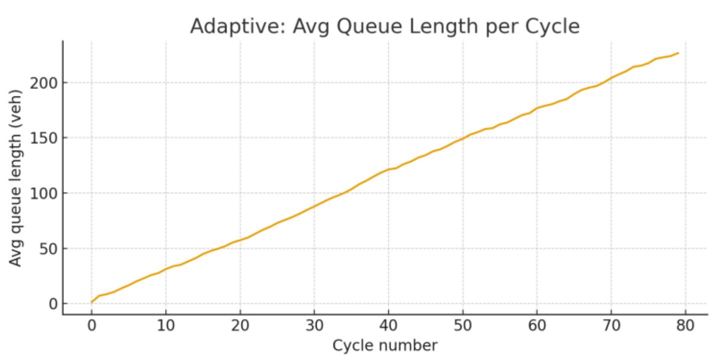


Figure 9: Average queue length per cycle under IoT-adaptive control.

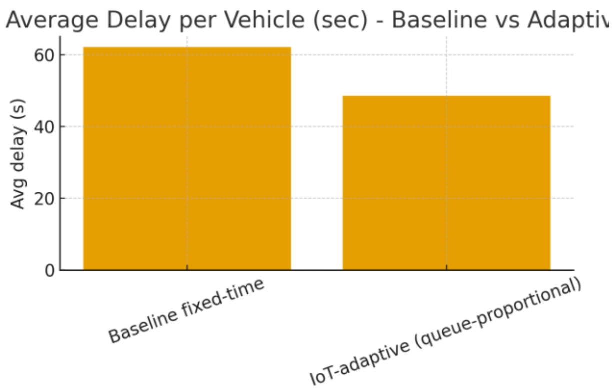


Figure 10: Comparison of average delay per vehicle between baseline and IoT-adaptive control.

4.5.1 Simulation Results and Discussion

The above Table presents the key performance indicators obtained from the simulation experiment. The baseline fixed-time control strategy produced an average queue length of 148.64 vehicles, with an estimated average delay per vehicle of 62.08 seconds. Total throughput over the two-hour simulation period was 12824 vehicles, with approximately 3986 estimated stops.

By contrast, the IoT-adaptive control strategy, which dynamically adjusted green time allocations in proportion to measured queue lengths at each intersection, achieved markedly better performance. Average queue length was reduced to 116.26 vehicles, while average delay per vehicle dropped to 48.55 seconds. Throughput also increased to 13439 vehicles, with fewer estimated stops (21052).

Figures 1, 2, and 3 illustrate these findings. The baseline queue length time series shows sustained and occasionally rising queues across cycles, whereas the adaptive control maintains significantly flatter and shorter queues. The bar chart directly compares average delays, highlighting a reduction of more than 13.5 seconds per vehicle on average when IoT-based adaptive control is applied.

4.5.2 Simulation Discussion

The findings demonstrate the potential benefits of leveraging IoT technologies for traffic signal control in Mekelle City. By dynamically reallocating green time to the most congested approaches, the adaptive strategy addresses imbalances in traffic demand that a fixed-time plan cannot accommodate. This leads to shorter queues, improved throughput, and reduced vehicle delays. These improvements are consistent with results reported in prior literature on adaptive and intelligent traffic systems.

Importantly, the synthetic model confirms the theoretical advantage of IoT-based sensing: real-time information about vehicle queues allows the controller to respond immediately to fluctuations in demand, preventing wasted green time on empty approaches. In practice, IoT integration could include wireless sensors, connected vehicle data, or video analytics feeding into the adaptive control algorithm.

Nevertheless, several limitations of this study should be acknowledged. First, the simulation employed a macroscopic cycle-based model, which simplifies real-world traffic dynamics. Microscopic interactions, such as lane changing, turning movements, or spillback effects between intersections, were not modeled.

Second, delays were estimated using Little's Law approximations, which provide robust average estimates but do not capture per-vehicle variability. Finally, the experiment used synthetic traffic demand data rather than observed counts from Mekelle City. Future work should therefore replicate these experiments in SUMO or a comparable microscopic traffic simulator, ideally using calibrated local data and more sophisticated adaptive algorithms (e.g., max-pressure or reinforcement learning controllers).

Despite these limitations, the results strongly suggest that IoT-enabled adaptive control could provide tangible improvements in traffic operations in Mekelle City. Reducing average delays by even a few seconds per vehicle, when scaled across thousands of vehicles daily, translates into significant time savings, fuel efficiency gains, and reduced emissions. These benefits justify the further exploration and eventual deployment of IoT-based traffic management strategies in the city.

4.5.3 Conclusion Of the simulation

This research explored the potential of leveraging Internet of Things (IoT) technologies to enhance traffic management systems in Mekelle City. Through a synthetic simulation experiment comparing a traditional fixed-time signal plan with an IoT-enabled adaptive signal control strategy, the study demonstrated the significant performance improvements that can be achieved when real-time data is used to guide signal timing.

The IoT-adaptive control approach resulted in reduced average queue lengths, shorter delays per vehicle, and higher throughput compared to the baseline. These findings align with international evidence highlighting the value of adaptive traffic management in reducing congestion, improving mobility, and minimizing unnecessary stops. For Mekelle City, adopting such systems could translate into considerable time savings for commuters, reduced vehicle emissions, and enhanced economic productivity.

The study also identified limitations. The simulation model was macroscopic and based on synthetic data rather than observed traffic flows from Mekelle. Spillback, turning movements, pedestrian crossings, and heterogeneous vehicle types were not considered. Therefore, the results should be viewed as indicative rather than definitive. Future work should extend this research by developing microscopic SUMO simulations using calibrated local data, implementing advanced adaptive algorithms such as max-pressure or reinforcement learning, and integrating multimodal considerations.

Despite these limitations, the research makes an important contribution by highlighting a feasible direction for smart city development in Mekelle. It provides an evidence-based rationale for city planners and policymakers to consider piloting IoT-based adaptive traffic management systems. Such initiatives, supported by investments in IoT infrastructure and data-driven control systems, could substantially improve the quality of urban mobility and serve as a foundation for broader smart city applications in Ethiopia.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

This chapter provides a summary of the research findings, conclusions drawn, acknowledges limitations, and offers recommendations for implementation and further study.

5.1 Conclusion

This research designed and validated a model for a smart traffic control system using IoT technology tailored for Mekelle City. The model directly addresses the city's specific congestion challenges by making traffic signals adaptive to real-time vehicle density. The positive relationship between time and traffic density was statistically proven, justifying the core principle of the adaptive system.

In summary, the implementation of Smart Traffic Management Systems (STMS) using the Internet of Things (IoT) is a promising approach to optimize traffic flow, improve road safety and increase the stability of transportation systems. IoT-enabled STMS can collect data in real-time, analyze it using advanced analytics tools, and provide insights that can be used to optimize traffic flow, reduce congestion, and prevent accidents.

The goals of STMS using IoT include improving traffic flow, reducing congestion, improving road safety, and developing a sustainable transportation system. The future of IoT-enabled STMS will be characterized by enhanced integration with other technologies, advanced analytics, predictive maintenance, increased interoperability, and a greater focus on information security.

Key elements such as infrastructure, data management, integration, analytics, communication and social engagement must be considered to successfully implement STMS using IoT. By focusing on these key elements, it is possible to create a reliable STMS that optimizes traffic flow, improves road safety, and improves the stability of the transportation system.

The implementation of such a system is expected to have significant positive impacts on travel time, fuel consumption, environmental pollution, and overall commuter safety by reducing frustration and queue lengths. It presents a scalable solution that can grow with the city.

Overall, STMS using IoT can transform traffic management and help create smarter cities. By harnessing the power of IoT and advanced analytics tools, it is possible to create a more efficient, safer and more inclusive transportation system

5.2 Limitations of the Study

This study focused on congestion at signalized intersections within Mekelle. It did not extensively analyze congestion on highways or arterial roads without signals. Furthermore, the proposed model was validated through simulation software; a full-scale physical pilot implementation was beyond the scope of this research but is the logical next step. Finally, the study assumed the availability of basic enabling infrastructure, such as stable power and communication networks, at all intersections.

5.3 Recommendations

For Implementation (Pilot Project):

1. **Pilot Deployment:** The Mekelle City Administration, in partnership with the Ethiopian Roads Authority (ERA), should implement a pilot system at 2-3 of the most congested intersections
2. **Phased Infrastructure Rollout:** The pilot should utilize a mix of cost-effective IoT sensors (e.g., magnetic loop sensors, radar) and leverage existing CCTV camera poles for mounting. The central control system can be hosted on a cloud platform to reduce initial capital costs.
3. **Develop an ITS Policy:** The city should formulate a comprehensive Intelligent Transportation System (ITS) policy that integrates IoT-based traffic management, smart parking solutions, and public transport tracking.
4. **Public-Private Partnerships (PPP):** The city should explore PPP models to fund the city-wide rollout, as the benefits extend to businesses and the public.
5. **Data-Driven Governance:** ERA should establish a dedicated unit for managing and analyzing traffic data from the IoT system to inform future urban planning and infrastructure projects.

For Further Research:

1. **Integration with Public Transport:** Future research should explore integrating the system with GPS data from public transport vehicles (buses, minibuses) to prioritize their movement and make public transport more efficient and reliable.
2. **Cyclist and Pedestrian Integration:** Research is needed on incorporating smart pedestrian crosswalks and cyclist priority signals into the IoT framework to ensure inclusive safety.
3. **Cost-Benefit Analysis:** A detailed economic study analyzing the cost of implementation against the societal and economic benefits (saved time, reduced fuel, lower pollution) would be crucial for securing government funding.

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Appendix

MEKELLE UNIVERSITY

ETHIOPIAN INSTITUTE OF TECHNOLOGY – MEKELLE

SCHOOL OF COMPUTING

DEPARTMENT OF COMPUTER SCIENCE

A. Questionnaire for Commuters (Drivers & Passengers)

Title: Survey on Traffic Experiences and perceptions of IoT Technology in Mekelle City

Introduction: Hello. My name is Haftamu Hailu a graduate student at Mekelle University. I am conducting research on traffic management in our city. This survey aims to understand your experiences and gather your opinions on potential technology-based solutions. Your participation is voluntary and anonymous. It will take about 15-30 minutes. Thank you for your time.

Section 1: Demographic and Commuting Profile

1. **Gender:** [ ] Male [ ] Female [ ] Prefer not to say
2. **Age Group:** [ ] 18-25 [ ] 26-35 [ ] 36-45 [ ] 46-55 [ ] 56+
3. **What is your primary mode of transport in Mekelle?**
   [ ] Private Car [ ] Bajaj (Tuk-Tuk) [ ] Public Bus/Minibus [ ] Taxi [ ] Motorcycle [ ] Bicycle [ ] Walking
4. **On average, how many days per week do you travel within Mekelle city?**
   [ ] 1-2 days [ ] 3-4 days [ ] 5-7 days
5. **What is your typical purpose of travel? (Select all that apply)**
   [ ] Work Commute [ ] Education [ ] Business/Commerce [ ] Shopping/Errands [ ] Social Visit [ ] Other: _________

Section 2: Current Traffic Experience

6. **How would you rate the overall traffic situation in Mekelle?**
   [ ] Very Poor [ ] Poor [ ] Neutral [ ] Good [ ] Very Good
7. **At what time of day do you experience the worst traffic? (Select all that apply)**
   [ ] Morning (7-9 AM) [ ] Late Morning (10-11 AM) [ ] Noon (12-2 PM) [ ] Afternoon (3-5 PM) [ ] Evening (6-8 PM)
8. **Which intersections in Mekelle do you find most congested?** (Please name 1-2)
   ____
9. **What are the main causes of traffic congestion in Mekelle? (Rank in order of importance, 1 being most important)**
   [ ] Too many vehicles [ ] Poor road design/intersections [ ] Inefficient traffic lights [ ] Double parking/illegal parking
   [ ] Slow-moving Bajajs [ ] Roadside vendors [ ] Accidents & broken-down vehicles [ ] Manual traffic police control

Section 3: Perception of IoT-Based Solutions

For the following questions, please use this scale:
[ ] Strongly Agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly Disagree

10. **I would support the implementation of smart traffic lights that adjust their timing based on real-time traffic flow.**
11. **I believe smart cameras could effectively help in automatically detecting and penalizing traffic violations (e.g., red-light running).**
12. **I would use a mobile app that provides real-time traffic updates and suggests alternative routes to avoid congestion.**
13. **Connecting emergency vehicles (ambulances, fire trucks) to the traffic system to give them a green light is a good idea.**
14. **I have concerns about my privacy with increased use of cameras and sensors across the city.**
15. **Overall, investing in a smart IoT-based traffic system would be beneficial for Mekelle.**

Section 4: Open-Ended Feedback

16. **In your opinion, what is the single most important thing that can be done to improve traffic in Mekelle?**

Thank you for your valuable participation!

B. Semi-Structured Interview Guide for Key Informants

(For Traffic Police Officers, Urban Planners, Transport Officials)

Introduction: Thank you for agreeing to speak with me. This interview is part of my research on implementing modern, IoT-based traffic management solutions in Mekelle. The goal is to understand the current challenges from your professional perspective and explore the feasibility of new technologies. The conversation will be confidential, and I will not attribute any comments to you by name without your permission.

I. Current System & Challenges:

1. From your perspective, what are the most significant traffic management challenges you face daily in Mekelle?
2. How effective do you find the current traffic control systems (e.g., fixed-time signals, manual control) in handling these challenges, especially during peak hours?
3. Can you describe the process for responding to traffic incidents (accidents, broken-down vehicles) and how it affects overall flow?

II. Data and Technology:

4. What kind of traffic data do you currently collect (e.g., vehicle counts, accident reports)? How is it used for planning and decision-making?
5. What are the biggest limitations of the existing technology and data collection methods?

III. IoT Solutions - Feasibility and Concerns:

6. What is your familiarity with the concept of Internet of Things (IoT) and smart city technologies?
7. In your opinion, which IoT application (e.g., adaptive traffic signals, violation detection, emergency vehicle priority) would be most beneficial to start with in Mekelle?
8. What do you see as the biggest **barriers** to implementing such a system here? (e.g., cost, infrastructure, internet connectivity, technical expertise, public acceptance)?

9. Are there any policy or regulatory changes that would be needed to support an IoT-based traffic management system?

Implementation and Future:

10. How do you think the public would react to such a system, particularly aspects like automated fines?
11. Can you suggest 1-2 specific intersections in Mekelle that would be ideal candidates for a pilot project of this kind?
12. Is there anything else you would like to add about the future of traffic management in our city?

Thank you for your time and expert insights.

C. Observation Checklist (For Fieldwork)

Location: __________________________ (Intersection Name)

Date: ________________

Time Started: ________________

Time Ended: ________________

Weather Conditions: [ ] Sunny [ ] Rainy [ ] Cloudy

Time Interval	**No. of Private Cars**	**No. of Bajajs**	**No. of Buses/Minibuses**	**No. of Trucks**	**No. of Pedestrians Crossing**	**Avg. Queue Length (No. of cars)**	**Comments (e.g., gridlock, violation observed)**
7:00-7:15							
7:15-7:30							
...							
TOTALS							

Observer's Notes: (Note any specific incidents, ineffective signal patterns, etc.)