A MATHEMATICAL MODEL FOR TRAFFIC CONGESTION AT UNSIGNALIZED ROUNDABOUT USING MICROSCOPIC TRAFFIC FLOW MODEL

By

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DECLARATION

This research project is my own work and has not been presented elsewhere for a degree award.

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ABSTRACT

Traffic flow in many urban centres continue to rise as mobility needs grow, especially at unsignalised roundabouts where vehicles must enter and circulate without the aid of traffic lights. These junctions form a key part of transport infrastructure in many developing countries and understanding how they function is essential for effective traffic management. This study develops and analyses a mathematical representation of vehicle movement at an unsignalised roundabout using a microscopic car-following framework based on the Intelligent Driver Model (IDM).

To investigate how straight-through and turning movements influence vehicle behaviour, numerical experiments were carried out in MATLAB. The simulation employed the fourth-order Runge–Kutta method preceded by a Fast Fourier Transform (FFT) to solve the system dynamics. Four vehicles were introduced into the model and observed over a defined time horizon. From these simulations, the velocity ranges associated with the three types of movement, as well as the different manoeuvres performed at the roundabout, were identified and used as indicators of traffic capacity and operational performance.

The findings reveal distinctive patterns in vehicle speed and acceleration. In particular, the emergence of V-shaped and W-shaped profiles reflects a rapid rise and subsequent drop in both velocity and acceleration as vehicles approach, enter, and exit the roundabout. These patterns consistently appeared in the simulated environment and align well with behaviour typically seen in real traffic conditions.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Traffic urban congestion has become a widespread and complex challenge in cities around the world. It creates a chain of problems that affects people's daily lives as well as the broader community. The impact of crowded and slow-moving roads goes far beyond simple inconvenience, bringing with it many negative effects that touch different aspects of urban life. First and foremost, congested traffic significantly increases the risk of accidents, as frustrated drivers may engage in aggressive behaviors or make poor decisions in their haste to navigate through crowded streets. This heightened danger not only puts lives at risk but also strains emergency services and healthcare systems. Moreover, the sheer amount of time wasted in traffic jams represents an enormous economic burden, reducing productivity and causing missed opportunities for both businesses and individuals. The environmental impact of traffic congestion is equally concerning, with a range of detrimental effects that contribute to the degradation of urban ecosystems. Noise pollution from idling engines and frequent honking creates a cacophony that disrupts the peace of residential areas and wildlife habitats alike. The psychological toll of being trapped in congestion day after day leads to increased stress levels among commuters, potentially contributing to a variety of mental health issues and decreased overall well-being. From an energy perspective, the excessive fuel consumption resulting from stop-and-start traffic and prolonged idling periods not only depletes finite resources but also places a financial burden on consumers. Perhaps most alarmingly, the emission of carbon dioxide and other greenhouse gases from congested vehicles exacerbates air pollution and accelerates climate change, posing long-term threats to global environmental stability. The cumulative effect of these factors increased accident rates, wasted time, noise pollution, stress, fuel inefficiency, and air pollution creates a vicious cycle that perpetuates and intensifies both traffic congestion and environmental degradation. Ultimately, this complex web of issues translates into elevated living costs in urban regions, as cities grapple with the need for infrastructure improvements, healthcare expenses, and environmental mitigation measures. The multifaceted nature of traffic congestion underscores the urgent need for comprehensive urban planning strategies and innovative transportation solutions to address this growing challenge in our increasingly urbanized world Zhang (2004).

Over the past decade, a remarkable transformation has taken place in the transportation landscape of developing nations experiencing rapid economic growth. As disposable incomes have risen and aspirations for personal mobility have soared, there has been an unprecedented surge in vehicle ownership across these countries. This phenomenon, while indicative of economic progress, has brought with it a host of complex challenges, chief among them being the escalating issue of air pollution that now plagues transportation companies and urban centers alike. The sudden influx of vehicles on roads ill-equipped to handle such volumes has created a perfect storm of congestion and emissions, leading to a marked deterioration in air quality in many bustling cities. This situation has put immense pressure on transportation companies, which now find themselves at the intersection of meeting growing demand for their services and mitigating their environmental impact.

In response to the burgeoning need for efficient and accessible transportation services in the rapidly expanding urban regions of these developing countries, policymakers and urban planners have been compelled to implement a diverse array of strategies. These initiatives aim not only to accommodate the increasing number of vehicles but also to provide alternatives that can help alleviate the strain on existing infrastructure and the environment. In several metropolitan areas, the construction of expansive highway networks has been prioritized as a immediate solution to ease traffic flow and connect burgeoning suburbs with city centers. This approach, while offering short-term relief, has often been criticized for potentially encouraging even greater car dependency and urban sprawl. Simultaneously,this has led to the development of bus rapid transit systems, light rail networks, and in some cases, full-fledged metro systems. Additionally, there has been a growing emphasis on promoting sustainable modes of transport, such as cycling and walking, through the creation of dedicated lanes and pedestrian-friendly urban design. Some forward-thinking cities have also started experimenting with congestion pricing schemes and vehicle quota systems to manage demand and encourage the use of public transport.

The challenge of balancing economic growth with environmental sustainability has also spurred innovation in the automotive sector. Many developing countries are now incentivizing the adoption of electric vehicles and hybrid technologies, seeing them as a way to reduce urban air pollution while supporting the growing demand for personal transportation. This shift has led to the emergence of new players in the automotive industry within these nations, as well as collaborations with established global manufacturers to produce more environmentally friendly vehicles tailored to local markets.

However, these efforts have not been without their challenges. The rapid pace of urbanization often outstrips the ability of infrastructure development to keep up, leading to a constant game of catch-up. Moreover, cultural preferences for personal vehicle ownership, coupled with inadequate public transportation options in many areas, continue to drive demand for cars. The result is a complex and evolving situation where cities in developing nations are simultaneously trying to accommodate growing vehicle numbers while also attempting to mitigate their negative impacts through a combination of infrastructure development, policy initiatives, and technological adoption.

As these developing nations continue on their trajectory of economic growth, the challenge of sustainable urban mobility remains at the forefront of their development agendas. The coming years will likely see further innovations and policy experiments as these countries strive to find a balance between meeting the transportation needs of their growing urban populations and addressing the pressing environmental concerns that accompany rapid motorization.

Modern societies are grappling with an increasingly complex and pervasive challenge: the comprehension and management of traffic. This issue has evolved from a mere inconvenience to a major problem that permeates various aspects of urban life, directly impacting people's quality of life, environmental health, time management, and economic productivity. The multifaceted nature of traffic congestion makes it a formidable obstacle for urban planners, policymakers, and citizens alike, as its consequences ripple through society in often unexpected ways. The economic toll of traffic congestion is staggering. Research conducted by Kakooza et al. (2005) revealed a sobering statistic: in the year 2000, drivers in 75 of the world's largest metropolitan areas collectively squandered over \$ 68 billion on wasted work hours and fuel. This figure not only represents a significant drain on individual resources but also points to a broader economic inefficiency that hampers productivity and growth on a global scale. The lost time spent in traffic translates to reduced output, missed opportunities, and increased stress levels for workers, all of which contribute to a less dynamic and less competitive economy.

The problem is particularly acute in rapidly developing regions, such as Africa, where the growth in vehicle ownership has outpaced infrastructure development at an alarming rate. Between 2007 and 2010, Africa's vehicle fleets experienced remarkable growth, ranging from a modest 5% increase in Southern Africa to a staggering 67% surge in Western Africa (Futsaeter and Wilson (2013)). This rapid motorization reflects the continent's economic progress but also highlights the urgent need for sustainable transportation solutions. The current transportation system in Sub-Saharan Africa, as noted by Schindler (2013), is woefully inadequate to handle even the existing number of vehicles, let alone accommodate future growth. This mismatch between vehicle numbers and infrastructure capacity creates a perfect storm of congestion, pollution, and economic inefficiency. Urbanization has further exacerbated the demand for transportation infrastructure. As cities grow and populations become increasingly concentrated in urban areas, the pressure on existing road networks intensifies. This urbanization trend has led to widespread traffic congestion in most urban centers, a problem that seems to be far from resolved Chen et al. (2012). The challenge is not merely one of physical space but also involves complex issues of urban planning, public transport integration, and the adoption of smart city technologies.

The environmental implications of traffic congestion are equally concerning. This pollution has direct health consequences for urban populations, leading to increased rates of respiratory diseases, cardiovascular problems, and other health issues. Moreover, the noise pollution generated by constant traffic creates a stressful urban environment, impacting mental health and overall well-being. Time management, a crucial aspect of modern life, is severely affected by traffic congestion. The unpredictability of travel times due to varying traffic conditions forces individuals to allocate extra time for commuting, reducing leisure time and work-life balance. This constant struggle with time has psychological repercussions, contributing to stress, anxiety, and decreased job satisfaction. Addressing these challenges requires a multifaceted approach that combines infrastructure development, technological innovation, and policy reform. Many cities are exploring solutions such as intelligent transportation systems, congestion pricing, and the promotion of alternative modes of transport like cycling and walking. The rise of electric vehicles and the potential of autonomous driving technologies offer hope for reducing emissions and improving traffic flow, but their integration into existing urban fabrics presents its own set of challenges. Furthermore, the COVID-19 pandemic has added a new dimension to traffic management, with shifts in work patterns and public transport usage potentially reshaping urban mobility in the long term. As cities adapt to these changes, there's an opportunity to rethink traditional approaches to traffic management and urban planning.

The challenge of comprehending and managing traffic in modern societies is a complex issue that touches on economics, environment, urban planning, technology, and public health. As urbanization continues and vehicle ownership grows, particularly in developing regions, finding sustainable solutions to traffic congestion will be crucial for maintaining livable cities and supporting economic growth. The path forward will likely involve a combination of smart infrastructure, policy innovation, and behavioral changes, requiring collaboration between governments, businesses, and citizens to create more efficient and sustainable urban transportation systems.

Despite significant advancements in urban planning, infrastructure development, and transportation technologies, traffic congestion remains a persistent and formidable challenge in cities across the globe Wei et al. (2017). This enduring issue continues to frustrate commuters, strain economies, and pose environmental concerns, underscoring the complexity of managing vehicular flow in increasingly dense urban environments. Over the past decade, researchers in the field of traffic flow dynamics have narrowed their focus to two critical aspects of urban road networks that significantly impact overall traffic patterns: lane changing behaviors at T-junctions MAITHYA (2018) and the capacity and efficiency of roundabouts Macioszek (2020). These areas of study have emerged as key focal points due to their outsized influence on traffic flow and their potential to either alleviate or exacerbate congestion depending on their design and management.

The investigation into lane changing at T-junctions has revealed the intricate decision-making processes of drivers and the cascading effects these choices can have on traffic flow. Researchers have explored factors such as gap acceptance, driver aggression, and the impact of signaling systems on lane-changing behaviors. This body of work has highlighted how seemingly minor individual decisions can collectively lead to significant traffic disruptions or, conversely, smoother traffic flow when properly managed. The findings from these studies have implications not only for junction design but also for the development of advanced driver assistance systems and, looking further ahead, the programming of autonomous vehicles to

navigate complex urban intersections more efficiently.
Simultaneously, the study of roundabout capacity has gained prominence as cities increasingly turn to this traffic management solution to improve flow at intersections. Roundabouts have been touted for their potential to reduce accidents, improve traffic flow, and decrease emissions by minimizing stop-and-go traffic. However, their effectiveness can vary widely based on design parameters, local driving cultures, and traffic volumes. Researchers have delved into aspects such as entry capacity, circulating flow, and geometric design to optimize roundabout performance under various conditions. This research is particularly crucial as many cities retrofit existing intersections with roundabouts or incorporate them into new urban developments.

Building on these focused areas of research, the primary objective of this project is to develop a comprehensive macroscopic model that accurately represents the complex traffic dynamics within roundabouts. This ambitious goal seeks to synthesize the myriad factors that influence roundabout performance into a cohesive framework that can predict and analyze traffic flow under various conditions. The macroscopic approach allows for a broader view of traffic patterns, enabling researchers and planners to understand how individual vehicle behaviors aggregate to form overall traffic flow characteristics. This model aims to capture not only the physical aspects of roundabout design but also incorporate behavioral factors, such as driver decision-making processes, cultural norms, and the impact of different vehicle types on roundabout capacity. The development of such a model requires a multidisciplinary approach, drawing on fields such as traffic engineering, behavioral psychology, data science, and computer modeling. It involves collecting and analyzing vast amounts of real-world traffic data, conducting simulations to test various scenarios, and refining the model to account for the diverse range of factors that influence roundabout performance. The challenge lies in creating a model that is both comprehensive enough to capture traffic dynamics and flexible enough to be applied across different urban contexts and roundabout designs. Furthermore, this project aims to translate its theoretical findings into practical applications. Based on the insights gained from the macroscopic model and the broader body of research on traffic flow dynamics, the project will provide valuable advice to road authority regulators regarding traffic management strategies and infrastructure characteristics. This advice will be grounded in empirical evidence and sophisticated modeling, offering policymakers and urban planners a robust foundation for decision-making.

Recommendations may cover a wide range of areas, including optimal roundabout design parameters for different traffic volumes and urban contexts, strategies for managing peak hour flows, integration of smart traffic management systems, and approaches to public education on efficient roundabout usage.

The implications of this research extend beyond immediate traffic management concerns. By improving the efficiency of roundabouts and, by extension, overall urban traffic flow, the project has the potential to contribute to broader goals of reducing urban emissions, improving air quality, enhancing road safety, and increasing the overall livability of cities. Moreover, this study could inform the development of future transportation technologies, such as connected and autonomous vehicles, by providing an understanding of the complex dynamics at play in urban traffic systems.

While traffic congestion remains a stubborn challenge of modern urban life, focused research on critical components of traffic systems, such as T-junctions and roundabouts, offers promising avenues for improvement. By developing a comprehensive macroscopic model of roundabout dynamics and translating these findings into practical recommendations, this project aims to make a significant contribution to the ongoing effort to create more efficient, safe, and sustainable urban transportation networks.

The extensive research conducted on traffic flow dynamics, particularly focusing on roundabouts, has yielded significant and multifaceted results that have proven immensely beneficial for both mathematicians and road engineers. These findings have enhanced our understanding of traffic patterns, driver behavior, and the complex interactions that occur within circular intersections. Mathematicians have gained valuable insights into modeling complex systems and have developed new algorithms to simulate and predict traffic flow under various conditions. Road engineers, on the other hand, have been able to apply these theoretical advances to practical design improvements, optimizing roundabout geometry, entry and exit angles, and lane markings to enhance overall efficiency and safety. Nonetheless, despite these advancements, the roundabout remains an area of considerable concern and ongoing study due to its inherent instability, particularly when it comes to lane changing dynamics and the often unpredictable nature of drivers' behavior. This instability is not merely a minor inconvenience but a critical factor that can significantly impact the overall performance and safety of the roundabout. The circular design, while efficient in many respects, introduces unique challenges that are not present in traditional intersections. Drivers must make quick decisions about entry points, lane selection, and exit strategies, all while navigating around other vehicles in a continuous flow. This decision-making process, coupled with varying levels of driver skill and familiarity with roundabout navigation, contributes to the system's instability. Regrettably, this critical aspect of roundabout dynamics has not received adequate research attention thus far. While numerous studies have focused on capacity analysis, entry flow rates, and geometric design optimization, the intricate dance of lane changing within the roundabout itself has been somewhat overlooked. This gap in research is particularly concerning given the pivotal role that lane changing behavior plays in the overall stability and efficiency of roundabout operations. Each lane change represents a potential point of conflict and disruption, capable of triggering a cascade of reactions from other drivers that can rapidly deteriorate traffic flow.

The instability present at the roundabout is not an isolated phenomenon; rather, it has far-reaching consequences that contribute to traffic congestion in all the lanes connected to it. As vehicles hesitate or make abrupt lane changes within the roundabout, the smooth flow of traffic is disrupted. This disruption can quickly propagate, causing queues to form at entry points and potentially leading to gridlock in severe cases. The impact extends beyond the immediate vicinity of the roundabout, affecting the broader road network and potentially causing delays and increased travel times across a significant urban area. To address this pressing issue, the current study aims to focus on a critical yet underexplored aspect of roundabout dynamics: determining the optimal number of allowed lane changes within the roundabout. This approach recognizes that while lane changes are often necessary for drivers to reach their desired exits, excessive lane changing can lead to instability and reduced efficiency. By identifying an optimal balance, it may be possible to maintain the flexibility that drivers need while minimizing the disruptive effects of frequent lane changes. This research will involve complex modeling of traffic flow, taking into account factors such as roundabout size, number of entry and exit points, typical traffic volumes, and peak hour demands.

Additionally, the study will delve deeper into the capacity of the roundabout, building upon existing research to develop a more nuanced understanding of how capacity is affected by lane changing behavior. This analysis will consider not just the theoretical maximum number of vehicles that can pass through the roundabout in ideal conditions, but also how real-world factors such as driver hesitation, varying vehicle sizes, and the presence of pedestrians and cyclists impact effective capacity. By gaining a more comprehensive view of capacity dynamics, it will be possible to design roundabouts that are better equipped to handle fluctuations in traffic volume and composition. A crucial component of this research will be the analysis of drivers' behavior within roundabouts. This will involve observational studies, surveys, and possibly even simulator-based experiments to gain insights into the decision-making processes of drivers as they navigate roundabouts. Factors such as driver confidence, familiarity with roundabouts, perception of gaps in traffic, and response to signage and road markings will be examined. Understanding these behavioral aspects is essential for devising effective strategies to guide and influence driver behavior in ways that promote stability and efficiency.

The ultimate goal of this comprehensive study is to devise effective strategies for avoiding instability and, consequently, reducing traffic congestion in and around roundabouts. These strategies may include a combination of physical design modifications, such as optimized lane markings or improved signage, as well as policy recommendations, like public education campaigns on efficient roundabout usage or the implementation of smart traffic management systems. By addressing the root causes of instability, particularly those related to lane changing behavior, it may be possible to significantly enhance the performance of roundabouts, reducing congestion and improving overall traffic flow.
Furthermore, the findings of this study could have broader implications for urban traffic management. Insights gained from understanding lane changing behavior and driver decision-making in roundabouts could be applied to other complex traffic scenarios, potentially leading to improvements in intersection design, freeway management, and even the development of autonomous vehicle navigation systems. As cities continue to grow and traffic volumes increase, the ability to optimize flow through critical nodes like roundabouts will become increasingly important for maintaining urban mobility and quality of life.

Although roundabouts have proven to be an effective traffic management solution in many contexts, their inherent instability, particularly concerning lane changing behavior, presents an ongoing challenge. By focusing on this critical aspect, determining optimal lane change allowances, analyzing roundabout capacity in real-world conditions, and deeply understanding driver behavior, this study aims to contribute valuable insights to the field of traffic engineering. The potential outcomes of this research extend beyond theoretical interest, offering practical solutions that could significantly improve the efficiency and safety of urban transportation networks, ultimately benefiting commuters, city planners, and the environment alike.

1.2 Statement of the Problem

The pervasive issue of traffic congestion in urban areas has reached critical levels, with far-reaching consequences that extend beyond mere inconvenience to drivers. A significant contributor to this problem is the behavior of vehicles entering their preferred lanes with little regard for other road users, a phenomenon that has become increasingly common in busy intersections and roundabouts. This self-centered approach to navigation not only disrupts the smooth flow of traffic but also catalyzes the widespread growth of congestion, creating a ripple effect that impacts entire road networks. The resulting surge in travel duration and frequent occurrences of gridlock have culminated in a host of adverse consequences, profoundly affecting both the economic vitality and ecological well-being of states and municipalities Raslavičius et al. (2015). The economic impact is particularly stark, manifesting in lost productivity, increased fuel consumption, and higher transportation costs for businesses and individuals alike. From an ecological standpoint, the prolonged idling of vehicles in congested areas leads to elevated levels of emissions, contributing to air pollution and exacerbating urban heat island effects, thereby posing significant challenges to environmental sustainability efforts.

The complexity of this issue has not gone unnoticed by the research community. Previous studies have made significant strides in understanding and modeling traffic dynamics at various types of intersections. Notably, the work conducted by MAITHYA (2018) delved into the simulation of traffic congestion at unsignalized intersections, with a particular emphasis on T-junctions. This research provided valuable insights into the behavior of vehicles at these critical points in the road network, highlighting the factors that contribute to congestion and suggesting potential mitigation strategies. Building upon this foundation, Muleta and Obsu (2020) further advanced the field by analyzing traffic patterns in roundabouts with three entering and three exiting roads. Their work shed light on the unique dynamics of circular intersections, particularly how the flow of traffic is affected by the number and configuration of entry and exit points.

However, the rapid evolution of urban infrastructure and the increasing complexity of modern highway systems have outpaced some aspects of this research. In contemporary urban and suburban landscapes, roundabouts with four entering and four exiting roads have become increasingly prevalent. These more complex configurations present new challenges and dynamics that were not fully addressed in previous studies. The increased number of entry and exit points introduces a higher level of complexity in terms of vehicle interactions, lane-changing behaviors, and overall traffic flow patterns. This shift in infrastructure design necessitates a reevaluation and expansion of existing traffic models and analyses.

Recognizing this gap in the literature, it has become crucial to build upon and expand the foundational work of Muleta and Obsu (2020). The current research aims to develop more comprehensive procedures that integrate various local traffic characteristics, with a specific focus on modern roundabouts featuring four entering and four exiting roads. This approach acknowledges the need for models that can accurately represent the intricacies of these more complex intersections, taking into account factors such as driver behavior, vehicle types, peak hour dynamics, and the impact of surrounding road networks on roundabout performance.

To achieve this ambitious goal, the study will utilize and adapt the General Motor model, a well-established framework in traffic flow theory. The innovation lies in extending this model to include lane-changing maneuvers, a critical aspect of roundabout dynamics that has not been fully explored in previous research. These lane-changing behaviors serve as the foundation for describing and predicting traffic flow at unsignalized roundabouts, capturing the decision-making processes of drivers as they navigate through the circular intersection. By incorporating these maneuvers into the model, researchers aim to create a more realistic and nuanced representation of roundabout traffic dynamics.

The primary emphasis of this research shall be on the General Microscopic Motors car model, a choice motivated by its comprehensive characteristics and the promising possibilities it offers for further expansion. This model is renowned for its ability to capture individual vehicle behaviors and interactions, making it particularly well-suited for analyzing the complex dynamics of roundabouts. By focusing on microscopic elements, the study can delve into the nuanced aspects of driver decision-making, gap acceptance, and lane selection that collectively contribute to overall traffic flow patterns.

To ground this theoretical work in real-world conditions, the traffic flow under consideration is inspired by a scenario observed at the United States roundabout in Bujumbura, Burundi. This specific junction presents a unique case study due to the absence of green signalization, as depicted in the accompanying figure. The lack of traffic signals introduces an additional layer of complexity to the roundabout's operation, relying entirely on driver judgment and adherence to right-of-way rules. This unsignalized environment closely mimics many modern roundabout designs and provides an excellent opportunity to study natural traffic flow dynamics without the influence of external control mechanisms.

The choice of this particular roundabout as a model for the study is significant for several reasons. Firstly, it represents a typical example of modern roundabout design in a rapidly developing urban context, making the findings potentially applicable to similar intersections worldwide. Secondly, the absence of signalization offers a pure environment to study driver behavior and decision-making, uninfluenced by the rigid structure imposed by traffic lights. This natural flow allows for a more authentic analysis of lane-changing behaviors, gap acceptance, and the self-organization of traffic within the roundabout.

Furthermore, by focusing on a roundabout in Burundi, the study acknowledges the importance of considering diverse geographical and cultural contexts in traffic research. Driver behaviors and road use patterns can vary significantly across different regions and cultures, and by incorporating data from a non-Western setting, the research aims to broaden the applicability of its findings and contribute to a more globally relevant understanding of roundabout dynamics.

The synthesis of empirical observations and advanced modeling approaches likely produced valuable insights that are both theoretically sound and practically applicable. By analyzing the patterns of vehicle movement, lane usage, and congestion formation at this specific roundabout, researchers can calibrate and validate their extended General Motor model, ensuring that it accurately reflects the complexities of actual traffic scenarios.

This comprehensive approach, combining theoretical model development with real-world case study analysis, has the potential to significantly advance our understanding of traffic flow in modern roundabouts. The findings from this research could have far-reaching implications for urban planning, traffic management strategies, and the design of future roundabouts. By identifying the key factors that contribute to efficient traffic flow and those that lead to congestion, the study aims to provide valuable guidance for traffic engineers and urban planners working to optimize roundabout performance and reduce congestion in busy urban areas.

Moreover, the insights gained from this research could inform the development of more sophisticated traffic simulation tools, aiding in the design and evaluation of new roundabouts before they are constructed. This proactive approach to infrastructure planning could lead to more efficient road networks, reduced congestion, and ultimately, improved quality of life for urban residents.

By building upon previous research and extending established models to address the complex-

ities of modern four-way roundabouts, this study aims to make a significant contribution to the field of traffic engineering. The focus on lane-changing behaviors and the incorporation of real-world data from an unsignalized roundabout in Burundi offers a unique perspective that bridges theoretical modeling with practical application. As urban areas continue to grow and traffic volumes increase, the insights gained from this research will be invaluable in developing more efficient, safe, and sustainable urban transportation networks
The traffic flow under consideration is inspired by a scenario observed at the United States roundabout in Bujumbura, Burundi. At this specific junction, there is an absence of green signalization, as depicted in the accompanying figure.

1.3 Objectives of the Study

1.3.1 General Objective

The main goal is to create a model microscopic for traffic flow that accurately represents movements of vehicles at unsignalized roundabouts. Additionally, the aim is to simulate the occurrence of traffic congestion specifically at these unsignalized roundabouts.

1.3.2 Specific Objectives

1. To enhance fundamental General microscopic Motors car model by integrating lane changing maneuvers that occur roundabout.
2. The extended model will be employed study the development of traffic congestion unsignalized roundabout.
3. To identify suitable strategies for merging vehicles at unsignalized roundabouts.

1.4 Study Justification

Traffic congestion problem for urban highways is a widespread issue faced globally in our road systems. Researchers in traffic, including those in mathematics and traffic engineering, face a considerable challenge in comprehending the root causes of traffic congestion. Creating a model that can accurately predict and alleviate traffic jams while identifying their source in real-time is a crucial step towards effectively addressing this problem. Such a model would serve to notify road engineers, government authorities, traffic users, and passengers, providing them with valuable information.

1. The aims is to support the sector of transport in optimizing roundabouts, leading to a reduction in travel times wasted due to traffic congestion at these junctions.
2. The research will enhance control strategies aimed at minimizing congestion at roundabouts, with potential applicability to similar intersections.
3. Public transport and policymakers will be guided by optimal control strategies at roundabouts through the insights gained from this study.
4. According to the research findings, transport administrators will be empowered to design informative seminars, workshops, and training sessions. These efforts aim to increase awareness among transport stakeholders and the wider public about the necessity of adhering to traffic regulations. Furthermore, the initiatives will encourage active involvement in the formulation of policies and the decision-making processes related to traffic management.

As a result of this study, residents of the northern region of Bujumbura city in Burundi will experience reduced traffic congestion and lower travel costs.

1.5 Scope of Study

The scope of the proposed research is limited to the computational analysis of traffic flow within an unsignalized roundabout. The study aims to develop mathematical models for traffic movement and lane changing, specifically focusing on predicting and identifying sources of traffic congestion at the unsignalized roundabout located in Bujumbura, Burundi, which resembles roundabouts in the United States.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Numerous investigations have been carried out to emphasize methods of intervention and traffic congestion management. Within this chapter, an evaluation of acceleration, and lane changing models is analysis through a literature review.

2.2 Roundabout and Microscopic traffic flow model

Roundabouts are commonly found in urban road networks and play a vital role in reducing traffic crashes by minimizing vehicle conflicts. However, the implementation of road restrictions at the entrances and exits can increase the likelihood of collisions between vehicles as they enter or exit the roundabouts. Various researchers have worked on roundabout models, with macroscopic analysis being applied in several studies focusing on multi-lane roundabouts. On the other hand, microscopic models delve into the individual behavior of each vehicle, considering factors like driver acceleration and deceleration. While microscopic models offer valuable insights into individual vehicles' movements within the traffic stream, they have a drawback of heavily relying on extensive data about specific vehicle interactions Haight (1960). Traffic flow models, which have been developed and utilized since the early 20th century, serve the purpose of comprehending, describing, and predicting traffic flow dynamics Polus and Shmueli (1997).

2.2.1 Lane changing theory and Microscopic traffic flow model

In recent years, the field of traffic flow modeling and simulation has experienced a remarkable surge of interest, as noted by Delis et al. (2014). This growing fascination is not merely an academic pursuit but a response to the increasingly complex challenges posed by modern urban transportation systems. Vehicular traffic, far from being a simple matter of cars moving along roads, represents an intricate and highly dynamic process that involves the interplay of numerous car systems, human behaviors, and environmental factors. The complexity of this phenomenon is primarily rooted in the nonlinear interactions between a multitude of elements, including but not limited to travel decision behavior, vehicle routing within the traffic network, and the emergence and evolution of traffic congestion.

The term "spatiotemporal" in the context of traffic flow is crucial, as it underscores the fundamental nature of empirical traffic congestion as a phenomenon that unfolds in both real space and time. This dual dimension adds layers of complexity to the analysis and modeling of traffic patterns, necessitating sophisticated approaches that can capture both the spatial distribution of vehicles across a network and the temporal evolution of traffic states. Understanding this spatiotemporal nature is essential for developing accurate predictive models and effective management strategies.

Typically, traffic flow can be broadly categorized into two primary states: the free flow state and the congested state. The free flow state is characterized by vehicles moving at or near their desired speeds, with minimal interference from other vehicles. In this state, the traffic density is relatively low, allowing for smooth and efficient movement. Conversely, the congested state occurs when the density of vehicles increases to a point where individual vehicle movements are significantly impeded by the presence of other vehicles, leading to reduced speeds and increased travel times.

A critical insight that has emerged from extensive research in this field is the identification of traffic breakdown as a key mechanism in the transition from free flow to congested states within traffic networks. This breakdown phenomenon is particularly significant because it often marks the onset of widespread congestion, transforming what was initially a smoothly flowing system into one plagued by delays and inefficiencies. Researchers have observed that this traffic breakdown is not a random occurrence but typically manifests at specific locations within the network, commonly referred to as highway bottlenecks.

These bottlenecks can arise from a variety of factors, both structural and incidental. On and off-ramps, for instance, represent critical points in highway systems where the merging and diverging of traffic streams can disrupt the smooth flow of vehicles. The sudden influx of vehicles from an on-ramp or the deceleration of vehicles exiting via an off-ramp can create turbulence in the traffic flow, potentially triggering a breakdown. Similarly, areas where the number of lanes is reduced present another common type of bottleneck. As vehicles are forced to merge into fewer lanes, the increased density and potential for conflicts can easily lead to congestion. Beyond these structural elements, incidental factors such as accidents play a significant role in the formation of bottlenecks and subsequent traffic breakdowns. An accident not only directly obstructs traffic flow but also introduces an element of unpredictability that can ripple through the system, causing drivers to alter their behavior in ways that further contribute to congestion. Road construction, while necessary for maintenance and improvement of infrastructure, represents another major source of bottlenecks. The reduction in capacity and changes in road geometry associated with construction zones can significantly impact traffic flow, often leading to prolonged periods of congestion.

Lane changes, a seemingly routine aspect of driving, have been identified as a particularly influential factor in the dynamics of traffic flow and the potential for breakdown. The act of changing lanes introduces perturbations into the traffic stream, which, under certain conditions, can amplify and propagate, leading to the formation of stop-and-go waves or even full-blown traffic jams. The complex interplay between lane-changing behavior, traffic density, and road geometry makes this aspect of traffic flow particularly challenging to model and manage effectively. The identification of these various factors contributing to traffic breakdown and congestion has profound implications for both the theoretical understanding of traffic dynamics and the practical approaches to traffic management. From a modeling perspective, it highlights the need for sophisticated simulation tools that can account for the myriad factors influencing traffic flow, from the macro-scale of network topology to the micro-scale of individual driver behaviors. Such models must be capable of capturing the nonlinear interactions that can lead to the emergence of congestion from initially free-flowing conditions.

For traffic engineers and urban planners, this understanding informs the development of strategies to mitigate congestion and improve the overall efficiency of transportation networks. These strategies might include targeted infrastructure improvements to address known bottlenecks, the implementation of advanced traffic management systems that can dynamically respond to changing conditions, and the development of public policies aimed at influencing travel behavior to reduce peak demand on critical network elements.

Moreover, the recognition of temporal nature of traffic congestion underscores the importance of real-time data collection and analysis in modern traffic management. Advanced sensor technologies, coupled with learning algorithms, offer the potential for predictive congestion management, where potential breakdowns can be identified and mitigated before they fully develop. The surge of interest in traffic flow modeling and simulation reflects the growing recognition of the critical importance of understanding and managing vehicular traffic in our increasingly urbanized world. The complex, nonlinear nature of traffic dynamics, characterized by the interplay of numerous factors and the potential for sudden transitions from free flow to congested states, presents both significant challenges and opportunities for researchers and practitioners in the field. As our understanding of these dynamics continues to evolve, supported by advances in modeling techniques and data analytics, there is hope for the development of more efficient, resilient, and sustainable urban systems capable of meeting the mobility needs of future generations.

The process of lane changing within traffic flow dynamics represents a complex and multifaceted phenomenon that plays a crucial role in the overall behavior of vehicular traffic systems. Concentrating on this specific aspect of traffic flow, it becomes evident that the accomplishment of a lane change maneuver is far from a simple or instantaneous action. Instead, it involves a sophisticated sequence of three primary stages, each of which contributes significantly to the successful execution of the maneuver and, by extension, to the broader patterns of traffic flow and potential congestion formation. The first stage in this process is the generation of lane change motivation, a cognitive step that involves the driver's assessment of their current situation and the perceived benefits of moving to an adjacent lane. This motivation can arise from a variety of factors, including the desire to maintain or increase speed, to position the vehicle for an upcoming turn or exit, or to avoid obstacles or slower-moving vehicles in the current lane. The second stage, equally critical, is the selection of an appropriate gap in the target lane. This phase requires the driver to engage in a rapid and complex analysis of the spatial and temporal dynamics of surrounding vehicles, assessing the size of available gaps, the speed differentials between lanes, and the potential reactions of other drivers to the intended maneuver. The challenge here lies not only in identifying a gap of sufficient size but also in predicting how that gap might evolve in the time it takes to execute the lane change. The final stage involves the actual execution of the lane change movement, a physical process that requires precise control of the vehicle, awareness of blind spots, and coordination with the movements of surrounding vehicles. This execution phase is where the intentions formed in the previous stages are translated into action, with potential impacts on the flow of traffic in both the original and target lanes. The complexity of this three-stage process is further compounded by the fact that the driver's underlying motivation for changing lanes can significantly influence how each stage is approached and executed. Recognizing this, researchers have developed various classifications of lane change motivations, each with its own implications for traffic flow dynamics. Mandatory lane changes, for instance, are those necessitated by the road configuration or the driver's intended route, such as moving to an exit lane or responding to lane closures. These types of lane changes are often characterized by a higher level of urgency and may be executed even in suboptimal gap conditions, potentially leading to more disruptive effects on traffic flow. Discretionary lane changes, on the other hand, are voluntary moves made by drivers seeking to improve their driving conditions, such as moving to a faster-moving lane or avoiding slow vehicles. These changes tend to be more flexible in their timing and execution, allowing drivers to be more selective about when and how they make their move. Preemptive lane changes represent a forward-thinking approach, where drivers anticipate future needs or potential obstacles and change lanes well in advance to avoid future mandatory situations. This classification, as noted by Lin et al. (2005) in their comprehensive review, highlights the diverse motivations driving lane change behaviors and underscores the complexity of modeling and predicting lane change patterns within traffic flow. The interplay between these different types of motivations, combined with the three-stage process of lane changing, creates a rich and dynamic environment that significantly influences the overall characteristics of traffic flow. Understanding these nuances is crucial for developing accurate traffic models, designing effective traffic management strategies, and ultimately improving the efficiency and safety of road networks. As research in this area continues to evolve, incorporating these insights into traffic flow theories and simulation models promises to enhance our ability to predict, manage, and mitigate congestion in increasingly complex urban transportation systems.

The process of lane changing is a complex and dynamic aspect of traffic flow that significantly impacts both safety and efficiency on roadways. When a driver develops the desire to change lanes, they initiate a multifaceted decision-making process that involves searching for a suitable gap in the target lane and subsequently executing the lane change maneuver.

However, the occurrence of improper lane changes, which can be attributed to two primary factors—the acceptance of an inadequately small gap or the execution of an inappropriate lane change trajectory—can have far-reaching consequences on traffic flow dynamics. These improper maneuvers can create ripple effects throughout the traffic stream, leading to disruptions that potentially escalate into more severe congestion or safety hazards. Research conducted by Brookhuis et al. (2001) has shed light on the prevalence of improper lane changes among human drivers, particularly those with insufficient driving skills and experience. This finding underscores the critical role that driver education and training play in maintaining smooth and safe traffic flow. The safety implications of improper lane changes are stark and well-documented. Studies by van Winsum et al. (2005) have revealed a concerning statistic: approximately 4% to 10% of accidents can be directly attributed to improper lane changes. This range indicates that a significant portion of road accidents could potentially be prevented through improved lane-changing practices. Further emphasizing the gravity of this issue, Amin et al. (2014) analyzed Canadian traffic accident investigation data and uncovered that 10% of major vehicle collisions are directly associated with lane change behavior. Perhaps most alarmingly, statistics from the China Highway Traffic Safety Administration paint an even more dire picture, indicating that a staggering 60% of highway accidents can be attributed to lane changes, as reported by Sun et al. (2021). These figures collectively highlight the critical need for enhanced driver awareness, improved vehicle technologies, and potentially more stringent traffic management strategies to mitigate the risks associated with lane changing. Beyond the immediate safety concerns, the efficiency impacts of lane changes on traffic flow are equally significant. As noted by Laval and Daganzo (2006), lane changes introduce disturbances and congestion into the traffic stream, disrupting the smooth flow of vehicles. These disruptions can propagate through the traffic, leading to the formation of stop-and-go waves and potentially triggering more widespread congestion. The cumulative effect of numerous lane changes, especially in high-density traffic conditions, can substantially reduce the overall capacity and efficiency of the roadway. Addressing these challenges requires a multifaceted approach that combines empirical research, theoretical modeling, and practical applications. In this context, the work of Obsu et al. (2015) represents a significant contribution to understanding and optimizing traffic flow, particularly in the complex environment of roundabouts. By modeling a roundabout as a series of 2x2 junctions and considering various cost functionals such as total travel time and total waiting time, their research provides valuable insights into estimating the time spent by drivers navigating through this critical network section. The analytical minimization of these cost functionals for each junction, focusing on optimizing the right of way parameter of the incoming road, offers a methodological framework for enhancing roundabout efficiency. The subsequent numerical simulations conducted to study traffic behavior throughout the roundabout, comparing the optimized parameter to a fixed constant parameter, provide a practical demonstration of how theoretical optimizations can be applied to real-world traffic scenarios. This approach not only contributes to our understanding of traffic dynamics within roundabouts but also offers potential strategies for improving their design and operation. The comprehensive nature of this research, encompassing both safety and efficiency aspects of lane changing and traffic flow, underscores the interconnected challenges facing traffic engineers and policymakers. It highlights the need for integrated solutions that address driver behavior, vehicle technology, road design, and traffic management systems simultaneously. As urban populations continue to grow and the demand for efficient transportation increases, the insights gained from such studies will be crucial in developing more resilient, safe, and efficient road networks capable of meeting the complex mobility needs of modern societies.

In the research conducted by MAITHYA (2018), the focus was on simulating traffic congestion at unsignalized intersections, specifically T-junctions. To achieve this, the author devised Traffic Flow microscopic Model that considered lane changing maneuvers for simulating traffic flow at the level of intersection. The study involved numerisation of traffic formation using this model. In the paper, I explored a model based on the General Motors Theory (GM) to simulate traffic in unsignalized intersections. Furthermore, the GM model was extended by incorporating lane change (turning) maneuvers, forming the foundation for describing traffic flow at unsignalized intersections. The author employed the Microscopic car following model by representing vehicles discretely and utilized the finite (forward) difference method for discretization. The analysis showed that during situations where a right-turning vehicle and a through-moving vehicle converge at the intersection, priority is granted to the vehicle traveling straight, compelling the right-turning vehicle to yield until the path is unobstructed. Additionally, if another movement is positioned lower in the hierarchy,The vehicles are required to exercise patience and wait until the vehicles from the higher-ranked movements in the traffic hierarchy have completely passed through the intersection before proceeding further.

A recent study by Muleta and Obsu (2020) investigated the evolution of traffic patterns on road networks of a roundabout with three entrance and exit roads. The paper explores the traffic evolution on the roundabout's road network from a macroscopic perspective. The roundabout's road networks are represented as merging and diverging junctions. The study focuses on two scenarios: demand-limited and supply-limited cases, aiming to examine traffic evolution at the junction. The researchers provide comprehensive mathematical analyses and numerical tests for each scenario.

2.3 Research gaps

Developing countries are experiencing a rise in traffic demand, and roundabouts with four entry and four exit roads have become quite common. The study conducted by Muleta and Obsu (2020) needs to be expanded to include a Microscopic model, considering the lane changing aspect for these types of roundabouts. To identify relevant research papers, searches were performed on platforms like Scopus, Google Scholar, and Science Direct, specifically filtering by publication year. However, despite the search efforts, the authors could not find any study that focuses on Unsignalized roundabouts utilizing the General Motor model. Existing papers primarily address traffic flow and congestion issues rather than concentrating on the effective design of roundabouts and the instability within them using mathematical modeling and control strategies.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

Roundabouts have emerged as a critical component of transportation infrastructure in developing countries, serving multiple essential functions that address the unique challenges and constraints faced by these nations in their pursuit of efficient, safe, and sustainable urban mobility. The significance of roundabouts in this context cannot be overstated, as they offer a multifaceted solution to several pressing issues in traffic management and urban development. As a primary advantage, roundabouts improve overall network efficiency by lowering congestion levels and reducing the operational necessity for traffic signal systems. This enhancement in efficiency is particularly valuable in developing countries where rapid urbanization often outpaces the development of sophisticated traffic management systems. By facilitating a continuous flow of traffic, roundabouts help alleviate the bottlenecks that frequently occur at traditional intersections, especially during peak hours. This improved flow not only reduces travel times but also contributes to decreased fuel consumption and lower emissions, aligning with broader environmental sustainability goals. Secondly, the cost-effectiveness of roundabouts compared to traditional intersections equipped with traffic lights makes them an exceptionally attractive option for countries grappling with limited financial resources. The initial investment required for constructing a roundabout is often lower than that of installing and maintaining traffic signal systems, especially when considering the long-term operational costs. This economic advantage allows developing nations to allocate their scarce resources more efficiently, potentially enabling the implementation of more comprehensive transportation infrastructure improvements across a wider area. The reduced need for electricity to power traffic signals also contributes to energy conservation, an important consideration in regions where power supply may be unreliable or costly. Thirdly, the safety benefits of roundabouts cannot be overstated, particularly in the context of developing countries where road safety is often a significant concern. By their very design, roundabouts encourage slower vehicular speeds and provide clearer, more intuitive traffic patterns. This reduction in speed, combined with the elimination of perpendicular intersections where high-speed collisions are more likely to occur, significantly lowers the risk of severe accidents. The circular design of roundabouts also reduces the number of potential conflict points between vehicles, further enhancing safety. In countries where enforcement of traffic rules may be less stringent or where driver education programs are still evolving, the self-regulating nature of roundabouts can play a crucial role in promoting safer driving behaviors and reducing accident rates. Lastly, roundabouts make a substantial contribution to urban planning and development strategies in developing countries by offering a flexible and scalable solution to accommodate increasing traffic volumes as cities expand. The adaptability of roundabouts to varying traffic conditions makes them particularly suitable for rapidly growing urban areas where traffic patterns may change dramatically over relatively short periods. Their capacity to handle higher volumes of traffic compared to traditional intersections makes them an ideal choice for emerging city centers and expanding suburban areas. Moreover, roundabouts can be designed to incorporate aesthetic elements, such as landscaping or public art, contributing to the visual appeal and cultural identity of urban spaces. This multifunctional aspect of roundabouts aligns well with the holistic approach to urban development that many developing countries are striving to adopt, where infrastructure not only serves a practical purpose but also enhances the overall quality of urban life. Additionally, the space efficiency of roundabouts compared to large, multi-lane intersections can free up valuable urban land for other uses, supporting more compact and sustainable city designs. In the broader context of sustainable development, roundabouts also offer environmental benefits through reduced vehicle idling times and smoother traffic flow, contributing to lower air pollution levels in urban areas where air quality is often a significant concern. Furthermore, the adaptability of roundabouts to future transportation trends, such as the integration of pedestrian and bicycle traffic, positions them as forward-thinking solutions in the evolving landscape of urban mobility. As developing countries continue to face the dual challenges of rapid urbanization and limited resources, the multifaceted benefits of roundabouts encompassing improved traffic flow, cost-effectiveness, enhanced safety, and support for sustainable urban development—make them an indispensable tool in the arsenal of urban planners and transportation engineers. Their widespread adoption and strategic implementation can play a crucial role in shaping more efficient, safer, and more livable cities in the developing world, ultimately contributing to improved quality of life and economic development.

Developing countries have increasingly relied on roundabouts as major intersections for multiple roads, a trend highlighted by researchers such as Šarić and Lovrić (2017); Akçelik (2005). This widespread adoption reflects the recognition of roundabouts' potential to improve traffic flow and safety in urban environments. However, the auto-control of this infrastructure poses a significant challenge in many developing nations due to constraints in energy resources and technological capacity, as noted by Colombo et al. (2010); Assolie et al. (2022). This limitation underscores a crucial disparity in infrastructure management capabilities between developing and developed countries. The effectiveness, safety, and efficiency of transportation systems, including the ability to move people and goods seamlessly, are widely recognized as key indicators of a nation's development level, a point emphasized in global studies by the Organization (2009); Vasconcellos (2013). In this context, unsignalized roundabouts emerge as particularly interesting subjects for studying traffic congestion, primarily because they operate without direct control in many developing countries, potentially serving as critical bottlenecks in the broader transportation network. The academic community has responded to these challenges with increased research focus on traffic dynamics at junctions, including roundabouts. Notable contributions in this area include the work of Coclite et al. (2005); Fouladvand et al. (2004), who proposed models capable of describing complex junction dynamics. Specific to roundabouts, researchers like Annunziata et al. (2007); Cutolo et al. (2011) have developed models that capture the unique flow characteristics of circular intersections. The growing popularity of circular roundabouts, as observed by Krogscheepers and Watters (2014), is attributed to their management flexibility, enhanced safety features, and improved mobility outcomes. However, despite these advantages, traffic congestion remains a pervasive problem in transportation systems worldwide, with no immediate end in sight, as highlighted by Chen et al. (2012); Huang and Sadek (2009). In response to this ongoing challenge, recent research in civil engineering and mathematical modeling, exemplified by the work of Kondyli et al. (2017); Pilko et al. (2017), has focused on developing both microscopic and macroscopic models to identify the sources of traffic congestion. A common finding across these studies is the significant impact of poorly managed intersections, including T-junctions and roundabouts, on overall traffic flow, as discussed by Goerigk et al. (2013); Lo et al. (2011). The urban development patterns in many cities, characterized by disintegrated forms spreading along major traffic corridors Raslavičius et al. (2015), have further complicated traffic management challenges. Within unsignalized roundabouts, traffic flow is characterized by three distinct types of maneuvers: two types of straight movements and lane-changing movements, as analyzed by Annunziata et al. (2007); Zakeri and Choupani (2021). This research aims to analyze the evolution of traffic congestion through simulation analysis, proposing a theoretical framework for understanding roundabout traffic flows and strategies for optimizing the use of unsignalized roundabouts. The study focuses particularly on the three different types of movement within roundabouts, recognizing their critical role in overall traffic dynamics. To address the persistent issues of congestion, accidents, and delays commonly observed in African road networks, as reported by Flannery et al. (2004); Associates et al. (2003), this research develops a microscopic model that incorporates lane-changing behavior into the Intelligent Driver Model (IDM). This enhanced model aims to provide a more comprehensive and accurate representation of traffic dynamics within roundabouts, offering insights that could lead to improved design and management strategies for these critical infrastructure elements in developing countries.

This research primarily aims to recommend inclusive safety measures and planning improvements to strengthen transport systems in developing countries, with a particular focus on African nations. This goal is of paramount importance given the unique challenges and constraints faced by these countries in their efforts to enhance urban mobility and road safety. The significance of this objective cannot be overstated, as it directly addresses the critical need for sustainable and cost-effective solutions in regions where traditional approaches to infrastructure expansion are often prohibitively expensive and environmentally unsustainable. Recognizing these limitations, the research emphasizes the crucial importance of redeveloping procedures that integrate various local traffic characteristics for a thorough analysis. This approach is particularly relevant in the context of African countries, where expanding roads and allocating substantial resources for large-scale infrastructure projects are often not viable options due to financial constraints and environmental considerations. By focusing on optimizing existing infrastructure and developing tailored solutions that account for local conditions, the research aims to provide more feasible and context-appropriate strategies for improving traffic management and safety. To ensure the robustness and reliability of the study, all parameters and variables chosen for analysis have been meticulously evaluated, reflecting a commitment to scientific rigor and the production of actionable insights. The research methodology is structured around five consecutive steps, each building upon the previous to create a comprehensive framework for understanding and addressing traffic dynamics in developing urban environments. These steps comprise mathematical modeling, model discretization, computer programming, numerical simulation, and careful observation of simulation results. This systematic approach allows for the development of detailed, nuanced models that can capture the complexities of real-world traffic scenarios while remaining computationally manageable. In modeling the real-world road network, the research focuses on several specific events that occur as vehicles navigate through the system, recognizing these as critical points for intervention and optimization. The first of these is the arrival of vehicles into the network, a process that requires careful modeling given that simulations typically include only a restricted area of the broader road system. Developing an accurate and realistic model for vehicle arrivals is crucial for understanding how traffic patterns develop and evolve over time. Once vehicles are within the network, their behavior as they move along roads is simulated with a high degree of realism, taking into account factors such as driver behavior, vehicle characteristics, and road conditions. This attention to detail in traffic flow modeling is essential for identifying potential bottlenecks and areas where interventions could significantly improve overall system performance. The turning behavior of vehicles at intersections represents another critical aspect of the simulation, as these decision points can significantly impact traffic flow and congestion patterns throughout the network. By accurately modeling how vehicles choose their directions at intersections, the research aims to provide insights into potential strategies for optimizing intersection design and traffic management. To address these complex dynamics, the research team has formulated several essential models that govern the movement, arrival, and decision-making processes of vehicles within the network. A sophisticated model for traffic flow has been developed, capable of simulating both free-flowing traffic conditions and scenarios where vehicles must follow others closely. This dual capability is crucial for accurately representing the full spectrum of traffic conditions that occur in real-world urban environments. Additionally, detailed models for vehicle arrivals and turning behavior have been created, drawing on real-world vehicle count data to ensure their accuracy and relevance. This data-driven approach to model development enhances the reliability of the simulations and increases the potential for generating insights that can be directly applied to improving real-world traffic management strategies. The integration of these various models—covering traffic flow, vehicle arrivals, and turning behavior—into a cohesive simulation framework represents a significant advancement in the field of traffic modeling for developing urban environments. By combining sophisticated mathematical modeling techniques with real-world data and local contextual factors, this research aims to provide a powerful tool for urban planners, traffic engineers, and policymakers in developing countries. The insights generated through this comprehensive approach have the potential to inform targeted interventions that can significantly improve traffic safety, reduce congestion, and enhance overall urban mobility without relying on resource-intensive infrastructure expansion projects. Ultimately, this research contributes to the broader goal of developing sustainable, efficient, and safe transportation systems in African countries and other developing regions, addressing critical challenges in urban development and mobility in a manner that is both innovative and contextually appropriate.

3.2 Assumptions of the models

The assumptions concerned the drivers' behavior when reaching the roundabout of the highway:

1. The density of the traffic stream belongs to [0,ρ max]
2. The speed of the whole lane changing traffic stream is influenced by the average speed of the traffic stream.
3. The drivers are following the keep right rule even at the time of changing lane.
4. From the macroscopic model to microscopic the vehicles approach the cells in aggregate groups

3.3 The microscopic model development

The study takes into account the generalized General Motors car following model, as employed by Borsche et al. (2012), which is represented by the following equation(s). (3.3.1) and (3.3.2)

$$\dot{x}_i = v_i \tag{3.3.1}$$

$$\dot{v}_i = C\left(\frac{v_{i+1}-v_i}{l_i-H}\right)+\frac{1}{T}\left(U\left(\rho_i\right)-v_i\right) \tag{3.3.2}$$

where; $\dot{x}_i$ is the velocity of the i^{th} vehicle

$\dot{v}_i$ is the acceleration of the i^{th} vehicle

l_i denotes the spacing between a leading vehicle and the vehicle that follows it.

H represents the vehicle length, which is assumed to remain constant throughout the analysis.

$U(\rho_i)$ represents the equilibrium velocity, meaning the preferred or steady-state speed of the i^{th} vehicle.

T refers to the reaction time, indicating how long the vehicle takes to adjust its speed toward the equilibrium value. It captures the duration required for the i^{th} vehicle to respond to changes in traffic conditions and move from one position to the next. Additionally, with the changes ΔT that denotes the reaction interval corresponding to a driver's response to evolving traffic situations.

C is a scaling constant applied to the anticipation component in the acceleration formulation.

The acceleration model consists of two components: the first term accounts for anticipation effects, while the second term describes the relaxation process.

Given the above discussions, we now focus on employing the following microscopic equations for our analysis.

$$\dot{x}_i = v_i \tag{3.3.3}$$

$$\dot{v}_i = C\left(\frac{v_{i+1}-v_i}{l_i-H}\right)+\frac{1}{T}\left(U\left(\rho_i\right)-v_i\right) \tag{3.3.4}$$

The local density surrounding vehicle i, along with its inverse,the local (normalized) specific traffic is defined as follows:

$$\rho_i = \frac{H}{l_i} \tag{3.3.5}$$

and

$$\tau_i = \frac{1}{\rho_i} = \frac{l_i}{H}. \tag{3.3.6}$$

The motion of vehicles following a leading vehicle is explained by a car following model. The primary objective of this model is to replicate the behavior of vehicles following each other in real world situations. Hence, it is sensible to compare this model to the driving patterns of human drivers in order to obtain empirical findings. Essentially, any vehicle that is not freely flowing adapts its driving behavior to maintain a safe distance from the vehicle ahead. Car following models have the potential to be applicable to various types of vehicles in theory.

Effective management of roundabouts is a key part of modern traffic infrastructure, especially in developing countries where urban mobility continues to grow. Understanding how roundabouts function—particularly unsignalised ones is essential for maintaining smooth and safe traffic flow. In this study, we construct and demonstrate a microscopic traffic simulation for an unsignalised roundabout, employing a car-following framework grounded in the Intelligent Driver Model (IDM).

At an unsignalised roundabout, movement depends largely on yielding behaviour and right of way rules. Vehicles entering the circle must give way to those already circulating. When this rule is respected, traffic generally flows more smoothly than at signalised intersections. However, during busy periods or when drivers fail to yield delays and congestion can quickly build up. A proper understanding of roundabout operation, therefore, plays a major role in maintaining efficiency and reducing the risk of accidents.

This paper explores a mathematical description of traffic dynamics designed specifically for unsignalised circular roundabouts. We carefully examine the underlying models that treat traffic flow as a continuous process and also highlight their limitations.

The effects of straight-through and turning movements within the IDM framework are analysed numerically in MATLAB using a fourth order Runge Kutta method following a Fast Fourier Transform (FFT). Four vehicles are placed in a simulated environment and observed over a defined period. The simulation results allow us to determine the range of velocities associated with the three types of movement examined, as well as the different manoeuvres performed. These findings serve as indicators of roundabout capacity and performance. Overall, the study provides useful insights for researchers and road engineers involved in designing and improving roundabouts in developing countries.

3.4 Model Problem

The traffic model in this research is generated based on the (IDM) Intelligent Driver Model , a widely used microscopic car-following model that realistically captures how individual drivers adjust their speed and spacing in response to surrounding vehicles. The primary objective of this study is to extend the IDM framework to evaluate traffic congestion inside a roundabout by incorporating lane-changing behavior, particularly for vehicles that move straight through the roundabout rather than exiting immediately.

For the simulation setup, we consider a typical four-leg roundabout, consisting of four entry lanes and four exit lanes. This configuration is one of the most common designs in developing countries, as it has high throughput potential, helps minimize delays, and is relatively low-cost compared to signalized alternatives. By applying our extended IDM model, we aim to identify the optimal range of vehicle speeds that supports smooth circulation while preventing congestion. In addition, the model allows us to estimate the time required to clear the roundabout under different traffic maneuvers, including both straight-through movement and turning movement.

For mathematical tractability, we represent the geometry of the roundabout by conceptualizing it as a combination of two unsignalized T-junctions that merge to form a circular flow. This abstraction enables a clearer analytical approach while preserving the fundamental characteristics of roundabout interactions, such as yielding rules, merging behavior, and priority of circulating lanes.

3.5 Equations of the Model

A microscopic traffic model describes how each vehicle behaves on the road, including both its car-following behaviour and its lane-changing actions. In modern roundabouts, priority is given to the vehicles already circulating, whereas in conventional roundabouts, entering vehicles are given priority. Chang et al. (2013); Wang and Ruskin (2002),This theoretical framework underpins all subsequent equations in this study. The initial condition governing motion along the **A,B or C Paths** (3.5) is specified by $0 < \theta < 2\pi$. The initial conditions of the model change depending on the direction a vehicle intends to turn. When a vehicle leaves a straight approach and enters the connecting lane of the roundabout, its motion follows an arc-shaped path. To capture this movement, we parametrize the arc. As the vehicle continues along this path, it travels as though it is moving along part of a circle with a fixed centre and a constant radius AB, A vehicle initially follows the straight segment and then transitions onto a

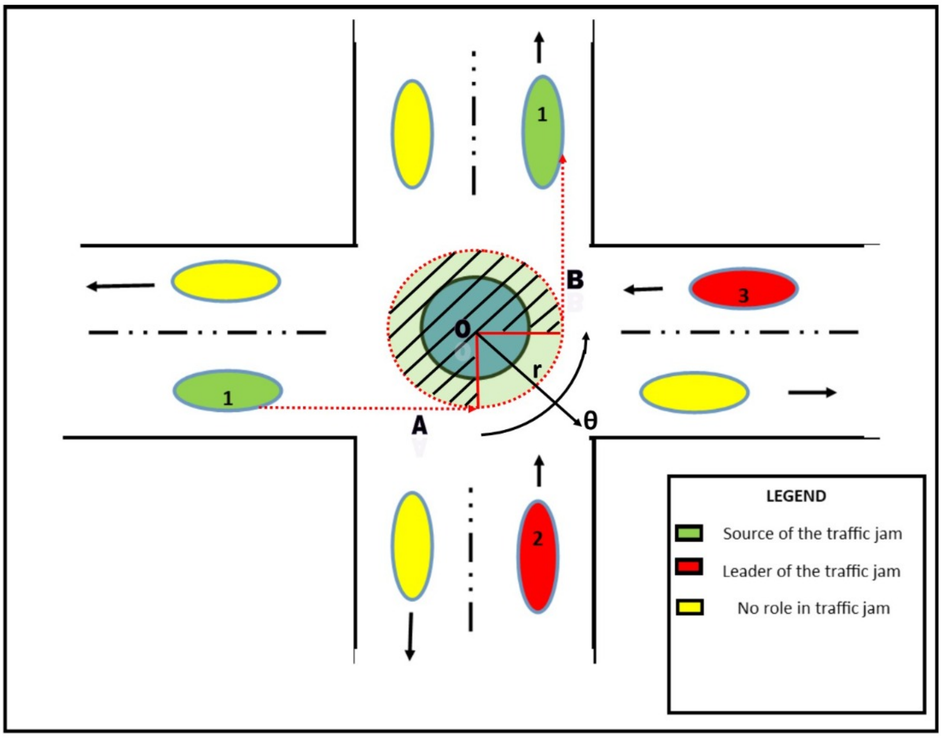

Figure 3.1: Turning Movement along circular roundabout

connecting path, resulting in a curved trajectory. To characterize this motion, the corresponding arc is parameterized. Extending this trajectory shows that the vehicle proceeds along a portion of a circle whose center remains fixed and whose radius r is constant for the entire movement, while the angular parameter θ varies as the vehicle travels along path AB. The vehicle's motion takes place on a two-dimensional plane along the x- and y-axes. When expressing x and y in polar coordinates, we obtain: $x = 2\pi r\cos\theta$ and $y = 2\pi r\sin\theta$. Looked this way, r is a vector and is given as $\vec{r}(\theta) = 2\pi r\left(\cos\theta_i e_1 + \sin\theta_j e_2\right)$. A velocity v_i is applied on the vehicle as it travels through the desired distance xy or the r path., In modelling this motion, three key factors must be included:the radius of the circular path,the number of available paths or lanes, and the gradient or transition angle required to enter each path.
These parameters are incorporated into the vehicle-motion equation to analyse how they influence traffic flow into and out of the roundabout.

According to the three segments of the roundabout A, B, and C described in (3.5), vehicles both enter and exit the circulating flow. Because of these inflows and outflows, the continuity

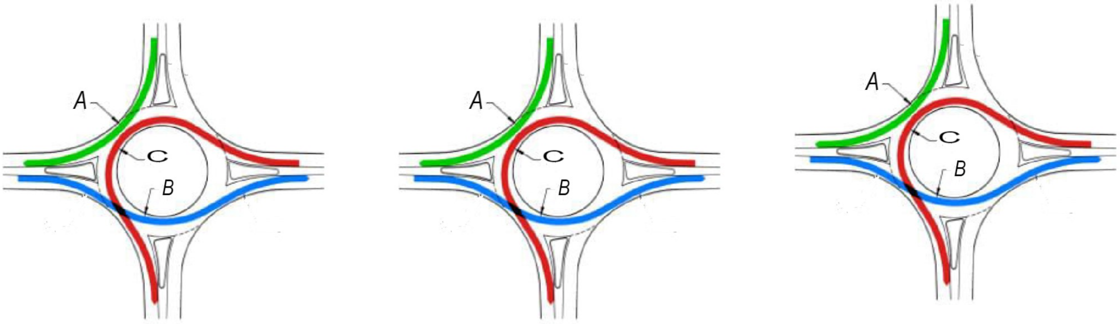

Figure 3.2: A
Straight Movement

Figure 3.3: B
First type of turning Movement

Figure 3.4: C
Second type of turning Movement

Figure 3.5: The three considered Movements inside the roundabout

equation must be modified. In this context, the parameter α represents the rate at which vehicles join the roundabout, while β denotes the rate at which vehicles depart from it during a given time interval.

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = \alpha_j(x,t) - \beta_i(x,t) \tag{3.5.1}$$

α_j : The leading car

β_i : The leading car

The term on the right-hand side of equation (3.5.1) represents the spacing difference between the leading and following vehicles as they exit along any of the three defined movement paths within the roundabout. This quantity is treated as constant with respect to both time and position and is expressed by $\gamma(x,t)$. Accordingly, this leads to the final form of the motion equation.

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = \gamma_k(x,t) \tag{3.5.2}$$

The traffic flow is represented by $\rho(x,t)$, which denotes the density of vehicles at position x and time t, while q denotes the traffic flux measured at the point (x,t). To analyze the behavior of individual vehicles, we then consider a dynamical system consisting of n vehicles, expressed as follows:

$$x(t) = \begin{pmatrix} x_1(t) \\ x_2(t) \\ . \\ . \\ x_n(n) \end{pmatrix} \tag{3.5.3}$$

The i^{th} component of the $x(t)$ is $x_i(t) \quad i \in \{1,\ldots,n\}$ and $x(t)$ is again the vector position. By differentiation, we obtain;

$$v(t,x) = \frac{dx}{dt} = \begin{pmatrix} \frac{d}{dt}x_1(t) \\ \frac{d}{dt}x_2(t) \\ . \\ . \\ \frac{d}{dt}x_n(t) \end{pmatrix} \tag{3.5.4}$$

It can be seen that $\frac{dx}{dt} = f(t,x)$ where $f(t,x)$ is the vector field of the system. In our case, $f(t,x) = v(t,x)$. By integration;
$\int \frac{dx}{dt}dt = \int v(t,x)dt$ For the turning movement, we now use approximation for x which is given by; $x(t) = \int v(t,x)dt$. This approximation will give us a formula for the turning angles θ. For each vehicle i, its position $x_i(t)$ is given by;

$$x_i(t) = \int v_i(t,x)dt; \text{ where } i = 1,2,\ldots\ldots\ldots,n \tag{3.5.5}$$

Looking at Fig.(4.5) and Fig.(4.6) below, three distinct vehicle movements are considered for analysis. In formulating the governing equations, we rely on the assumption that vehicles are conserved within the system—none are created or lost. Consequently, any vehicle entering the roundabout at point A must exit through point B. The specific path taken depends on the turning choice and the selected exit among the three defined movement types.

$$\begin{aligned} \dot{x}_i &= v_i(t) \\ \dot{x}_i(t) &= 2\pi r_1 \left[\cos\theta_i(t)e_1 + \sin\theta_i(t)e_2\right] \\ \dot{x}_i(t) &= 2\pi r_2 \left[\cos\theta_i(t)e_1 + \sin\theta_i(t)e_2\right] \\ \dot{x}_i(t) &= 2\pi r_3 \left[\cos\theta_i(t)e_1 + \sin\theta_i(t)e_2\right] \end{aligned}$$

Figure 3.6: Illustration of Car following Model in straight Movement

Where; $\theta_i(t) \cong \int v_i(t)dt$ and e_1 and e_2 are unit orthogonal vectors,the final function of the motion $F(M)$ in the whole roundabout is finally given by a microscopic model of traffic flow that describes the behavior of individual vehicles within the traffic stream. One common microscopic model is the car-following model the Intelligent Driver Model (IDM) which represents the interactions between a vehicle and the vehicle immediately in front of it .
The IDM is expressed by the Four following equations:

$$\frac{\partial\rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \tag{3.5.6}$$

$$v(t+\Delta t) = v(t) + \frac{dv}{dt}\Delta t \tag{3.5.7}$$

$$a(t+T) = cv^m \frac{\Delta v}{(\Delta x)^l} \tag{3.5.8}$$

$$\frac{dv}{dt} = a\left(1 - \left(\frac{v}{v_0}\right)^\delta - \left(\frac{s^*}{s}\right)^2\right) \tag{3.5.9}$$

Where: v is the velocity of the vehicle, a is the maximum acceleration, v_0 is the desired velocity, s is the spacing between the current vehicle and the vehicle in front, s^* is the desired minimum spacing, δ is the exponent determining the sensitivity to velocity differences.

Update Equation of Velocity adding the change of position:

$$x(t+\Delta t) = x(t) + v(t)\Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \tag{3.5.10}$$

Final equation for Position in circular roundabout:

$$x(t+\Delta t) = x(t) + v(t)\Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \tag{3.5.11}$$

For circular Roundabout the turning angle is given by the following equations:

$$\theta(t+\Delta t) = \theta(t) + \frac{v(t)}{R}\Delta t$$

Where: - θ is the angular position of the vehicle on the roundabout. - R is the radius of the roundabout/circular path.

adding the turning movement to the above equations we have the following equations:

$$x(t+\Delta t) = x(t) + v(t) * r_i \left[\cos\theta_i(t) e_1 + \sin\theta_i(t) e_2\right] \Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \tag{3.5.12}$$

Where; $\theta_i(t) \cong \int v_i(t)dt$ and e_1 and e_2 are unit orthogonal vectors, the final function of the motion $F(M)$ in the whole roundabout. Which helps to get the final update equation for the position of vehicle i in Microscopic Model inside the circular roundabout motion.

For straight Movement:

$$F(Str_{Mov}) = \begin{pmatrix} v_1 = \dot{x}_i(t+\Delta t) = \dot{x}(t) + v(t)\Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \\ v_2 = \dot{x}_i(t+\Delta t) = \dot{x}(t) + v(t)\Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \\ v_3 = \dot{x}_i(t+\Delta t) = \dot{x}(t) + v(t)\Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \\ \frac{\partial\rho(x,t+\Delta t)}{\partial t} + v_{\max}\frac{\partial\rho(x,t+\Delta t)}{\partial x} - \frac{v_{\max}}{\rho_{\max}}\frac{\partial\rho^2(x,t+\Delta t)}{\partial x} = \gamma_1(x,t+\Delta t) \\ \frac{\partial\rho(x,t+\Delta t)}{\partial t} + v_{\max}\frac{\partial\rho(x,t+\Delta t)}{\partial x} - \frac{v_{\max}}{\rho_{\max}}\frac{\partial\rho^2(x,t+\Delta t)}{\partial x} = \gamma_2(x,t+\Delta t) \\ \frac{\partial\rho(x,t+\Delta t)}{\partial t} + v_{\max}\frac{\partial\rho(x,t+\Delta t)}{\partial x} - \frac{v_{\max}}{\rho_{\max}}\frac{\partial\rho^2(x,t+\Delta t)}{\partial x} = \gamma_3(x,t+\Delta t) \end{pmatrix} \tag{3.5.13}$$

For two types of turning movement we have the following system:

$$F(Turn_{Mov}) = \begin{pmatrix} v_1 = \dot{x}_i(t+\Delta t) = \dot{x}(t) + v(t) * r_1 \left[\cos\theta_i(t) e_1 + \sin\theta_i(t) e_2\right] \Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \\ v_2 = \dot{x}_i(t+\Delta t) = \dot{x}(t) + v(t) * r_2 \left[\cos\theta_i(t) e_1 + \sin\theta_i(t) e_2\right] \Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \\ v_3 = \dot{x}_i(t+\Delta t) = \dot{x}(t) + v(t) * r_3 \left[\cos\theta_i(t) e_1 + \sin\theta_i(t) e_2\right] \Delta t + \frac{1}{2}\frac{dv}{dt}(\Delta t)^2 \\ \frac{\partial\rho(x,t+\Delta t)}{\partial t} + v_{\max}\frac{\partial\rho(x,t+\Delta t)}{\partial x} - \frac{v_{\max}}{\rho_{\max}}\frac{\partial\rho^2(x,t+\Delta t)}{\partial x} = \gamma_1(r_1\left[\cos\theta_i(t) e_1 + \sin\theta_i(t) e_2\right], t+\Delta t) \\ \frac{\partial\rho(x,t+\Delta t)}{\partial t} + v_{\max}\frac{\partial\rho(x,t+\Delta t)}{\partial x} - \frac{v_{\max}}{\rho_{\max}}\frac{\partial\rho^2(x,t+\Delta t)}{\partial x} = \gamma_2(r_2\left[\cos\theta_i(t) e_1 + \sin\theta_i(t) e_2\right], t+\Delta t) \\ \frac{\partial\rho(x,t+\Delta t)}{\partial t} + v_{\max}\frac{\partial\rho(x,t+\Delta t)}{\partial x} - \frac{v_{\max}}{\rho_{\max}}\frac{\partial\rho^2(x,t+\Delta t)}{\partial x} = \gamma_3(r_3\left[\cos\theta_i(t) e_1 + \sin\theta_i(t) e_2\right], t+\Delta t) \end{pmatrix} \tag{3.5.14}$$

TThese equations describe how each vehicle's velocity and position change over time based on its interaction with the vehicle ahead. The IDM reflects a driver's natural tendency to reach a preferred speed while maintaining a safe following distance, and it incorporates both acceleration and braking behaviour.

In real applications, four extensions of the IDM have been developed to account for factors such as differences in driver behaviour, varying traffic conditions, and the influence of road geometry. Microscopic traffic models like the IDM serve as essential tools for analysing and simulating traffic behaviour at the level of individual vehicles.

3.6 Method of Solution

The resolution of complex traffic dynamics within roundabouts, particularly in the context of developing countries, necessitates a sophisticated and multifaceted approach to mathematical modeling and numerical analysis. This research undertakes a comprehensive methodology that begins with the transformation of a non-linear first order partial differential equation, derived from the initial traffic flow model, into a more manageable first order ordinary differential equation. This crucial step is accomplished through the application of the Fast Fourier Transform (FFT), a powerful mathematical tool that allows for the efficient analysis of complex waveforms and signals. The utilization of FFT in this context represents a novel approach to traffic flow modeling, enabling the researchers to capture and analyze the intricate patterns and periodicities inherent in roundabout traffic dynamics with unprecedented precision. Following this transformation, the research proceeds to establish and fix initial parameters that accurately reflect the specific characteristics of the roundabout under study. These parameters serve as the initial conditions for the subsequent numerical analysis, ensuring that the model's outputs are grounded in the real-world conditions of the roundabout in question. The core of the numerical analysis involves solving for the traffic density (ρ) using a fourth order Runge Kutta method, a robust and widely respected numerical technique known for its accuracy in solving differential equations. This method is implemented within the MATLAB environment, leveraging its powerful computational capabilities to handle the complex calculations required. A key aspect of this approach is the assumption of periodic boundary conditions for maximum velocity and maximum density, which allows for a more realistic representation of the cyclical nature of traffic flow within a roundabout. This assumption is particularly crucial for accurately determining the movement of each vehicle considered in the model, as it reflects the continuous and repetitive nature of traffic circulation in roundabout environments. The resolution of the roundabout problem extends beyond simple differential equation solving, incorporating advanced numerical techniques to capture the full complexity of traffic dynamics. A pivotal step in this process involves the transformation of partial differential equations into integral equations using Green's Formulation method. This transformation is significant as it allows for a more tractable mathematical representation of the complex traffic flow phenomena, particularly when dealing with boundary conditions and non homogeneous terms that are common in roundabout scenarios. The resulting integral equations are then solved using the Runge Kutta Method, chosen for its ability to provide high accuracy solutions for a wide range of differential equations. To capture the critical aspect of lane changing within the roundabout, which significantly impacts traffic flow and congestion patterns, the numerical method is implemented through a bespoke computer algorithm developed in Matlab. This algorithm is designed to simulate the effects of lane changing, a key factor in roundabout traffic dynamics that has often been overlooked in simpler models. The inclusion of lane changing behavior in the simulation represents a significant advancement in the realism and applicability of the model, particularly for developing country contexts where driver behavior may be less predictable and adherence to lane discipline more variable. The outcomes of these simulations are meticulously presented through a series of figures and tables, providing clear and interpretable results that can inform traffic management strategies and infrastructure design decisions. Further enhancing the sophistication of the analysis, the research employs the method of moments to model traffic congestion near roundabouts. This statistical approach allows for the derivation of microscopic traffic flow equations from the General Motor Model, with the crucial addition of considering detached lane changes. The incorporation of detached lane changes into the model is particularly significant, as it addresses a key aspect of real-world driver behavior that can have substantial impacts on overall traffic flow, especially in the complex environment of a roundabout. The resulting microscopic equations, which provide a detailed representation of individual vehicle behaviors and interactions, are solved using the Fourth Order Runge-Kutta method, chosen for its high accuracy and stability in solving systems of differential equations. The implementation of this numerical method to simulate the impact of lane changes on car merging maneuvers at the roundabout is achieved through a sophisticated computer algorithm developed in MATLAB. This algorithm is designed to capture the intricate dynamics of vehicle interactions, including the critical moments of lane changing and merging, which are often the source of congestion and potential conflicts within roundabouts. The findings from these simulations are presented in a comprehensive set of figures and tables, offering detailed insights into traffic behavior under various conditions and scenarios. This multifaceted approach to modeling and simulating roundabout traffic dynamics represents a significant advancement in the field of traffic engineering, particularly in its application to the unique challenges faced by developing countries. By combining advanced mathematical techniques, sophisticated numerical methods, and powerful computational tools, this research provides a robust framework for analyzing and optimizing roundabout performance. The insights generated through this comprehensive approach have the potential to inform targeted interventions and design improvements that can significantly enhance traffic flow, reduce congestion, and improve safety in roundabout environments. Moreover, the methodology developed here offers a template for future studies, potentially extending to other complex traffic scenarios beyond roundabouts, and contributing to the broader goal of developing more efficient, safe, and sustainable urban transportation systems in developing countries.

3.7 NUMERICAL ANALYSIS

3.7.1 Discretisation using Fast Fourier Transform(FFT)

By Fast Fourier Transform (FFT) we transform our partial differential equation(PDE) to ordinary differential equation(ODE)

$$(t+\Delta t) \neq 0 : \begin{cases} F\left(\frac{\partial \rho}{\partial t}\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{\partial \rho}{\partial t} e^{i\omega x} dx = \frac{\partial \hat{\rho}(k,t+\Delta t)}{\partial t} \\ F\left(\frac{\partial \rho}{\partial x}\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{\partial \rho}{\partial x} e^{i\omega x} dx = i\omega\hat{\rho}(x,t+\Delta t) \\ F\left(\frac{\partial \rho^2}{\partial x}\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{\partial \rho^2}{\partial x} e^{i\omega \pi} dx = i\omega\hat{\rho}^2(x,t+\Delta t) \\ F\left(\gamma(x,t+\Delta t)\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \gamma(x,t+\Delta t) e^{i\omega x} dx = \gamma(x,t+\Delta t) \times \frac{1}{2\pi}\delta(t+\Delta t) \\ F\left(v_{\max}\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} v_{\max} e^{i\omega x} dx = v_{\max} \times 2\pi\delta(t+\Delta t) \\ F\left(\frac{v_{\max}}{\rho_{\max}}\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{v_{\max}}{\rho_{\max}} e^{i\omega x} dx = \frac{v_{\max}}{\rho_{\max}} \times 2\pi\delta(t+\Delta t) \end{cases} \tag{3.7.1}$$

By replacing in the equation of continuity I have the following equation,

$$\frac{\partial \hat{\rho}(K,t+\Delta t)}{\partial t} + v_{\max} \times \frac{1}{2\pi}\delta(K) iK\hat{\rho}(x,t+\Delta t) - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K) iK\hat{\rho}^2(K,t+\Delta t) = \gamma(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \tag{3.7.2}$$

I have the final equation of continuity in the ordinary differential form:

For (t+Δ t) $\neq 0$:

$$\frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \tag{3.7.3}$$

we have the final model which will be analyzed using simulated data for one straight movement and two turning movement:

$$F(Str_{Mov}) = \left(\begin{array}{l} v_1 = \dot{x}_i(t+\Delta t) \\ v_2 = \dot{x}_i(t+\Delta t) \\ v_3 = \dot{x}_i(t+\Delta t) \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_1(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_2(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_3(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \end{array} \right) \tag{3.7.4}$$

For first turning Movement we incorporate the gradient of turning in different directions inside the roundabout:

$$F(Fir_{T}urn_{Mov}) = \left(\begin{array}{l} v_1 = \dot{x}_i(t+\Delta t) = r_1\left[\cos\theta_i(t+\Delta t)e_1 + \sin\theta_i(t+\Delta t)e_2\right] \\ v_2 = \dot{x}_i(t+\Delta t) = r_2\left[\cos\theta_i(t+\Delta t)e_1 + \sin\theta_i(t+\Delta t)e_2\right] \\ v_3 = \dot{x}_i(t+\Delta t) = r_3\left[\cos\theta_i(t+\Delta t)e_1 + \sin\theta_i(t+\Delta t)e_2\right] \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_1(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_2(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_3(x,t+\Delta t) \times \frac{1}{2\pi}\delta(K) \end{array} \right) \tag{3.7.5}$$

For second type of turning Movement we incorporate the gradient of turning in different directions inside the roundabout and the radius becomes a conference of the circle around the radius of the turning movement:

$$F(Sec_{T}urn_{Mov}) = \left(\begin{array}{l} v_1 = \dot{x}_i(t+\Delta t) = 2\pi r_1 \left[\cos\theta_i(t+\Delta t)e_1 + \sin\theta_i(t+\Delta t)e_2\right] \\ v_2 = \dot{x}_i(t+\Delta t) = 2\pi r_2 \left[\cos\theta_i(t+\Delta t)e_1 + \sin\theta_i(t+\Delta t)e_2\right] \\ v_3 = \dot{x}_i(t+\Delta t) = 2\pi r_3 \left[\cos\theta_i(t+\Delta t)e_1 + \sin\theta_i(t+\Delta t)e_2\right] \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_1(x, t+\Delta t) \times \frac{1}{2\pi}\delta(K) \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_2(x, t+\Delta t) \times \frac{1}{2\pi}\delta(K) \\ \frac{d\hat{\rho}}{dt} + v_{\max} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho} - \frac{v_{\max}}{\rho_{\max}} \times \frac{1}{2\pi}\delta(K)iK\hat{\rho}^2 = \gamma_3(x, t+\Delta t) \times \frac{1}{2\pi}\delta(K) \end{array} \right) \tag{3.7.6}$$

CHAPTER FOUR

RESULTS AND DISCUSSION

The objective of this project is to create a mathematical model for examining traffic flow dynamics at a roundabout featuring four entrance and exit roads. The focus is on the United Nations roundabout in Bujumbura, Burundi. By utilizing this model, we aim to accurately predict potential scenarios at the roundabout, optimize its capacity, and enhance control strategies to manage traffic effectively.

4.1 Results and Discussions

In this section, I present the results from a simulation study involving four vehicles performing different types of movements within a roundabout. The analysis focuses on three scenarios: straight movement inside the roundabout (Case A) and two turning movements inside the roundabout (Case B and Case C). The study is further extended to include simulations with multiple vehicles performing the same type of movement, and the outcomes of these additional simulations are also discussed.

The simulations were carried out using the Fast Fourier Transform (FFT) combined with a fourth-order Runge–Kutta method, all implemented in MATLAB. This setup enables the generation of both numerical outputs and graphical representations directly within the MATLAB environment. In the simulation design, vehicles are generated randomly and assigned specific movement patterns within the roundabout under study, which is located in Bujumbura. (**??**).

The study examines how vehicles interact within the roundabout under different traffic scenarios. For example, when two cars approach the roundabout one intending to turn right and the other left the vehicle making the left turn is given priority, while the right-turning car must wait until the circulating lane is clear. When several vehicles attempt different movements at the same time, similar yielding behaviour occurs, ensuring that each car enters the roundabout only when it is safe to do so.

The analysis provides valuable insight into both the efficiency and safety of these movements. Graphical outputs, represented by the Red, Blue, and Green lines, illustrate the trajectories of turning vehicles and show how their paths interact with one another. The simulation results highlight the key factors affecting traffic flow, such as the total number of vehicles, their intended movements, and the order in which they enter the roundabout.

Understanding these movement dynamics is essential for improving traffic flow and enhancing road safety. The findings of this study can support urban planners and traffic engineers in designing better roundabouts and developing more effective traffic management strategies. By identifying potential sources of congestion and optimizing movement patterns, policymakers can improve the overall performance of road networks, ultimately benefiting both drivers and pedestrians.

4.1.1 Simulation Analysis for the straight Movement(Case A)

In our analysis, we examined roundabouts with radii ranging from 15 to 45 meters. Over a five-minute observation period, we closely tracked vehicle speeds along their assigned paths, focusing especially on segments within the roundabout where no conflicts occur. The evaluation involved adjusting vehicle velocities based on several factors: the distance to the roundabout, the time required to navigate through it, and the speed needed when exiting. To model these adjustments, we implemented the Intelligent Driver Model (IDM), which dynamically adapts vehicle velocity according to changing traffic conditions. In this section, our attention is directed specifically toward straight-line movement within the conflict-free zone of the roundabout.

The simulation produced several notable findings. We observed that drivers generally begin to reduce speed about 25 meters before reaching the roundabout. In addition, vehicles require an average of 2 to 3 minutes to fully pass through the roundabout, and they tend to accelerate to at least 45 km/h upon exit. These results illustrate the subtle dynamics that influence how vehicles move through roundabouts and highlight the value of intelligent driving models in optimizing traffic flow and ensuring safe, efficient navigation.

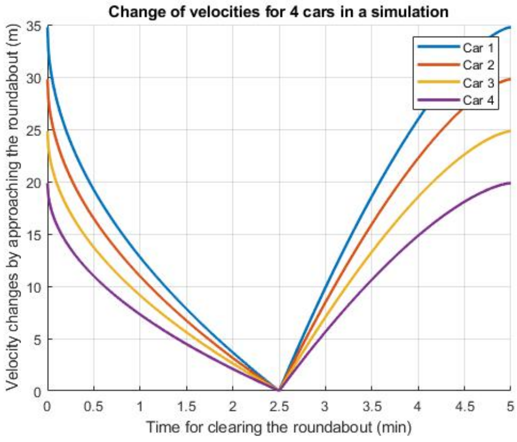

Figure 4.1: 4 Cars for Simulation Analysis Straight Movement

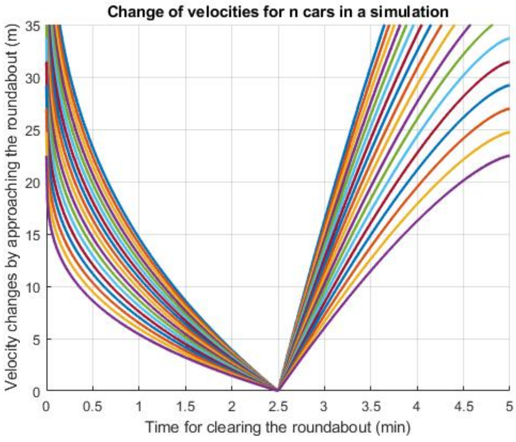

Figure 4.2: n Cars for Simulation Analysis Straight Movement

In an unsignalised roundabout, a V-shaped pattern in vehicle speed and acceleration usually reflects a quick rise followed by a sharp drop as vehicles move through the roundabout. As vehicles approach the entry point, velocities and accelerations rise as drivers accelerate to merge into circulating traffic. Once within the roundabout, velocities and accelerations decline as vehicles negotiate the curvature and adjust speed to safely exit. This V-shaped pattern highlights the dynamic nature of traffic flow in a roundabout, where acceleration and deceleration occur in response to changing geometry and driving conditions. As vehicles approach the entry point, their speeds and acceleration tend to increase as drivers prepare to merge into the circulating flow. This acceleration phase forms the upward slope of the V-shape.

Once inside the roundabout, vehicles maintain relatively high speeds but begin to slow slightly as they follow the curve of the roadway. During this stage, acceleration decreases as drivers either hold a steady pace or gently decelerate to navigate the circular path safely. This forms the downward slope of the V-shape.

Overall, the V-shaped profile in speed and acceleration captures the natural transition from entry acceleration, to speed maintenance while circulating, and finally to deceleration before exiting. Recognizing this pattern helps in designing more efficient roundabouts and developing traffic management strategies that support smooth and safe vehicle movement through these intersections.

4.1.2 Simulation Analysis for the first turning Movement (Case B)

In the simulation, the roundabout radius was allowed to vary between **15 m** and **45 m** over a 5-minute observation period. We evaluated vehicle velocities along the section of movement that does not involve conflict points. The Intelligent Driver Model (IDM) was used to adjust speeds based on the distance to the roundabout, the time required to traverse it, and the new trajectory after exiting. Lane-changing behavior was also incorporated.

For vehicles following the straight-through path inside the roundabout (i.e., the non-conflict trajectory), the results indicate that drivers begin to decelerate approximately 25 m before reaching the entry point. Depending on geometric conditions and traffic stimuli, it takes about 2 to 3 minutes for a driver to fully pass through the roundabout. The minimum exit speed observed in the simulation was approximately 45 km/h.

In unsignalized roundabouts, turning movements generate a characteristic W-shaped pattern in vehicle speeds and accelerations. This behavior arises from the dynamic interactions among multiple vehicles entering and circulating within the roundabout. As drivers approach the entry zone, they typically increase their speed and acceleration in preparation for merging with the circulating flow, producing the first rise in the W-shaped profile. Subsequently, as vehicles negotiate the curvature of the roundabout, velocities and accelerations may decrease as drivers adjust their speed to safely navigate the turn, resulting in the first trough of the W-shape. As vehi-

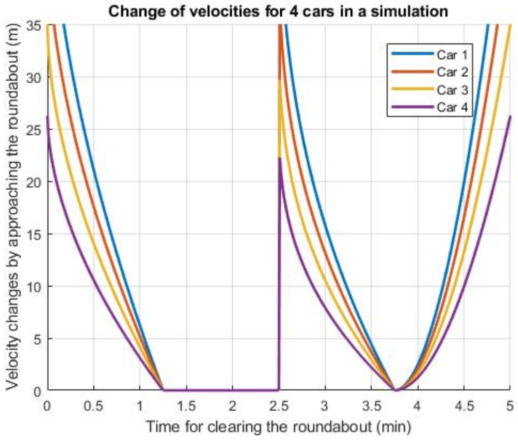

Figure 4.3: 4 Cars for Simulation Analysis First type of turning Movement

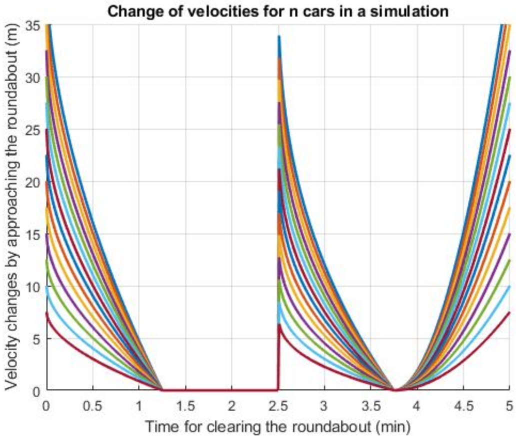

Figure 4.4: n Cars for Simulation Analysis First type of turning Movement

cles continue through the roundabout, velocities and accelerations rise again as they straighten their trajectory and exit the roundabout, forming the second peak of the W-shape. Finally, as vehicles complete the turn and exit the roundabout, velocities As vehicles proceed through the roundabout, their acceleration decreases again and settles to a lower magnitude, thereby creating the second trough of the W-shaped profile. This behavior reflects the inherently dynamic characteristics of turning movements at unsignalized roundabouts, where fluctuations in traffic demand, geometric design features, and driver responses collectively shape the observed motion patterns.

4.1.3 Simulation Analysis for the Second turning Movement(Case C)

The roundabout assessed in this study has a radius ranging from **15 m** to **45 m.** Over a **5 minute** simulation period, we examined vehicle velocities along the conflict-free movement path. By adjusting speeds according to the distance to the roundabout, the time required to traverse it, and the velocity adopted after exiting while incorporating lane changing behavior through the Intelligent Driver Model (IDM) we focused specifically on the straight, non-conflicting trajectory. The simulation results indicate that drivers on the straight through path begin to decelerate approximately 25 m before reaching the roundabout. Furthermore, vehicles require between 2 and 3 minutes to complete the passage through the roundabout, maintaining a minimum exit speed of about 45 km/h.

In turning movements within an unsignalized roundabout, a combined W and V shaped pattern in vehicle velocity and acceleration profiles captured the nuanced dynamics of driver behavior

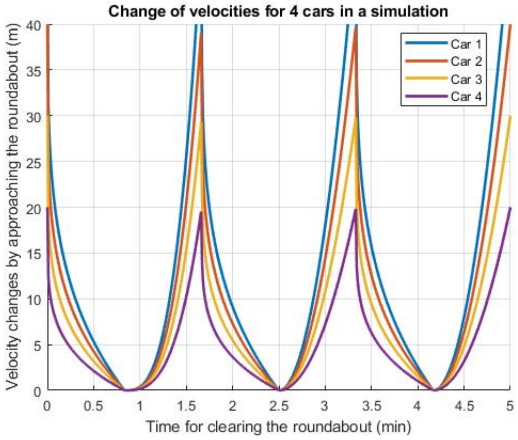

Figure 4.5: 4 Cars for Simulation Analysis Second type of turning Movement

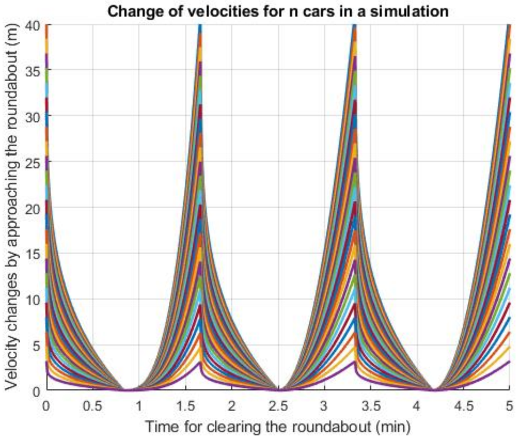

Figure 4.6: n Cars for Simulation Analysis Second type of turning Movement

and traffic interactions. As drivers approach the entry point, they typically increase speed to merge into the circulating stream, producing the rising segment of the V-shape. Once inside the roundabout, speed and acceleration oscillate as drivers adjust to the geometric curvature, respond to circulating vehicles, and perform yielding maneuvers. These fluctuations create alternating peaks and dips that resemble a W-shaped pattern. During the exit phase, drivers generally reduce speed while transitioning back to the main roadway, forming the descending segment of the V-shape.

This combined pattern reflects the interplay between acceleration, deceleration, and path-following behavior in unsignalized roundabouts. It highlights how geometric constraints, traffic density, and driver decision-making collectively shape vehicle movement. Recognizing these dynamics is essential for improving roundabout design and for enhancing both operational efficiency and road safety.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter summarises the key conclusions of the study and offered recommendations for both practical application and future research. By employing advanced simulation techniques and testing different traffic scenarios, the study has provided valuable insights into the dynamics of vehicle movement within unsignalized roundabouts. These findings contribute to a deeper understanding of traffic behavior and highlight several opportunities for improving transportation system performance.

The simulation results indicate that the proposed model and methodological approach are both effective and feasible for evaluating roundabout design. When applied to the study area, the method demonstrated strong performance and produced reliable outputs, suggesting its potential usefulness for similar traffic environments.

Future research can build upon these results in several ways. First, collaborative studies focusing on road channelization and traffic information optimization could further enhance traffic flow and safety. Second, the development of a real-time traffic simulation system that incorporates actual traffic data would allow for more accurate analysis and more dynamic decision-making. Finally, validating the current model using real-world roundabout data represents an important next step toward strengthening its applicability and improving its predictive capability.

5.2 Conclusions

This work has tried to determine how velocity of traffic flow between two lanes connected to the roundabout(entering and getting out lanes), get affected when applying the gradient of getting out the roundabout.The consideration of the number of other lanes connected to the roundabout and the radius of the roundabout.

5.3 Recommendations

The deterioration of traffic conditions in many developing countries has become far more severe than it should have been, largely due to the adoption of inappropriate or uncoordinated measures by the responsible authorities. The rapid growth in private vehicle ownership has outpaced institutional capacity to manage the resulting pressure on urban transport systems. In most cases, authorities respond in a fragmented and reactive manner, as responsibilities for transport planning and management are dispersed among numerous institutions national ministries, regional governments, municipal authorities, suburban railway or metro companies, and the traffic police. Each institution tends to act according to its own priorities, often without considering the broader implications for the overall transport network or for the mandates of other agencies.

For instance, a municipality may authorize the construction of multi-storey car parks or allow extensive on-street parking to avoid the potential relocation of economic activity to other parts of the city. However, such measures frequently increase congestion for road users passing through the area. A similar example arises in relation to mass transit systems such as metro networks: improved accessibility often attracts dense commercial development, including office buildings that must, by regulation, provide a minimum number of parking spaces. These parking provisions unintentionally encourage employees to commute by car, thereby increasing congestion around transit corridors. In addition, multiple organized groups such as road transport operators and political actors exert pressure in defense of their interests, further complicating decision-making and contributing to policy distortions.

These challenges highlight the need for stronger institutional capacity, not only to respond to emerging issues but also to anticipate them. Authorities must be able to resist the diverse pressures that arise in the sensitive domain of urban transport. Achieving this requires higher levels of professional expertise and specialized competence in transport management across public agencies, universities, and national consulting firms. Most importantly, traffic and transport must be addressed in a holistic and integrated manner. It is unrealistic to assume that urban congestion can be resolved through isolated, unilateral, or short-term policy measures.

5.3.1 Future work

The primary objective of this study was to investigate how the roundabout radius (r), the gradient of the turning movement (θ), and the number of lanes (n) influence vehicular throughput velocities. A mathematical model tailored to a specific roundabout configuration was developed and used to evaluate the effects of these parameters on velocities across all exit movements under various scenarios.

From the simulations, it is evident that a two-lane circulating roundabout generally provides greater efficiency; however, unless traffic volumes justify the complexity and additional cost, a one-lane configuration may remain preferable. Increasing the roundabout radius enhances operational performance but simultaneously raises per-vehicle delay. Thus, if spatial and financial conditions permit, constructing a roundabout with a radius of no less than 50 meters is recommended. Maintaining safe headway between vehicles is also essential for safe merging and circulation. Additionally, vehicles should ideally exit the roundabout at sufficient speeds to ensure smooth flow and facilitate entry for approaching vehicles.

The simulation results confirm that the proposed modeling framework is both effective and feasible. The method has been successfully applied to the selected study area, demonstrating strong practical relevance. Future research should include collaborative work on road channelization, optimization of traffic information systems, and the development of real-time simulation platforms using empirical traffic data. Validating the model with actual roundabout observations represents a critical next step for strengthening its accuracy and practical applicability.

i Enhance the numerical component by incorporating additional numerical schemes, such as the finite difference method, and compare outcomes to evaluate improvements in accuracy.

ii Extend the analysis to multiple roundabouts and develop a generalizable performance metric applicable across different roundabout types.

iii Compare the construction and operational costs of traffic signal control with those of building and maintaining roundabouts.

iv Introduce additional control strategies and integrate more operational parameters to broaden the model's applicability and robustness.

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