Development of a Floating Car Data (FCD) Model to Evaluate Traffic congestion. A case of Kampala, Uganda

by
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Declaration

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Abstract

Traffic congestion remains a stumbling block in an efficient and accessible road network. Attempts have been investigated to monitor congested areas and propose mitigation measures to alleviate the issue. However, transport planning models, such as the four-step traditional models, are expensive and complex. This research develops a novel floating car data (FCD) model similar to the traditional model but is more cost-effective and efficient for transport planning. Many African cities cannot afford complex planning models, but the need to improve road networks remains indisputable. Using FCD's cost-effective traffic data collection strategy, this research proposes a model designed to monitor and thus alleviate city traffic congestion.

This study focuses on a novel FCD model for evaluating traffic congestion in developing African countries like Uganda. This research aims to contribute to alleviating traffic congestion in African cities by exploiting FCD. The methodology adopted to achieve this was developing a novel FCD model. This study utilized traffic speeds and travel times during peak and off-peak hours to determine the congestion intensities in different sections of Kampala. The speed reduction index (SRI) was used to classify the congestion levels into no, low, and high congestion areas. Delay rates were used to determine the varying delays in different city areas. Then, PTV VISUM software was utilized to develop a road network model and visualize the varying intensities of congestion. Then, two highly ranked zones in terms of delay rates were analysed to ascertain the causes. The causes were mainly high volumes of vehicles on the major arterials, non-operational traffic lights, and social and economic hubs in the adjacent areas of those zones. This study further proposed mitigation measures using the PTV VISSIM software by conducting a simulation analysis. When signal timings were altered, the simulation indicated a 42% reduction in vehicle delay on the major route at the intersection in zone 13. The research concluded that African cities could embrace technological advancement in traffic statistics and improve their cities.

Opsomming

Verkeersopeenhopings bly 'n struikelblok in 'n doeltreffende en toeganklike padnetwerk. Pogings is ondersoek om oorbelaste gebiede te monitor en versagtingsmaatreëls voor te stel om die probleem te verlig. Vervoerbeplanningsmodelle, soos die vierstap tradisionele modelle, is egter duur en kompleks. Hierdie navorsing ontwikkel 'n nuwe drywende motordata (FCD) model soortgelyk aan die tradisionele model, maar is meer koste-effektief en doeltreffend vir vervoerbeplanning. Baie Afrika-stede kan nie komplekse beplanningsmodelle bekostig nie, maar die behoefte om padnetwerke te verbeter bly onbetwisbaar. Deur FCD se kostedoeltreffende verkeersdata-insamelingstrategie te gebruik, stel hierdie navorsing 'n model voor wat ontwerp is om stadsverkeersopeenhopings te monitor en sodoende te verlig.

Hierdie studie fokus op 'n nuwe FCD-model vir die evaluering van verkeersopeenhopings in ontwikkelende Afrikalande soos Uganda. Hierdie navorsing het ten doel om by te dra tot die verligting van verkeersopeenhopings in Afrika-stede deur FCD te ontgin. Die metodologie wat gebruik is om dit te bereik, was die ontwikkeling van 'n nuwe FCD-model. Hierdie studie het verkeersnelhede en reistye tydens spits- en buite-spitsure gebruik om die opeenhopingsintensiteite in verskillende dele van Kampala te bepaal. Die spoedverminderingsindeks (SRI) is gebruik om die opeenhopingsvlakke in geen, lae en hoë opeenhopingsgebiede te klassifiseer. Vertragingskoerse is gebruik om die wisselende vertragings in verskillende stadsgebiede te bepaal. Toe is PTV VISUM-sagteware gebruik om 'n padnetwerkmodel te ontwikkel en die verskillende intensiteite van opeenhoping te visualiseer. Toe is twee hoogs gerangskik sones in terme van vertragingskoerse ontleed om die oorsake vas te stel. Die oorsake was hoofsaaklik hoë volumes voertuie op die hoofkare, nie-operasionele verkeersligte, en sosiale en ekonomiese spilpunte in die aangrensende gebiede van daardie sones. Hierdie studie het verder versagtingsmaatreëls voorgestel deur gebruik te maak van die PTV VISSIM sagteware deur 'n simulasie-analise uit te voer. Toe seintydberekeninge verander is, het die simulasie 'n vermindering van 42% in voertuigvertraging op die hoofroete by die kruising in sone 13 aangedui. Die navorsing het tot die gevolgtrekking gekom dat Afrika-stede tegnologiese vooruitgang in verkeerstatistieke kan aangryp en hul stede kan verbeter.

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List of Acronyms

AADT	Annual Average Daily Traffic
ACC	Adaptive Cruise Control system
AFC	Automated Fare Collection
AFD	French Development Agency
ANPR	Automatic Number Plate Recognition
APTS	Advanced Public Transportation System
ASToN	Africa Smart Towns Network
ATIS	Advanced Traveller Information Systems
ATMS	Advanced Traffic Management Systems
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
BRT	Bus Rapid Transit
BTMB	Beijing Traffic Management Bureau
CACC	Cooperative Adaptive Cruise Control system
CAV	Connected and Autonomous Vehicles
CBD	Central Business District
CCTV	Closed Circuit Televisions
CDR	Call Detail Records
CORSIM	Corridor Simulation
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DHV	Design Hourly Volume
DR	Delay Rate
DSRC	Dedicated Short Range Communication
EMS	Emergency Management Service
FCD	Floating Car Data
FHWA	Federal Highway Administration
GCM	Grid Congestion Mode
FMS	Freeway Management System
GIS	Geographic Information System
GKMA	Greater Kampala Metropolitan Area
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communication
HCM	Highway Capacity Manual
HCQS	Highway Capacity and Quality of Service
HGV	Heavy Goods Vehicles
ICT	Information and Communications Technology
IIMS	Intelligent Information Management System
IoT	Internet of Things
ITS	Intelligent Transportation System
KCCA	Kampala City Council Authority
KCRRP	Kampala City Roads Rehabilitation Project
LBS	Location-Based Services
LoS	Level of Service
LRT	Light Rail Transit
MoWT	Ministry of Works and Transport
NHTS	National Household Travel Survey
NMT	Non-Motorised Transport

OBU	On-Board Unit
ODM	Optimised Dispersion Model
OECD	Organisation for Economic Co-operation and Development
OSM	Open Street Maps
P2I	Pedestrian to Infrastructure
POI	Point of Interest
PTI	Planning Time Index
RCEP	Recurrent Congestion Evolution Patterns
RCI	Relative Congestion Index
RDR	Relative Delay Rate
RFID	Radio Frequency Identification
RSI	Road Safety Initiative
SANRAL	South African National Roads Agency Limited
SNN	Shared Nearest Neighbour
SPI	Speed Performance Index
SRI	Speed Reduction Index
SSML	Stellenbosch Smart Mobility Laboratory
STM	Speed Transition Matrix
SUMO	Simulation of Urban Mobility
TAZ	Traffic Analysis Zone
TCC	Traffic Control Centre
TCI	Traffic Congestion Index
TMC	Traffic Management Centre
TMS	Traffic Management System
TR	Travel Rate
TRB	Transport Research Board
TTI	Travel Time Index
UBOS	Uganda Bureau of Statistics
UK	United Kingdom
UNRA	Uganda National Roads Authority
USA	United States of America
US DoT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
V/C	Volume/Capacity
VACS	Vehicle Automation and Communication System
VDS	Vehicle Detection Systems
VGI	Volunteered Geographic Information
VMS	Variable Message Signs

Chapter One

Introduction

1.1 Introduction

This research study explores the application of Floating Car Data (FCD) to analyse traffic congestion in the Kampala metropolitan area in Uganda. It seeks to bridge a gap between the unavailability of traffic statistics and relevant stakeholders' improvement of the road network. Current methods used to analyse traffic congestion in Uganda are generally time-consuming, resource-intensive, and may yield subjective results. Utilising FCD for traffic congestion analysis has been widely researched and promoted as a feasible alternative to conventional methods in determining congestion zones in big cities. However, despite its potential, FCD has received no attention in many developing countries like Uganda.

Traffic data is an essential element needed for any improvement of road networks. This study seeks to utilise FCD to develop a model to identify traffic congestion areas in major cities of developing countries and propose mitigation strategies. The analysed data gives an overall status of the network. Coupled with a study survey to fully understand the causes of congestion in the road network, this thesis proposes different measures to mitigate the causes identified in the particular sections of Kampala.

This chapter introduces the current traffic and mobility status in Kampala, Uganda. It also addresses the current strategies undertaken to mitigate traffic congestion. This is followed by an argument clarifying the significance of a cost-effective and reliable alternative for data collection to facilitate traffic flow improvement in the road network. Then, a discussion on the relevance of a FCD model ensues. Finally, sections on the research question and a statement of the problem, hypothesis, research aim, research objectives, significance, limitations, assumptions, key terminologies, and a brief summary of the thesis chapters, follow.

1.2 Background

Many cities all over the world experience some degree of traffic congestion. 55% of the world's population – or approximately 4.2 billion inhabitants – live in cities. By 2050, nearly seven out of ten people will reside in cities due to the expected increase in the ongoing trend of urban population densification (World Bank, 2020). Africa, the fastest growing and youngest region, has the highest urban growth rates globally (World Bank, 2020). As the population increases, the number of motorists, cyclists, and pedestrians also booms. An increase in the number of cars on often obsolete infrastructure will become inevitable in many cities, hence an upsurge in traffic congestion on major roads leading to them (Jain, Sharma and Subramanian, 2012). Also, typically economic activities and government institutions are all restricted to a particular area in most cities, which leads to increased travel to and from that area during peak hours. This has led to economic, social, and environmental devastations in many contexts due to long travelling hours and high emissions of gases, among others (Koźlak and Wach, 2018).

In Uganda, the population of over 42 million is expected to reach 100 million by 2050. The country's annual urban growth rate of 5.2%, among the highest in the world, is anticipated to grow from 6.4 million (2014) to 22 million by 2040 (World Bank, 2021). Owing to urbanisation, the increasing need for transport services will be dire, thus intensifying traffic congestion. This escalation poses a potentially detrimental threat to the country's economy. The Central Business District (CBD) of Kampala city has a road network of 2,110km, and only 35% is paved (KCCA, 2019). This minimal infrastructure system constrains traffic on the available paved roads, causing congestion. As a result, the major routes to the city centre experience a lot of traffic during the peak periods. Commuters lose a combined 24,000 man-hours daily due to traffic congestion in Kampala (KCCA, 2016).

1.1.1 The role of Kampala City Council Authority

The Kampala City Council Authority (KCCA) is a statutory body responsible for the city's operations (www.kcca.go.ug). One of the core functions of the directorate of engineering and technical services associated with the KCCA is to monitor and suggest areas to improve the city's traffic conditions. The KCCA has implemented several initiatives for combating traffic congestion. One of its recent projects is the Kampala City Roads Rehabilitation Project (KCRRP), whose specific objectives are:

- To enhance transport efficiency by alleviating traffic congestion. This will further improve mobility and accessibility, thus realising the agglomerative benefits through the upgrade and expansion of the road network;
- To improve air quality in the city by implementing scheduled eco-bus transit services and increasing travel choices for non-motorised transport (NMT) through expanded walkways and cycling pathways.

Kampala is a member of the Africa Smart Towns Network (ASToN) under the French Development Agency (AFD), which operates in 12 African countries in different thematic areas. Kampala's thematic area is mobility. This indicates a need for Uganda to develop a sustainable solution for improving mobility, thereby combating traffic congestion.

KCCA runs an online survey to help plan improvements in areas of Kampala impacted by traffic congestion. This survey enquires about congestion-related problems experienced by commuters (www.kcca.go.ug). The data obtained enables KCCA to evaluate the overall traffic conditions through the perceptions of commuters. However, this study has observed some of the system's limitations. Very few responses from commuters. It may also not cover all the transport system users, presenting potential biases. This research, therefore, aims to improve the methodology used by KCCA. It introduces a novel method for analysing transport network traffic conditions in an urban environment. It incorporates the smart technology of FCD.

1.1.2 Current situation of transport system in Kampala

Kampala has a diverse transportation system. The system includes; private cars, public transport vehicles such as buses and minibuses, freight vehicles, motorised and non-motorised bicycles, commonly known as "bodaboda" (KCCA, 2019). All these transport vehicles use the same narrow roads, impeding overall mobility. According to the Uganda Bureau of Statistics (UBOS), there were 145,455 newly private registered cars and motorcycles, of which 38,182 were cars and 107,273 were motorcycles in 2019 (“Statistics-Uganda,” 2019). This implies that more than 70% of traffic systems are motorcycles.

Bodabodas are common in mainly Kampala because of their accessibility, faster means, and because they allow passengers to disembark at their exact stop points. However, they disrupt the overall traffic flow at intersections, affecting thoroughfare and often causing gridlock (Ministry of Works and Transport, 2010). Bodaboda drivers often do not wait for their turn in traffic queues at different road intersections. They usually manoeuvre through the queues and cut ahead to the front of lane approaches. They generally ignore the traffic signals at intersections, crossing whenever they deem it safe. This practice adversely affects the safety of pedestrians, the bodaboda riders themselves, and their passengers. On the other hand, public transport vehicles are safe, comfortable, and commonly used, contributing to 30% of travel means to the city (Ministry of Works and Transport, 2010). However, these transit options are often subject to long travelling times because of congestion. Hence, many commuters prefer the bodabodas.

Public transport options consist of minibuses (commonly known as taxis) which carry 14 passengers, private buses/coaches on designated routes carrying 19-39 passengers, and special car hire (KCCA, 2019). In 2019, UBOS recorded 16,049 public service transport operators and taxis in Kampala, contributing to over 40% of the total number of cars registered that year (“Statistics-Uganda,” 2019). These statistics provide a glimpse of the congestion caused by taxis on the road network. As a result, the Ministry of Works and Transport (2010) suggested a need to shift from minibuses to high-capacity buses to alleviate the congestion.

In 2016, KCCA released a report stating the interventions it plans to undertake to improve the overall transit mobility in the city. The measures included construction of over 150km of new road network in the city, upgrading and expansion of major intersections, reconstruction of pedestrian walkways, dualling of major roads, installation of solar street lights, and lastly, developing a city-wide multimodal transport master plan with a detailed neighbourhood plan. On congestion management, they proposed various systems. These included the introduction of the Bus Rapid Transit (BRT) system, bodaboda-free zones, stricter regulations for heavy vehicles in the city, reviving Light Rail Transit (LRT), implementing congestion fees, and building a multi-story car park in the central business district (KCCA, 2016). For the BRT system, a feasibility study was conducted, which revealed that the proposed system must consider the internal diversity of the population, and evaluate the cost-benefit ratio (Vermeiren et al., 2015).

Several expressways designed to decongest the city have been proposed by the Greater Kampala Metropolitan Area (GKMA) Transport Master Plan (KCCA, 2019). The Uganda National Roads Authority (UNRA), a government agency under the Ministry of Works and Transport (MoWT), spearheads the projects. UNRA's sole responsibility is to maintain, manage, and develop the national road network (www.unra.go.ug). In addition, they work in partnership with KCCA on projects in the city to alleviate congestion and improve overall transport mobility (Ministry of Works and Transport, 2010).

KCCA lists its proposed projects and those currently under construction. For example, the toll road of the Kampala-Entebbe expressway, designed to ease access between Kampala and Entebbe International Airport and the neighbouring areas along the route, was opened in June 2018. At the time this thesis was completed, the Kampala northern bypass was still under construction in some sections, situated in the north-west of the city. It serves areas that experience a lot of congestion close to the city centre. It also aims at the geometric improvement and road segregation, allowing improved interconnectivity between adjacent nearby areas. Similarly, there is the ongoing project at the Queensway Junction, called the Kampala Flyover Project which is designed exclusively for private vehicles. This project will likely increase the road access in the city and reduce congestion (KCCA, 2019).

The construction of new roads and related infrastructure like road toll charging by KCCA in an effort to alleviate traffic congestion have been proved largely ineffectual. Researchers such as Metz (2018) and Duranton and Turner (2011) oppose the concepts applied by KCCA according to their studies in other contexts. The former investigated the issue of road user charging in London, Stockholm, and Singapore. Tolls are one of the mechanisms implemented in those cities to alleviate traffic congestion. According to the study, road toll charging proved effective in the first years of operation. However, in London, after a certain period, congestion returned to its previous levels, despite tolls remaining in use. Duranton and Turner concluded that expansion of roads or public transit are unlikely to reduce congestion, based on their investigation of the effect of additional lanes per kilometre of road on vehicle kilometres travelled in United States cities. It is therefore a presumption of this study that the ongoing construction in Kampala will improve the overall transport mobility based on information in the studies mentioned above. However, due to the recent advancement in Information and Communications Technology (ICT), an opportunity to improve the overall road network by analysing traffic trends has become inevitable (Sharif, Li and Sharif, 2019).

1.1.3 Significance of smart technology in analysing traffic trends

In broader terms, the use of smart technology could mean any infrastructure that utilises information and communications systems to improve community service delivery (Stübinger and Schneider, 2020). Smart technology application has also led to the concept of "smart cities." Neirotti et al. (2014) who discuss this concept, revealed that in terms of transport and mobility, the smart city concept addresses critical issues of city logistics, where integration of the city's infrastructure with traffic conditions, environment, and geographical issues are concerned. Secondly, info-mobility which is concerned with providing pre-trip and in-transit information to create a user-friendly transportation system. Lastly, people mobility which ensures sustainability by delivering the best transportation systems. For example, public transport and mode improvement using advanced technologies.

Smart technology tends to be synonymous with the internet of things (IoT) in the sense that the absence of one renders the other meaningless. The IoT is the medium through which responsible agents implement smart technology in the modern world. The IoT comprises three major components: sensors, communication channels, and processing units. The IoT enables the transfer of information from sensors to processing units or other devices (Ejaz and Anpalagan, 2019). Due to the large number of devices generating information, big data has evolved, which should be analysed to study varying trends in different community systems (ibid).

Recently, researchers have become interested in analysing traffic-related problems using Floating Car Data (FCD)/Probe Vehicle Data. This system uses the Global Navigation Satellite Systems (GNSS) installed in vehicles or mobile phones to provide information on the position and speed of particular cars (Messelodi et al., 2009). The moving probes act as sensors. From this information, traffic engineers can extract essential information about the transport system from the control centres of the GNSS. Some researchers regard FCD as a cooperative system utilising the vehicle to infrastructure (V2I) system, since the installed GNSS in vehicles provides information to control centres (Stahlmann et al., 2011). Cooperative systems can help improve overall traffic efficiency, safety, and travel comfort.

Using FCD in traffic studies is regarded as an Intelligent Transportation System (ITS) technique because of the technology employed when collecting data (Mfenjou et al., 2018). The application of ITS through the use of smart technology helps provide a safe and efficient transport system. In other words, ITS incorporates technologically advanced methods into the transport sector to allow transport institutions to more effectively manage traffic, and enable road users to experience the best in terms of mobility (Sun and Boukerche, 2021). ITS in general has gained traction in many developing countries. Nevertheless, many African countries have lagged behind in applying ITS solutions/applications.

Evaluating infrastructure or other conditions to support measures in addressing problems in the flow of traffic requires readily available traffic data (Sharif, Li and Sharif, 2019). Pfoser (2016) states that FCD provides real-time and historical data, whereas the latter evaluates only the current Level of service (LoS) of roads. The former provides information about travel times, which helps in implementing rerouting dynamics, something common to all traffic management systems. Historical data also enables system performance and analysis of traffic trends that aid transport planning.

FCD has recently become more readily available due to the increased digitisation of mobility, such as the growth in e-hailing companies like Uber, Bolt, DIDI, and In-driver (Manav, 2020). This increase is supported by the influx of smartphones on the African continent, whose penetration rate is 43% (Africanews, 2017). In Uganda, around 20% of the total population in 2020 accessed internet services, and 60% possessed mobile phones ("Telecommunication in Uganda," n.d.). This percentage in 2022 likely increased. The service providers for the FCD include companies such as TomTom, Google, and INRIX. They obtain data from Global Positioning Systems (GPS) installed in commercial and government vehicles and mobile phones. These companies have extensive traffic data platforms, which could provide information to traffic engineers and urban planners to enable them to restructure targeted areas of road networks to improve mobility. Likewise, Uber has a service called Uber movements that provides traffic data, much like the previous companies. Like other transport systems, Uganda offers the "SafeBoda," an e-hailing application for motorcycles (Winiecki, n.d.). Therefore, utilizing such available technologies could enable institutions involved, such as KCCA, to monitor the overall traffic flow and promptly mitigate any traffic-related problems.

African cities in general have not utilized this opportunity at its best, despite the growing tendency to digitise mobility. This thesis seeks to explore the use of FCD in evaluating traffic congestion. Song et al. (2019) argue that access to real-time traffic data has enabled in-depth traffic congestion analyses. In addition to this, it is a contention of this thesis that historical data also plays a vital role in understanding traffic trends. The parameters deduced from the probe data, including congestion zones and travel time, may help service providers identify highly congested areas. Hence, the possible causes of congestion in specific locations can be studied, and measures to address them prioritised. Agureev et al. (2017) contend that traffic congestion is complex, ever-changing, and volatile. Therefore, understanding the measures suitable for different locations is vital for an efficient transport network, which may eventually improve the overall traffic flow of an entire city's road system, since road networks in most of the world's cities are interconnected.

1.1.4 Relevance of a FCD model

This research study required the development of a reliable methodology for evaluating traffic congestion in urban areas. Studying traffic trends enables transport stakeholders to make informed decisions when implementing solutions. When evaluating congestion, there is a vital need to produce models. Models allow for adjustments and changes when creating or building a system. They illustrate how travel demands change according to input parameters. There are several models used to evaluate traffic conditions. Arroyo et al. (2015) state four types of models. These include, based on their complexity and level of detail; Sketch-Planning models, Strategic-Planning models, Trip-Based models, and Activity-Based models. One of the purposes of these models is to allow for the possibility of calculating travel delays, then prioritise them based on the results.

The traditional four-step planning model, or the trip-based model, includes trip generation, distribution, modal split, and assignment. This model requires a lot of data; therefore, it is time-consuming and expensive. Activity-based models have been more recently adopted. They include the traditional four-step model, supplementing it with the linkages among activities and travel. The trip-based and activity-based models are convenient for regional and sub-regional planning. Developing countries tend to avoid expensive planning models to the detriment of transport management. On the other hand, strategic-planning models are less costly but provide the necessary details for decision-making (Arroyo et al., 2015). This study falls under the strategic-planning model, using the already available FCD in a mesoscopic area. It designs a FCD model to evaluate traffic congestion in cities.

This model allowed for the identification of congestion areas in Kampala and prioritised them. Then a survey was conducted to ascertain the root causes of the congestion in such zones and their existing road links. Finally, this study proposes suitable measures to alleviate congestion. In a study by Afrin and Yodo (2020) on traffic congestion measures for a sustainable and resilient transportation systems, they concluded that mitigation strategies would not solve congestion problems entirely. However, this study shows that attaining even minimum levels of alleviation is guaranteed to reduce the severity of traffic congestion.

1.3 Research question

Based on the above background, this study posits that KCCA actively strives to improve traffic mobility in the city. This research seeks to contribute to the initiative by answering the following research question;

Can floating car data analysis evaluate traffic congestion zones in Kampala to propose suitable measures for alleviation?

1.4 Research statement

FCD has been extensively used to estimate traffic congestion and identify affected areas in different countries. Despite the available infrastructure, little or no such application seems employed in many African cities. Therefore, this thesis contends that evaluating traffic congestion in Kampala from FCD is possible. Transport planners, traffic engineers, and researchers are presented with the opportunity to explore transport dynamics. This initiative could help improve the transport network in the growing cities in Africa.

The availability of digitised mobility data is increasing with the continued growth of e-hailing and other mobility initiatives. The e-hailing companies have gained much popularity in recent years. E-hailing has increasingly replaced traditional hire cars (cabs/taxis). This is evident in the number of companies emerging in the e-hailing industry. As for private companies, installing a GPS device in a vehicle to continuously monitor its movements has proved advantageous. This has also led to the growth of these businesses due to the increase in timely deliveries. These private company cars also act as data sources for private companies that supply probe data. Therefore, the increasing number of probes on the road network provides an extensive traffic database. It also ensures a broader road network coverage which eases the evaluation of traffic-related problems.

FCD can enable traffic engineers and urban planners to obtain quantitative traffic information like travel time and speed. These parameters can be employed in transport models, such as those discussed in section 1.2.4, to plan for a better transport network. Many African cities lack sufficient traffic data from inductive loop detectors and monitoring devices. City planners in these contexts mainly carry out traffic counts, which are time-consuming and costly if the network is large. FCD bridges the gap, and provides traffic data to engineers and planners to improve mobility. There is a lack of knowledge about the factors influencing congestion and its spatio-temporal patterns (Song et al., 2019). This presents the need to study the possible causes of traffic congestion and how to alleviate them systematically.

Considering available traffic statistics, this thesis asserts that different researchers can pursue different studies on traffic-related problems. This study focussed on traffic congestion in Kampala. It designed a FCD model to identify congestion areas. It then categorised them into no, low, and high congestion areas. Selected zones of the city were further scrutinized to assess the possible causes of congestion in the road network. Knowing why traffic congestion exists in a particular area enables the proposal of suitable measures to alleviate it. This approach allows traffic congestion to be monitored and evaluated at any given time, thereby identifying potential anomalies. Improving one section of the road network reported as highly congested can enable the smooth flow of traffic in other areas in the road network since intersections usually are closely spaced and interrelated.

1.5 Hypothesis

This study is based on the following hypotheses:

i. Null hypothesis: Floating Car Data (FCD) cannot evaluate traffic congestion in Kampala.
ii. Alternative hypothesis: Floating Car Data (FCD) can evaluate traffic congestion in Kampala.

1.6 Research aim

Following the strategic plan of the engineering and technical services directorate of KCCA for managing transport in a modern and easily accessible city, this research aims to contribute to their vision, by developing a cost-effective FCD model. The model was designed using existing FCD to evaluate the performance of the Kampala road network. First, this study identified the congestion areas and visualised them in PTV VISUM software. Suitable measures were then proposed to be adopted after assessing the causes of traffic congestion. The measures, when considered, can potentially alleviate traffic congestion in the city, thereby improving the mobility and accessibility of its residents.

1.7 Research objectives

This study addressed the following objectives in achieving the research aim, and to answer the research question:

1. To identify the congestion areas in the Kampala metropolitan area using Floating Car Data.
2. To prioritise the congestion areas according to different road classes.
3. To assess the causes of congestion in high-priority areas.
4. To propose appropriate measures to relieve congestion in the city.

1.8 Significance of the study

This research is designed to impact the dynamics of the state of traffic in Kampala. This study utilised FCD that was readily available to study congestion in the city and developed a FCD model to illustrate the areas that are highly affected by travel delays compared to others. This thesis also proposes a different data collection strategy of FCD for KCCA to evaluate traffic conditions. This dataset also seems unbiased compared to the present method of collection, of an online survey. Transport stakeholders can further use this dataset to monitor the performance of traffic mitigation efforts.

Stakeholders must adopt certain measures to help mitigate traffic on road sections identified as congested (Liu et al., 2017). The overall traffic network may improve by applying various strategies to relieve the congestion. Although different measures are employed to alleviate traffic in high congestion zones, this thesis proposes measures for alleviation using traffic engineering simulation/travel demand modelling software, particularly PTV VISSIM. This study, therefore, presents a methodology to assess various strategies before implementation through modelling.

FCD has not been extensively utilized on the African continent. More studies have been conducted elsewhere in the world outside of Africa. Traffic studies require reliable datasets for analysis. This analysis enables stakeholders to make informed decisions in managing the traffic dynamics. Since many countries with limited resources lack adequate data collection methods, FCD creates exceptional opportunities as a cost-efficient approach. Therefore, this research seeks to contribute to the scarce literature on FCD and its applicability in Africa.

1.9 Limitations of research

This research is limited to the specific traffic conditions associated with the City of Kampala. This is partially due to the researcher's personal experience and familiarity with the city's traffic dynamics. It is important to acknowledge that this study cannot necessarily be generalised and extended to other parts of the country. Nevertheless, the aim is to generalise its findings and provide a pragmatic approach toward visualizing and prioritising congestion in cities through a FCD model.

Different datasets can be employed to analyse traffic congestion. These may include trajectory and cross-sectional datasets (Treiber and Kesting, 2013). This study utilized FCD because of its availability following a recent trend in many parts of the world where FCD is used to address various traffic-related problems. Moreover, the data collection strategy used by KCCA to estimate traffic congestion at the time this research was carried out seemed subjective and unreliable.

The four-step transport demand and activity-based models remain the standard approaches to developing demand models for major cities. However, the advent and availability of digitised mobility data gave rise to the development of hybrid models. It is important to note that the output of the FCD approach is similar to that of a standard demand model, but the FCD model, as presented in this research, is not a predictive tool.

There are various approaches appropriate for analysing FCD to estimate congestion. PTV VISUM was used in this study for network coding, mapping, and visualisation. Then, PTV VISSIM software was used as a micro-simulation tool for detailed traffic analysis. Some researchers utilize clustering methods in the estimation of traffic congestion. These methods may include K means clustering algorithms, shared nearest neighbour (SNN) (Keler, Krisp and Ding, 2017a), density-based spatial clustering of applications with noise (DBSCAN) (Liu et al., 2017), and hierarchical clustering, among others. For simulation tools, some researchers utilise AIMSUN, CORSIM, and SUMO, among others, for traffic analysis. The software used for this study was readily available at the University where this research was carried out, and provided a platform for analysing traffic problems in a city-wide area.

Different studies use a variety of service providers like INRIX and TomTom and use different data periods in their analysis. This study used the Google API's average data for probe vehicles for 2021. The data obtained was for the base scenario (midnight traffic) and morning peak hour.

Generally speaking, Kampala experiences little or no traffic congestion on weekends in most parts of the city. This is most likely because it is not a tourist hub. For this reason, only workdays were deemed relevant for the analysis.

1.10 Assumptions

The underlying assumptions of the research are as follows;

i. The FCD obtained from Google API is reliable. Therefore, the data source is considered trustworthy.
ii. The data is assumed to possess a realistic penetration rate of vehicles.
iii. The approach of identifying traffic-congested zones using a FCD model was practical compared to other methods.
iv. The approach to studying the possible causes of congestion in the selected areas is realistic.
v. The causes of congestion on different road segments vary accordingly.

1.11 Key terminologies

- **Traffic congestion**

This alludes to a condition where the traffic volume exceeds a road section's capacity. Hence, low speeds and high car density lead to long queues indicating less supply to demand (Falcocchio and Levinson, 2015).

- **Floating car data (FCD)**

This is a current data collection technique where a Global Navigation Satellite System (GNSS), usually a GPS, is installed in a vehicle or on a mobile phone in a vehicle (Treiber and Kesting, 2013). A continuous data flow of the vehicle's speed, position, and travel time is recorded at a data centre. Therefore, it provides vehicle information while the car is moving (Kessler et al., 2018).

- **Intelligent transportation system (ITS)**

ITS has various definitions. Kazimil and Demzee (2012), describe ITS as all systems that use information technology. Therefore, it involves applying technology to provide a safe and efficient means of travel by city authorities to road users (Singh and Gupta, 2015). This includes providing commuters with the necessary information and services pertaining to the road network.

- **Spatial-temporal analysis**

This describes the phenomenon of data analysis in space and time relationships. This study used the term to refer to the position and the time frame of the analysis data. Its usage depended on the issue conferred, either used jointly or separately.

- **PTV VISUM**

This is a widely-used software for transportation engineers to analyse the traffic networks, like modelling, forecasting, and network data management to assess traffic at the city, regional, and national levels (PTV Group, 2016).

- **PTV VISSIM**

This is another PTV Group product, a widely-used software for microscopic simulation of traffic-flow analyses (PTV Group, 2020).

1.12 Chapter overview

Chapter one provides the background for the research, followed by the research question. This chapter also presents the research statement, which provokes the hypotheses, research aims, and objectives. The chapter also includes the significance of research relevant to this study, followed by the study's limitations and assumptions. Finally, a section on the key terminologies provides definitions of relevant terms.

The second chapter of the thesis is the literature review. This chapter is divided into three sections; Traffic congestion, Floating Car Data (FCD), and Measures to alleviate congestion. Firstly, the concept of traffic congestion is introduced, followed by details about its various types, causes, and effects. A discussion on the different mathematical indices of congestion follows. Secondly, Floating Car Data (FCD) is discussed. Traffic data sources are then discussed in detail, of which FCD forms part. Finally, a discussion on the different measures adopted in various parts of the world in combating traffic congestion follows. This study categorised these measures into four dimensions; construction of new infrastructure, improvement of existing facilities, congestion pricing, and intelligent transport system (ITS) measures.

Chapter three covers the research design and methodology used in this study. Firstly, the geographical location of Kampala, which forms the case study for this project, is discussed. Then, correspondingly, the road network of the city is described. After that, a discussion of the research design adopted and the methodology used in the analysis follows.

Chapter four discusses the data collection process. It describes how the data for the FCD model was collected. Also included is a description of how additional data sources for other components of the research were obtained.

Chapter five explains and discusses the results from the analysis of the data. This study based this discussion of results on the literature reviewed and on an understanding of different concepts in traffic engineering.

Chapter six discusses the application of the FCD model. This illustrates the step-by-step process in formulating this model. The aim is to allow easy application in other cities.

Chapter seven constitutes the conclusion and recommendations, including the final remarks of this study.

Chapter Two

Literature Review

2.1 Introduction

This chapter is divided into three sections. First, the three features of this dissertation's title, "Development of an FCD model to evaluate traffic congestion in Kampala, Uganda," are explained. The concept of traffic congestion is discussed at length, including its various definitions, types, causes, effects, and how it is mathematically measured. Due to the prerequisite of needing traffic data to design a model, FCD was the dataset utilized. The second section, therefore, discusses the FCD. This dataset provides the necessary information to evaluate traffic congestion elaborated in the first section. Included in the discussion is an overview of the different traffic datasets used in studying traffic-related problems, the advantages and disadvantages of FCD, and its applications. After analysing traffic congestion, possible mitigation solutions are proposed. Then, the third section comprises an explanation of the measures to alleviate congestion. Different approaches to alleviating city congestion in this literature review section are reviewed. The approaches incorporate five broad categories. These include; construction of new infrastructure, improvement of the existing network, mode improvement, congestion tolls, and intelligent transportation systems (ITS) measures. This chapter provides a greater understanding of the project concepts before data analysis. Moreover, the themes adopted provide greater insight into applying the methodology to achieve the research objectives and respond to the research question. Similarly, this chapter helps to frame the conclusions and recommendations of this study.

2.2 Traffic congestion

Traffic congestion is a complex phenomenon because of the many intricate factors leading to its occurrence. Falcocchio and Levinson (2015) define congestion as a disproportionate demand for and supply of transportation amenities. The supply is due to inadequate transport facilities by responsible agencies. Demand is due to increased travel in space and time. Nguyen-Phuoc et al. (2020) detail numerous definitions of traffic congestion from various scholars. These definitions stem from demand, delay, and cost relationships.

Congestion takes two main forms, physical and relative. The latter relates to commuters' expectations of roadway performance. In contrast, the former describes how one vehicle impedes another's movement in the traffic system as the road network reaches capacity (OECD, 2007). This study concurs with the OECD discovery regarding this description of congestion; however, it may not precisely measure congestion.

2.1.1 Types of congestion

Congestion is grouped into two; recurrent and non-recurrent.

- **Recurrent congestion**

This type of congestion describes the daily traffic congestion on the road. It occurs at fixed locations once the demand exceeds capacity (Liu et al., 2017), and occurs during peak periods. Therefore, travellers are generally aware of this type of congestion. According to the Federal Highway Administration (FHWA) of the U.S. Department of Transportation (US DoT), recurring congestion accounts for 50% of the causes of congestion on the roads in the U.S. (FHWA, n.d.).

There are various root causes of recurrent congestion. These may include poor traffic control systems. This is caused by inadequate traffic light systems, no stop signs, speed reductions, and railway crossings. These affect traffic flow, causing queue propagation and congestion (Afrin and Yodo, 2020). Moreover, in systems with adequate traffic lights, the causes may emanate from poor design of these systems; when they do not match the traffic volumes or the lights are not functional, and, traffic police must control the intersections. A study by Road Safety Initiative (RSI) in Uganda identified factors influencing traffic congestion in Kampala (RSI, 2014). These included poor traffic lights, low road capacity utilization during peak hours, ongoing road activities, incorrect parking, and competitive driving along intersections. In addition, city roundabouts tend to cause traffic congestion due to over-saturation, reducing the throughput in specific directions. Bashingi, Mostafa and Kumar Das (2020) also listed poor control systems and road networks among the causes of congestion in their study in Botswana.

- **Non-recurrent congestion**

This type of congestion is synonymous with accidents, weather, random events, and car breakdowns (Keler, Krisp and Ding, 2017a). Non-recurring congestion can trigger traffic jams during off-peak hours, thus being unpredictable (Afrin and Yodo, 2020). Also, these types of congestion pockets can appear anywhere along the road network, adversely affecting commuters' travel time. According to FHWA, similar to recurrent congestion, non-recurrent congestion contributes to over 50% of the total causes of congestion on the roadway network. It further estimated incidents like accidents and car breakdowns at 25%, weather at 15%, and work zones at 10% (FHWA, n.d.). Following is a brief discussion of the major causes of non-recurrent congestion.

i. *Weather conditions*

Different areas have diverse weather conditions that adversely affect the traffic flow, causing congestion. In addition, the weather conditions may cause interruptions in traffic control systems, hindering throughput (Afrin and Yodo, 2020). For example, in Uganda, the rainy seasons badly affect the roads in

Kampala, causing floods; hence traffic flow is affected. In the USA, floods due to heavy rain, winter snow and ice, hurricanes, and high winds (FHWA, n.d) are significant causes of traffic disturbances by the weather.

ii. *Work zones*

Such areas cause stagnation of traffic flow due to construction on or along the road. Construction may include upgrading roads, maintenance activities, and new construction, like overpasses at a particular section of the road. Construction often causes reduction in lane width, inaccessible shoulders, lane diversions, roadway sharing with opposing traffic, and temporary closure; hence traffic congestion becomes unavoidable (Afrin and Yodo, 2020).

iii. *Roadway incidents*

Road incidents may occur due to traffic accidents, car breakdowns, and fuel run-outs which may cause delays on a particular section of the road. In addition, these incidents tend to obstruct the road, often causing a temporary lane closure, or roadway sharing with opposing traffic if the road is two-lanes and two-ways. Therefore, these types of incidents depend on prompt responses by emergency services like traffic police, car service providers, ambulances, and fire-fighters. In South Africa, as part of the Freeway Management System (FMS), the Emergency Management Service (EMS) is fully active, which reduces the overall delay time anticipated due to the immediate response (SANRAL, 2020).

iv. *Special events*

These are occasions that may alter the usual flow of traffic on particular sections in a road network. They may include sports activities like marathons, football games, marches for a particular cause, and concerts. The institution in charge may have to have a special events management system to ensure that commuters are not affected; otherwise, special events can result in disorder in the travel environment.

Understanding the various types of congestion is vital for comprehending the traffic flow of the system on a particular road network. There are quick identification of locations, times, and intensities for recurrent congestion. Based on this, urban transport managers and planners can take appropriate mitigation measures according to congestion patterns (Liu et al., 2017). Many studies have addressed traffic congestion in light of its various features. This study seeks to understand this phenomenon, building on other researchers that have explored it. This study also aims to help alleviate traffic congestion in Kampala by assessing its causes in the city, and then proposing measures to reduce it.

2.1.2 Causes of traffic congestion

Falcocchio and Levinson (2015) describe the causes of congestion in three broad categories: a large concentration of demand in a spatial-temporal pattern, high demand exceeding roadway capacity, and physical and operational bottlenecks. The second cause of traffic congestion, as described by Falcocchio and Levinson, is the most typical definition of traffic congestion. Nonetheless, a discussion on all three categories follows.

- **Concentration of demand**

For large traffic concentrations, Falcocchio and Levinson (2015) assert that if there were even distribution of travel demand throughout the day in various parts of the city, congestion would not occur. However, because of human travel behaviour, this remains a problem. The Central Business Districts (CBD) of most cities are the focal point for economic activities. This leads to high volumes of travel to and from these areas at particular hours of the day, causing traffic congestion on the road network. Afrin and Yodo (2020) similarly assert that the variation of traffic flow causes different traffic volumes on different days. In cases where there is no fixed volume capacity, congestion might be inevitable. This study agrees that the variation in human travel behaviours causes significant congestion increases. Litman (2013) further adds that the size of the city, as well as its density and employment opportunities contribute to congestion. These factors require definitive consideration when studying congestion trends.

- **High demand exceeding roadway capacity**

This is synonymous with over-saturation. Falcocchio and Levinson (2015) discuss high demand exceeding roadway capacity related to population-growth in cities. They determined that increased car usage and employment opportunities are inversely proportional to roadway capacities. Likewise, Bashingi, Mostafa and Kumar Das (2020) studied congestion in developing countries. Their case study states that congestion in Botswana is the result of high increases in densification due to urban settlements and a rise in motor vehicle use. This study concurs that all these factors in this category are interrelated. For example, when employment levels rise, the cities become more populated; consequently, higher-income earners tend to possess a vehicle, increasing traffic density on the roads.

This study posits that traffic congestion indicates a city's economic growth. Due to high population density and increases in motor vehicle usage, infrastructure may quickly become obsolete, unable to handle the increased flow of traffic; hence the system fails to meet its design purpose (Afrin and Yodo, 2020). As a result, the infrastructure is overwhelmed by the traffic volumes, causing long travel time, and thus congestion.

Several studies attribute traffic congestion to the construction of buildings in already developed cities. Wang et al. (2013) argue that it is paramount to understand how new construction will affect the transport system. This enables mitigation plans which can be implemented, and thus relieve congestion caused by urban land construction. In addition, they discuss how redevelopment might impact the demand-supply curve for transport facilities.

- **Bottlenecks**

Many developing countries are significantly affected by this category. Bottlenecks subdivides into physical and operational bottlenecks. Bottlenecks typically occur when roads converge. Their severity depends on the number of lanes, width, road alignment, and merging length before the interchange (Afrin and Yodo, 2020). The roads' converging affects the existing congestion on the main road, often causing a blockage. The Blockages are due to the number of lanes merging exceeding the capacity of the road. It usually occurs at tunnels, bridges, ramps, and adjoining streets to the main road.

Falcocchio and Levinson (2015) further divide bottlenecks into recurring and non-recurring, where the former is due to road design deficiency like converging lanes, topographic and physical barriers. The latter are due to roadwork zones, accidents, and weather that can lead to a lane closure. Based on the above discussion, this study contends that bottlenecks are among the more prominent causes of traffic congestion in developing countries.

2.1.3 Effects of traffic congestion

Traffic congestion has adverse effects in the cities where it proliferates. These have been discussed differently by many researchers. In their study, Samal et al. (2020) classified the effects of congestion into three categories; the impact on the economy; health in terms of mental stress, fatigue, headaches; and impact on the environment. They also discuss the cost of fuel consumption, vehicle maintenance due to constant braking, and reduced work productivity due to delays, as far as the economic aspects are concerned. Seidel and Wickerath (2020) studied rush hour and urbanization in Germany. They concluded that congestion plays a significant role in a country's economy. They investigated how population, employment, the housing market, average labour productivity, and welfare all impact rush hour. Their study indicates that a reduction in travelling time causes significant increases in urbanisation, labour productivity and welfare. This further illustrates the impact on the economy, as discussed by Samal et al. (2020).

As for the environment, the gases released into the atmosphere by combustion engines, like carbon monoxide, carbon dioxide, sulphur dioxide, and nitrogen dioxide, impact human health. Motorised vehicles also contribute to noise pollution due to the honking of vehicles (Samal et al., 2020). Moreover, Dasgupta, Lall and Wheeler (2021) studied the spatial-temporal analysis of traffic congestion, air pollution, and exposure vulnerability. Their results indicate how congested areas emit high amounts of greenhouse gases into the atmosphere, exacerbated by seasonal weather changes. Pollution adversely affects everyone, but particularly the young and the old in communities where congestion is copious.

Falcocchio andand Levinson (2015: 111-180) conclusively discuss the impact of traffic congestion according to various factors like travel time, mobility, accessibility, roadway traffic productivity, and costs. This thesis contends based on the common aspects covered in previous studies that traffic congestion's primary effect is on travel time, which has social, economic, environmental, and psychological impacts.

2.1.4 How is traffic congestion measured?

Traffic congestion needs to be quantitatively measured. Nguyen-Phuoc et al. (2020) classify congestion measures into three categories: congestion indicators, congestion indices, and level of service (LoS). The fundamental congestion indicators include speed, travel time and delay. However, no single method for measuring congestion is standard across all countries. Every country has its criteria for measuring congestion levels. The following depicts some of the performance criteria often used.

1) Speed

Speed is the most common factor used for measuring traffic congestion. The recorded speed is compared to the threshold, or baseline speed to determine the delay. The threshold speed can be free flow speed measured in uncongested periods, or speed limits that indicate the maximum allowable speed on a particular roadway. Other studies consider capacity maximizing and efficiency optimizing speeds (Litman, 2013). Capacity maximising and efficiency optimising speeds play a more significant role in congestion cost evaluations than free-flow speeds, which exaggerate congestion costs (Litman, 2013). The following two categories make up this speed factor.

- **Speed reduction index (SRI)**

This category measures travel speeds on a scale of 10. For example, 5-10 indicates high congestion, below four, low congestion, and zero represents no congestion (Afrin and Yodo, 2020). The results are in comparison to free-flow speed. Bruwer and Andersen (2022) affirm that SRI is the most appropriate congestion measure because of its standard scale and is readily available from FCD.

$$SRI = \left[1 - {V_c}/{V_{ff}}\right] X\ 10$$

V_c = Actual travel speed

V_{ff} = Free-flow Speed

- **Speed performance index**

In China, the Beijing traffic management bureau (BTMB) uses the Speed performance index (SPI) to evaluate traffic conditions. It bases its results according to table 1. The index illustrates the relationship between the travel speed and the maximum permissible road speed (He et al., 2016).

$$SPI = {}^{V}/{}_{V_{max}} X100$$

V = Average travel speed (Km/hr)

V_{max} = Maximum permissible road speed (Km/hr)

Table 2- 1: Speed performance index with traffic condition

SPI	Traffic condition level	Description of the traffic condition
From 0 to 25	Heavy Congestion	The average speed is low, and road traffic state poor.
Between 25 and 50	Mild Congestion	The average speed is lower, and road traffic state a bit weak.
Between 50 and 75	Smooth	The average speed is higher, and road traffic state better.
Between 75 and 100	Very Smooth	The average speed is high, and road traffic state good.

2) **Travel time**

Travel time is the time a vehicle takes to pass a particular roadway segment. Some of the metrics used for measuring travel time include:

- **Travel rate (TR)**

Travel rate denotes the ratio of the segment travel time to the segment length. In other words, it is the rate of movement of a vehicle on a particular road segment (Ter Huurne and Andersen, 2014).

$$TR = {}^{T_t}/{}_{L_s}$$

T_t = Travel time (min)

L_s = Segment length (km)

- **Travel time index (TTI)**

This is an increase in the estimated travel time in relation to the free-flow travel time (Erdelić et al., 2021). In the USA, FHWA uses travel and planning time indexes to compare congestion to previous years' congestion hours (FHWA, 2019). They consider the congested hours as the average number of hours the road segment is crowded, identified as the reduction in 90% of free-flow speed on weekdays. The Planning Time Index (PTI) is the 95th percentile travel time ratio to the free-flow travel time. For example, a PTI of 1.50 indicates that commuters should anticipate an additional 50% of travel time to arrive at 95% of the time. For the travel time index, it follows the computation below:

$$TTI = \frac{TT_{est} - TT_{ff}}{TT_{ff}}$$

TT_{est} = Travel time estimated

TT_{ff} = Free flow travel time

3) Delay

Delay refers to the lost time of the vehicle or commuter on a road segment. The following metrics measure this parameter:

- **Delay rate (DR)**

This is the rate of time loss for commuters during congestion periods on a specific road segment or trip. It is the difference between the actual and acceptable travel rates (Afrin and Yodo, 2020). Ter Huurne and Andersen (2014) assert that an acceptable travel rate is the one motorists can distinguish based on their own perception. It is usually between 60%-70% of the regular free-flow speed.

$$DR = TR_A - TR_{AC}$$

TR_A = Actual travel rate (min/km)

TR_{AC} = Accepted travel rate (min/km)

- **Relative delay rate (RDR)**

This measure compares two or more road sections in the network according to their congestion variations (Ter Huurne and Andersen, 2014). It is dimensionless and expressed as the ratio of delay rate to acceptable travel rate.

$$RDR = {}^{DR}/_{TR_{AC}}$$

- **Delay ratio (D_i)**

This measure is the ratio of delay rate and the actual travel rate. It also compares roadway congestion levels (Aftabuzzaman, 2007).

$$D_i = {DR}/{TR_A}$$

4) **Congestion indices**

- **Relative congestion index (RCI)**

This is the ratio of delay time and free-flow travel time. It takes the presumption that zero indicates low congestion, and values greater than two indicate significant congestion levels (Tang and Heinimann, 2018).

$$RCI = \frac{T_{ac} - T_{ff}}{T_{ff}}$$

T_{ac} = Actual travel time

T_{ff} = Free flow travel time

Where;

$$T_{ac} = {L_s}/{V_s} \quad \text{and,} \quad T_{ff} = {L_s}/{V_{ff}}$$

L_s = Spatial Length (km)

V_s = Spatial Mean Speed (km/hr)

V_{ff} = Free flow Speed(km/hr)

- **Road segment congestion index (R_i)**

The standard road segment state and the duration of the non-congestion state in the particular observation period measure the degree of road segment congestion. Moreover, the Speed Performance Index (SPI) higher than 50 depicts a non-congestion state. The value of Ri ranges from 0-1, where the lesser the value, the more congestion on the segment (Afrin and Yodo, 2020).

$$R_i = \frac{SPI_{avg}}{100} \; x \; R_{NC}$$

$$R_{NC} = \frac{T_{NC}}{T_t}$$

SPI_{avg} = Average Speed Performance Index

R_{NC} = Proportion of non-congested state

T_{NC} = Duration of the non-congested state

T_t = Time Length of the observation period

5) Level of service

The level of service (LoS) of the road network is measured to understand the overall performance of the road network. Performance measurement is an essential aspect of traffic engineering. It rates the system beforehand to propose mitigation measures. It also monitors whether a particular strategy has caused an effect on the system. According to the Highway Capacity Manual (HCM), the level of service is a quantitative representation of the overall quality of the road (TRB, 2010). Babit, Sharma and Duggal (2016) define LoS as a qualitative measure describing users' operational conditions. However, this definition contradicts the HCM, demonstrating that the LoS is qualitative not quantitative. The level of service includes various measures, such as the commuters' perspective, and help the institutions in charge of roadworks in decision-making.

❖ Factors affecting the quality of service

The HCM 2010 states the factors that affect the quality of service for commuters. These may include:

- *Travel time, speed, and delay*

This study grouped these factors according to their resultant effects. The speed used to traverse a particular section of a road determines the time taken to cross the section and, consequently, the delay experienced. These greatly influence commuters' perceptions of the quality of service.

- *Number of stops incurred*

These include the intersection points along a segment of the road. The stops may be due to four-way stops, roundabouts, and/or stoplight intersections. The fewer stops, the higher chances the segment will be perceived as providing a satisfactory quality of service.

- *Travel time reliability*

This refers to the attainment of the travel time expected to traverse a particular road segment. Otherwise, the system is deemed to be at a low service level. Therefore, travel time reliability is an essential factor by which commuters perceive the quality of service.

- *Maneuverability*

There should be sufficient provisions for vehicles to manoeuvre without affecting the traffic flow. These could include the ease of changing lanes along the roadway and the percentage of time-spent-following other slow-moving vehicles. Therefore, the choice to manoeuvre while moving at the same speed is an essential factor in measuring the quality of service (Babit, Sharma and Duggal, 2016).

- *Comfort*

This is associated with bicycle and pedestrian interaction and separation from traffic, transit vehicle crowding, and ride comfort due to the road's surface. The latter refers to levelled roads with no potholes that provides a certain comfort level. The road alignment should also be comfortable to navigate. Babit, Sharma and Duggal (2016) add that driving comfort and convenience reveal the state of the roadway network and traffic conditions to a driver.

- *Convenience*

The roadway should be easy to locate, and transit services should be available at regular intervals and at accessible stations. Commuters will perceive this as an added advantage in their travels, rendering them convenient.

- *Safety (actual or perceived)*

To be considered safe, a roadway should have few obstructions to traffic and limited interactions with pedestrians and bicycles. Potholes or other disrepairs that hinder road safety play a vital role in the quality of service.

- *User cost*

The user costs may include transit fares, tolls, fuel consumption, and vehicle maintenance. A system is considered user-cost-friendly when there are appropriate transit fares and minimized fuel consumption. Also, the reduction in vehicle maintenance costs due to better road surfaces and less braking in the traffic stream are also factors which users may appreciate.

- *Availability of facilities and services*

Commuters traveling shorter distances to services from bus stops render the system efficient. The services may include hospitals, police stations, civic centres, markets, and schools.

- *Facility aesthetics*

The roadway should be appealing to commuters' eyes. The appearance of the facility is vital in rating the system's quality. The facilities may have pedestrian overpasses, well-maintained roadside gardens, and well-marked roads that increase the road's physical appearance.

- *Information availability*

The information on or about the roads needs to be available and understandable to commuters. The roadway signage system should be placed at an appropriate location to allow for timely decision-making for the driver and conform to standards. The transit route and schedule information for transit services should be well illustrated and accessible for commuters and followed regularly.

❖ **Service Measure**

The HCM 2010 further describes the service measures for specific roadway systems. The systems are all affected by cross-cutting issues presented by motor vehicles, pedestrians, bicycles, and transit modes. The systems in the road network are broad. This research study deemed it valuable to discuss some of the different systems in a given road network, and these include:

- *Freeways and multilane highways*

In the case of motor vehicles, density functions as a service measure for freeway facilities, primary freeway segments, ramp junctions, weaving segments, and multilane highways. As the density increases, flow increases to a saturation point of the system capacity. Therefore, the quality of the service can easily be conceptualized by commuters.

For bicycles, motorized volumes and speed, percentage of heavy vehicles, separating lanes, and pavement quality influence riders' comfort in such systems. The higher the volumes and speeds of motor vehicles, the potential decrease in the comfort of cyclists. The LoS depends on the bicycle LoS score model.

- *Two-lane-highways*

For motor vehicles, the service measures for the system include the percentage of time-spent-following, average travel speed, and percentage of free-flow speed. These depend on the function of the particular highway. For example, some highways may require efficient mobility, primarily those connecting the primary links in the network and generating high volumes of traffic (major two-lane highways). Therefore, percentage of time-spent-following and average travel speed may be the service measures to gauge the LoS. On the other hand, some highways are designed for accessibility. These may include two-lane rural highways where delays as a percentage of free-flow speed acts as a service measure. In contrast, other two-lane highways designed for accessibility functions may utilize the percentage of time-spent-following to measure LoS.

In addition to the factors stated for multi-lane and freeway systems, highway parking also affects the LoS of bicycles. This tends to hinder the movement of bicycles, because stoppages cause insufficient space between bicycles and motorized vehicles.

- *Urban street facility and segment*

For motor vehicles, the percentage of base free-flow speed indicates the LoS. Motorists should always travel at the required speed limit between intersections. However, delays may be experienced due to limiting factors like; traffic control systems, dropping and picking passengers up at bus stops, pedestrian crossings, and vehicles turning; all of which tend to lower the average speed, hence low assumed LoS.

For pedestrians whose LoS relies on the pedestrian LoS score model, the LoS for this depends on two functions; pedestrian-density and non-density indicators. The former relates to the pedestrian volumes and sidewalk width, while the latter relates to the traffic separations, sidewalk presence plus width, and vehicle traffic volumes plus speeds. The worst of the two functions measures the LoS of a road in pedestrian mode. Generally, the pedestrian LoS improves by providing wider sidewalks, an expanse separation from traffic, and reduced delays when crossing the street at signalized and non-signalized locations. Additionally, higher traffic volumes, speeds, and broader streets all reduce pedestrian LoS.

For bicycles, as mentioned earlier, LoS is based on the bicycle LoS score model. The factors that influence the LoS for cyclists may include; separation from traffic, motorized traffic volumes and speeds, heavy-vehicle percentage, presence of parking, and pavement quality. The higher the mentioned factors, the lower the cyclist's perceived comfort and traffic exposure. Nonetheless, marked bicycle lanes or roadway shoulders improve the LoS of cyclists. Also, pavement quality affects riders' comfort.

LoS also hinges on the transit score model for the transit mode. This model involves studying the mass transit travellers' perceptions of LoS. It includes passengers' experiences walking to a transit stop on the street, waiting for the transit vehicle, and riding on the transit vehicle. In the case of walking to the transit stop along the street, the pedestrian LoS score accounts for this. Then the factors that influence the waiting for the transit vehicle are the availability of shelters and benches, transit vehicle frequency, and service reliability, including waiting for other passengers at various bus stops. Lastly, passengers riding on the transit vehicle consider the average travel speed as a service measure. Therefore, the above factors influence commuters' LoS for mass transit.

- *Urban street intersections*

For motorized vehicles, the service measure is determined by the control delay for stoplight intersections, all-way stop-controlled intersections, two-way stop-controlled intersections, roundabouts, and interchange ramp terminals. The control delay measures driver distress, fuel consumption due to braking, and increased travel time. The increase in the control delay measures leads to lower LoS. The control delay varies according to the type of intersection on the road segment. The Transport research board (TRB), a committee related to Highway capacity and quality of service (HCQS), believes that stoplight intersections carry higher traffic volumes and thus experience longer delays than intersections with other forms of stop-control.

For pedestrians on stoplight intersections, the perceived LoS depends on motor vehicle volumes and speeds, crosswalk length, average pedestrian delay, and island presence on right/left-turn lanes. These are measures on the LoS score model. The lower the factors, the higher the LoS for pedestrians. For two-way stop-controlled intersections, the pedestrian LoS relies on the average pedestrian control delay influenced by traffic volumes, the presence of a median, and the provision of a pedestrian crossing area.

The LoS for bicycles on stoplight intersections also depends on the bicycle LoS score model. These may be affected by separation with motor vehicles, vehicle volumes, cross-street width, and on-street parking.

- *Off-street pedestrian and bicycle facilities*

Pedestrians on off-street facilities like pathways, staircases, and arcades in urban centres use pedestrian space as a service measure. With adequate space, pedestrians will move at their own pace and focus on their travel direction without disturbances, hence higher LoS. If the facilities involve sharing between pedestrians and bicycles, the LoS will depend on the frequency pedestrians encounter bicycles per hour. The lower the times, the higher the LoS perceived by the pedestrians.

The LoS for pedestrians also depends on the bicycle score model for the bicycles on either shared or or exclusive facilities. The variables include; the number of times a cyclist meets other users per minute, potential delays due to the number of times per minute waiting/passing other users, path width, and the presence of a centreline. Therefore, the LoS declines with an increased number of cyclists and pedestrian users.

In summary, the LoS is an essential aspect of understanding a facility's optimization and indicates to service providers' potential needs to adjust accordingly to improve the road network. This study focusses on LoS on two-way highways in an urban environment, and urban street intersections for motorized vehicles. Two-lane highways leading to a city that is connected by arterial roads will provide an overview of the LoS traffic status. Since the function of two-way highways in urban centers is accessibility, the LoS relies on the delay in terms of percentage of free-flow speed. Likewise, the LoS for urban street intersections depends on the percentage of free-flow speed. Therefore, this study utilizes the delays experienced by motor vehicles in the Kampala road network to classify the intensities depending on traffic volumes and road class. Also, the transit, pedestrian, and bicycle LoS score models derived for stoplight intersections are inappropriate for intersections without stoplights, because of the different mechanisms for both intersections.

- **LOS Calculation**

Table 2 shows the LOS scale for a roadway from the equation below. LOS depends on the volume/capacity ratio (V/C):

$$\frac{V}{C} = \frac{V_S}{N_{max}}$$

V_s = Spatial mean volume

N_{max} = Maximum number of cars contained on a segment

$$N_{max} = \frac{L_S}{L_v} \, x \, N_l$$

L_s = Spatial segment length

L_v = Average vehicle lane occupancy

N_l = Number of lanes

Table 2- 2: LoS with corresponding V/C ratio and operating conditions

LoS Class	Traffic state and condition	V/C ratio
A	Free flow	0 - 0.60
B	Stable flow with unaffected speed	0.61 - 0.70
C	Stable flow but speed is affected	0.71 – 0.80
D	High density but stable flow	0.81 – 0.90
E	Traffic volume near at or at capacity level with low speed.	0.91 – 1.00
F	Breakdown flow	>1.00

Afrin and Yodo (2020) observed that the different congestion measures might have different values but consistently quantify congestion. Their study illustrates how the standards are reliable in measuring congestion. They all depend on travel time and speed, apart from LoS measurement, whose values deviated from the other measures. This is because LoS considers the volume of vehicles and the roadway capacity. Furthermore, travel rate, travel time index, planning time index, and road segment congestion index do not provide a range of values for estimating congestion. This could present difficulty in identifying the cut-off points for the congestion periods.

2.1.5 Characteristics of a good congestion measure

The HCM state the characteristics of service measures that require consideration before classifying roads in a network on the LoS scale. According to Afrin and Yodo (2020), the features also apply to other congestion measures. These include:

- *Commuters' perceptions and interpretability.*

This measure should reflect commuters' general experience while travelling on the roadway. This could involve enquiring from commuters how the road provides the service and whether their expectations are met. Such an inquiry could enable institutions in charge of traffic planning to obtain an overview of the general performance of the roads. Ideally, the results should be well understood by non-technical teams associated with traffic planning. However, it can be argued that getting such information from the general public might be expensive. The road network coverage might be small, and the sample size might not reflect the actual situation on the road. It is thus subjective. KCCA uses this system on its website portal, where it runs an online survey on the performance of the roadways in Kampala (www.kcca.go.ug).

- *Useful to responsible agencies*

Traffic engineers and urban planners should devise mitigation strategies according to the results presented by the adopted measures to positively impact a road's LoS. Engineers and planners must act accordingly to improve the network performance from using various service measures. Additionally, it should be adequate for the service measure to partake in the predictive and statistical analysis of road performance (Afrin and Yodo, 2020).

- *Measurable in the fields*

The relevant agents must ultimately quantify the service measures from the field or secondary data. In the case of the present research, Floating Car Data in terms of travel time and speed was used. This enabled evaluation of the performance of the road networks regarding traffic congestion. Also, HCM 2010 gives an example of a traffic engineer desiring to determine the LoS for a two-lane highway used for recreational access. The engineer must go to the field and directly measure the average travel time and speed using an appropriate measuring tool.

- *Predictable*

Service measures should conform to the prevailing conditions given a set of known or forecast situations. Therefore, the estimations can help predict a roadway's future needs.

2.1.6 Summary

In conclusion, traffic congestion is one of the significant problems in many urban environments. This research seeks to understand its causes and effects. This chapter gave a glimpse of the many ways congestion can be measured using different variables. Consequently, the relevant institutions, mostly traffic engineers and urban planners, can reduce the impact of congestion by mitigating the possible causes using a particular service measure. Also, understanding how traffic congestion can be measured allows for comprehensive investigations on how to deal with it. In other words, the service measure should be measurable, reflect the commuters' perceptions, and be predictable so the responsible agents can obtain the relevant mitigation strategies to combat any road traffic problems. However, this requires traffic data, from which congestion is categorized according to the intensities using different methodological approaches. Hence, in this study, FCD was utilized to develop a model for estimating the congestion areas. Section 2.3 gives an overview of FCD. Additionally, after identifying high-intensity zones, the causes of congestion in such areas are evaluated, and a proposal for different measures to alleviate congestion is given. Section 2.4 provides a general overview of measures to relieve congestion.

2.3 Floating Car Data (FCD)

2.3.1 Introduction

This research uses Floating Car Data (FCD) to design a model for evaluating traffic congestion in Kampala. Different traffic datasets are used for transport studies, as discussed in section 2.3.4. However, FCD is a current dataset used to evaluate traffic-related problems in studies such as the present one. Unfortunately, FCD has not gained considerable attention in Africa. This research aims to present this dataset to attract the attention of key transportation players in developing countries. The relevant authorities, such as state-run traffic departments and the engineers and urban planners who work for them in different African countries, are responsible for ensuring efficient, safe, and reliable transport systems.

FCD is data obtained from the moving vehicles in a traffic stream. It records the timestamp, location, and speed of cars with the help of a GPS (Kessler et al., 2018). GPS is one type of Global Navigation Satellite System (GNSS). It is a rich dataset because of the spatial-temporal characteristics it embeds. GPS is typically situated in vehicles or mobile phones to provide information about the road network. The dataset for this study also covers a wide area compared to the infrastructure-based approach. This is because the spatially distributed vehicles in the road network provide greater potential for analysis, which in turn results in a better traffic monitoring system. It is also a significant amount of data because of the many records generated by a single car in a traffic stream (Kong et al., 2018). Traffic engineers can extract relevant features of the transport system from the control centres of the GPS.

FCD also serves in different applications of traffic studies because of its ease in data collection (Kong et al., 2018). It does not require almost any infrastructure cost compared with other datasets. FCD is a cooperative system utilizing the vehicle to infrastructure (V2I) system (Stahlmann et al., 2011). This system that can help improve overall traffic efficiency, safety, and travel comfort. Moreover, Mfenjou et al. (2018) regard FCD as an intelligent transportation systems (ITS) technique because of the technology employed when collecting the data.

FCD has become more readily available in recent years due to an increasing number of e-hailing companies such as Uber, Bolt, DIDI, as well as the use of GPS in commercial and government vehicles. The service providers for the FCD may include TomTom, Google, and INRIX. These companies share traffic data with traffic engineers and urban planners to restructure particular sections on the road network to improve mobility. Likewise, Uber has a service called Uber movements that provides the same type of data. Therefore, utilizing the available system could enable service providers to monitor overall traffic flow and thus engage promptly.

Despite the increase in the number of probe vehicles in the road network, developing countries in Africa have not fully utilized this opportunity. Moreover, the improvement of several traffic-related problems in Africa is assured. Xu, Yue and Li (2013) contend that monitoring traffic trends provides a general overview of a network's performance from the FCD historical dataset. This can alleviate congestion, increase overall safety, and enable traffic managers to predict traffic patterns more accurately. Wu, Yin and Yang (2013) further assert that the advanced traveller information systems (ATIS) and advanced traffic management systems (ATMS), both of which are applications of intelligent transportation systems (ITS), depend on real-time traffic information. This positions FCD as a relevant dataset in acquiring information that informs road users of the status of a given road section, and expected delays. Wu, Yin, and Yang's study concurs with Moreno, Romana and Martínez (2016) on how FCD is a cost-effective data collection system on roadways.

In summary, following the introduction of FCD, this section explored the different traffic datasets used in transport studies. An explanation of the advantages and disadvantages of FCD compared to other datasets was also provided. This was followed by a discussion on how FCD works. Then, the mechanisms for obtaining the data and its usage were described. After that, an overview of some of the studies conducted using this particular dataset to emphasize its richness was provided. The studies were grouped into traffic, social, and environmental trends. Since this research deals with traffic congestion, a brief discussion on how FCD has been used to estimate traffic congestion in different studies in different countries was also included, as well as an exposition of the applications of FCD in different situations. Finally, a discussion on the challenges of FCD followed.

2.3.2 Traffic Data

The two generally known types of traffic datasets include trajectory and stationary datasets. Trajectory data is sometimes known as "big data" (Munizaga, 2019). This is because of the amount of data transmitted in a short period, attributed to technological capability. Munizaga further describes the relevance of big data as a collection mechanism due to advanced digital devices, enhanced storage capacity and computing power, and enhanced sensing and communication technologies.

Treiber and Kesting (2013) categorize traffic datasets into three types; trajectory dataset, floating car data, and cross-sectional datasets. Whereas Wang, Miwa and Morikawa (2020) consider floating car data as a trajectory dataset and depicts cross-sectional data as stationery data. Xia et al. (2017) refer to trajectory and stationery datasets as Lagrangian and Eulerian datasets, respectively. This is because of the mode of collection of the data. Eulerian datasets are generated from stationary sensors on the road and Lagrangian from moving vehicles. Therefore, according to Wang, Miwa and Morikawa (2020), Kong et al. (2018), and Treiber and Kesting (2013), there are different sources of traffic data. Adapted from the mentioned references, the illustration below depicts the data sources for different types of traffic data.

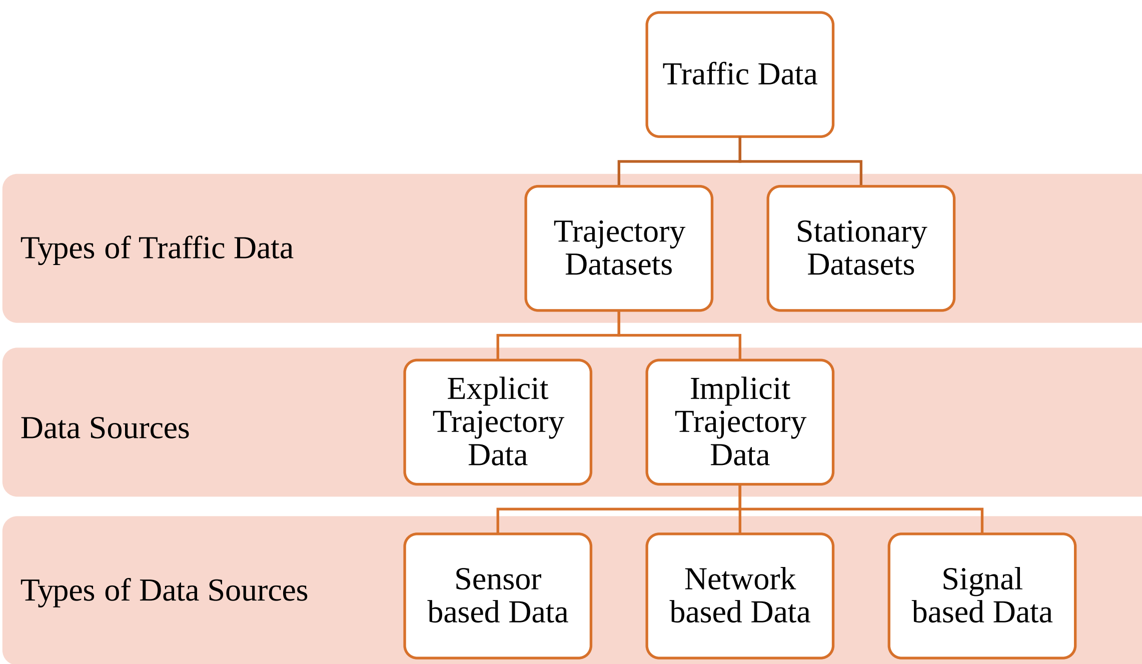

Figure 2- 1: Types of traffic data

1) Trajectory data

This is data generated by a moving object in space recorded in sequential timestamps. A tracking device extracts the position of each vehicle over time. The captured vehicles within the given road segment result in trajectory data (Treiber and Kesting, 2013). The trajectory is composed of two or more spatial points. This implies a sequence of points (Wang et al., 2021). According to Wang, Miwa andand Morikawa (2020), and Kong et al. (2018), there are two types of trajectory data; explicit and implicit trajectory data.

- Explicit trajectory data

This is data mainly from GPS. It is a well-structured type of data that records the time and position of an object using latitude and longitude. The GPS data is also called floating car data (Treiber and Kesting, 2013). Trajectory data includes other factors such as; altitude, speed, direction, and vehicle status (Hao, Zhu and Zhong, 2015). The data collected can be improved to provide extra features like distance to the leading car and its speed by equipping the car with a radar sensor. In this case, the data is called extended floating car data (xFCD) (Treiber and Kesting, 2013). However, this method is expensive. The GPS data normally collected does not provide information on the other cars on the road network. Hence, traffic density and flow are not attainable with this type of dataset.

- Implicit trajectory data

Implicit trajectory data requires high-level pre-processing and data mining techniques to obtain information suitable for analysis. Implicit trajectory data also has a weak spatio-temporal continuity in the traffic stream and possesses multiple storage formats like text messages, videos, images, and audios (Kong et al., 2018). This is because of the numerous data sources and collectors. An event triggers this type of data, such as smartcard transactions, check-ins on social media, or signal tower reception, among others. In case of no such event occurring, no data will be collected (Wang, Miwa and Morikawa, 2020). There are three types of implicit trajectory data; sensor-based data, network-based data, and signal-based data.

i. Sensor-based data

The data constitute information at specific locations triggered by sensors. They include automated fare collection (AFC) and traffic monitors. AFC is situated in public transport systems and generates data from smartcard transactions. AFC also enables the monitoring of public transportation systems and the different trends in the road network (Disson et al., 2021). Traffic monitors are also sensor-based data that record the object identity and time of passage. Sensor-based data have a high spatial-temporal accuracy due to the limited scope of data acquisition.

ii. Network-based data

This is data generated through the internet on social networking platforms. These may include; Facebook, Twitter, Instagram, Google, and others. It is also known as web-based data. These generate trajectory data using the geotags (adding a geographical location) on the platforms. However, the data is affected by lots of interference due to the high dependence on user behaviors, which implies complex data processing systems are needed (Kong et al., 2018).

iii. Signal-based data

This is a type of location-based services (LBS) data. It requires the endowment of several signal projectors in advance like; wifi transmitters, cell towers, and bluetooth connectors. A receiving device, like a mobile phone, is a requirement. Signal-based data includes long and short distances. The former consists of global system for mobile communication (GSM) networks and call detail records (CDR). GSM uses a chronologically ordered sequence of identifiers as the object moves along. The short distance uses wifi, radio frequency identification (RFID), and bluetooth. The signal-based data also includes information about device ID, signal strength, and connection/disconnection timestamps (Wang, Miwa and Morikawa, 2020).

2) **Stationary data**

This is situated in specific areas and usually built along road networks. Stationary data measures the traffic flow and volume on a given road segment. Types of devices include; inductive loop detectors, magnetometers, microwave radars, infrared sensors, and acoustic sensors (FHWA, 2011). The sensors are also called vehicle detection systems (VDS). Treiber andand Kesting (2013) refer to this type of dataset as cross-sectional data. The collected data can either be single or aggregated into macroscopic measures and transmitted to the data centre. However, transmission requires high infrastructure and maintenance costs.

There are other types of data besides those previously discussed. However, their usage depends on the particular scenario investigated. Wang, Miwa and Morikawa (2020), and Kong et al. (2018) in their studies considered supplementary/relevant datasets that include point of interest (POI) and map data. These complement the mining of trajectory datasets. Furthermore, POI may consist of buildings, hotels, supermarkets, parks, and public transportation stations. The map data includes maps from Google Maps, Bing Maps, OpenStreetMaps (OSM), etc. Such data is essential for use in traffic studies.

This study evaluates traffic congestion by utilizing floating car data (FCD) in Kampala. This explicit trajectory dataset is readily available and accessible. However, this type of data is not commonly studied on the African continent. The next section discusses the advantages and disadvantages of FCD over other datasets, followed by how FCD works. This is followed by a discussion on the current studies using this dataset and its services to stakeholders. Then, a review of some of the challenges of FCD is given.

2.3.3 Advantages of FCD

Kessler et al. (2018) compared the speed data from probe vehicles and stationary detectors. The comparison showed how the probe vehicles are efficient in detecting spatial resolution congestion.

However, stationary detectors outperform probe vehicles in terms of temporal resolution. This is due to the wide distribution of stationary detectors.

Data collection is always time-consuming and usually very costly. Also, its availability is contestable. Therefore, the major constraint in studying traffic trends is limited data availability (Loo and Huang, 2021). However, the advent of FCD provides a new paradigm for traffic studies due to its availability and reliability.

Singh andand Gupta (2015) recognised the use of GPS as paramount in traffic studies. This is because GPS provides real-time traffic information and large amounts of data over a long period (Cohn and Bischoff, 2012). This enables urban planners and engineers to adopt reactive measures to alleviate traffic congestion (Boukerche, Tao andand Sun, 2020).

Another advantage of FCD is that the penetration rate to achieve satisfactory results is 5% -10% of the total vehicles on the road network. A study by Sunderrajan et al. (2016), where a traffic simulation was performed on an expressway to determine the minimum number of probes required for analysis illustrated that a penetration rate of 5%-10% is sufficient. This reinforces the viability of FCD for obtaining reliable results.

FCD provides random sample sets for entire urban road networks (Liu et al., 2017). This enables the whole road system to be captured from a probabilistic point of view. Therefore, an entire road network is a sample space that allows for the collection of data from the monitored areas (Cohn and Bischoff, 2012).

High-quality FCD is readily available from reliable sources at a reasonable cost (Liu et al., 2017). The companies that provide the data are well-known and trusted worldwide. For instance, Kessler et al. (2018) used TomTom data in their study. This may motivate African countries with no stationary data collection systems to utilise the data from distinguished companies. Trajectory datasets generally require sophisticated mining techniques to obtain usable data.

FCD can incorporate different data sources beyond the explicit use of GPS. For example, fusing GPS data with data from Bluetooth devices and mobile phones is possible and a richer FCD is also produced (Cohn and Bischoff, 2012). Therefore, by utilising FCD, different traffic patterns are studied, from which mitigation measures can be sought, ultimately improving the road network.

2.3.4 Disadvantages of FCD

Kessler et al. (2018) noted inadequate penetration rate as a significant constraint of FCD. However, this can mainly be attributed to urban streets, because Sunderrajan et al. (2016) streamlined highway penetration rates through their study. D’Andrea andand Marcelloni (2017) also found a shortcoming on urban streets where a probe vehicle may be insufficient for reliable estimations. They added that probe vehicles avoid highly congested zones in the middle of the city. However, an exception to this is when the probe vehicles are taxis and delivery trucks; these vehicles use urban streets to search for passengers and make deliveries to retail shops.

Kessler et al. (2018) added that the data collection frequencies require high spatial resolution capacity. Therefore, it's better for large-scale monitoring and managing.

Kessler et al. (2018) also indicated that closely-spaced stationary detectors outperform probe vehicles. Their study revealed that the former detect congestion two minutes earlier than FCD in such areas. However, both datasets might complement each other if the stationary detector infrastructure is available.

Probe data sometimes encounters the problem of GNSS position inaccuracies (Liu et al., 2017) with map matching on the corresponding road segment (Keler, Krisp and Ding, 2017b). The distortion of the spatial positions may be due to high buildings, elevated road infrastructures, and tunnels.

Another disadvantage of FCD is the inability to detect lane changes due to its degree of accuracy. However, a study by Kan et al. (2019) proposed a machine learning approach that filters taxi-GPS data to reflect real-time traffic conditions as a way of analysing traffic congestion on a fine-grained level over a larger area at a low cost.

In most cases, FCD only provides data from a single car, unlike the other trajectory datasets that capture all the vehicles in the measured area (Treiber and Kesting, 2013:7), unless equipped with sensors that can give details of the distance to the leading car and its speed. Although such an extension may be expensive, Cohn and Bischoff (2012) added that FCD has no direct relationship to traffic density and flow.

Most vehicles equipped with GPS are taxis and commercial trucks. However, these tend to drive slowly, and as such are not generally representative of the traffic on the road (Treiber and Kesting, 2013:8). Liu et al. (2017) also noted that probe vehicles like taxis choose an optimal route when carrying a passenger, drive slowly, and choose a pathway in a higher travel demand region for potential customers. Nevertheless, both taxis and commercial trucks can be assumed to mostly travel at standard speeds when carrying passengers and delivering goods.

2.3.5 How does FCD work?

There are different ways by which researchers acquire FCD. Some have installed GPS in a single car or a particular number of cars like taxis (private hire) and trucks for their studies (Erdelić et al., 2021; Yao and Lin, 2016; Osei et al., 2022). This implies constant monitoring of these probe vehicles as data comes in. Also, different mining techniques need to be performed before data analysis to extract usable data. Others have used pre-processed data from companies that supply such data, for example, TomTom (Kessler et al., 2018; Perallos et al., 2016), INRIX, or other home-based organisations (Xu, Yue and Li, 2013; An et al., 2016; Song et al., 2019; Rempe, Huber and Bogenberger, 2016). Data acquired individually is generally quite expensive. It requires a lot of resources, hence the broader context of the research.

Researchers have also used different data time frames. Some have used data for five years (Erdelić et al., 2021), five months (Rempe, Huber and Bogenberger, 2016), one month (An et al., 2016; Keler, Krisp and Ding, 2017), one week (Xu, Yue and Li, 2013; Liu et al., 2017; Song et al., 2019) and one day (Yao and Lin, 2016). The non-uniformity of data time frames can cause misperceptions of the best time frame to adopt in an evaluation. Time frames should be uniform for easy referencing and consistent analysis. It is also important to acknowledge different periods in a given time frame. For example, for congestion studies, some focused on rush hours (Keler, Krisp and Ding, 2017), weekdays or weekends (Song et al., 2019), and seasonal periods (Erdelić et al., 2021). This gives a glimpse of the congestion tendencies in terms of temporal characteristics.

Liu et al. (2017) discuss FCD utilisation at three different levels. At the macro level, FCD analysis evaluates the efficiency of traffic planning implementation and assists urban planners in identifying any bottlenecks that were unaccounted for during the planning stage. Studies at the macro level may include congestion detection (Xu, Yue and Li, 2013), prediction analysis (Mzibri, Maach and Elhadri, 2019). At the meso level, travel speed characteristics can reflect road networks' general topographies and discover driving route distributions. Studies in this category may include; route choice modelling (Dabbas, Fourati and Friedrich, 2021), estimation of origin-destination matrices (Vogt et al., 2019), and traffic speed forecasting (Zhang et al., 2021). Furthermore, at the micro-level, specific scenarios can be studied. Studies may include; urban traffic incident analyses, segment demand capacity analysis, and intersection delays (Fourati, Dabbas and Friedrich, 2021). On the macro level, researchers tend to divide the area under study into fine-grained grids or zones (An et al., 2016; Liu et al., 2017) or use administrative boundaries (Song et al., 2019). This helps to reduce the volume of the data without compromising the quality. In addition, speeds are aggregated for the particular zones, simplifying the evaluation.

FCD can be utilised as historical or real-time traffic data. Some studies used real-time traffic data (D'Andrea and Marcelloni, 2017; Song et al., 2019). Also, D'Andrea and Marcelloni augmented congestion detections in their study by designing a platform informing the road users of the traffic status in particular road sections. Otherwise, historical data usage is prevalent among researchers and appropriate for evaluating traffic patterns (Keler, Krisp and Ding, 2017; Liu et al., 2017). This enables proactive approaches when addressing traffic problems. Yet, real-time data supports reactive measures like re-routing and adaptive traffic light control (Boukerche, Tao and Sun, 2020). However, reactive measures like using real-time data may be short-lived in cases where road capacity is exceeded, or the road network is overburdened because of traffic instabilities. On the other hand, historical data supports long-term decision-making for road network improvement, for example, setting tidal lanes, and public transport improvement, among others.

Researchers use different parameters extracted from FCD in their analyses. Some used speed (Tišljarić et al., 2020; Liu et al., 2017), travel times (Rahmani, Koutsopoulos and Jenelius, 2017; Mori et al., 2014), or distance (Yao and Lin, 2016) in studies of human mobility and density (Zhang et al., 2017) in detecting hotspots in urban areas. Also, experts generally use speed for congestion estimations and predictions (Keler, Krisp and Ding, 2017). Some use relative speed, and others absolute speed. For the former, the assumption of the free-flow speed in comparison differs. Some used night speed (Erdelić et al., 2021), others used speed limit, and Liu et al., 2017 used the 95th percentile of operation speed distribution in their analysis.

Different mining techniques are employed to extract relevant information from the FCD. Wang, Miwa and Morikawa (2020), and Mazimpaka and Timpf (2016) discussed the mining techniques in analysing trajectory datasets. The most appropriate methods in mining include clustering, classification, pattern-mining, outlier identification, and prediction. These enable researchers to obtain deductive results from the dataset under study. For instance, K means clustering to map spatial-temporal patterns (Song et al., 2019; Erdelić et al., 2021; Keler, Krisp and Ding, 2017), density-based spatial clustering of applications with noise (DBSCAN) (An et al., 2016; Liu et al., 2017). In a study by Wu, Yin and Yang (2013), pattern mining was used in determining the traffic status at an intersection. Bolbol et al. (2012) also used this classification technique to understand the transportation modes from sparse FCD, to determine the travel behaviours and demands.

2.3.6 Some studies conducted using FCD

Many scholarly works have employed FCD when evaluating different traffic-related problems. Wang, Miwa and Morikawa (2020) grouped their survey of studies into three categories; social, traffic, and operational dynamics. Kong et al. (2018) categorised traffic-related problems into travel behaviours, travel patterns, and others. In their discussions, the two articles considered the broader trajectory dataset as the big data. This particular thesis only considered research related to FCD. Based on this, this study draws on some of these previous studies conducted using FCD, grouping them into three categories: social, traffic and environmental trends. The terms FCD and GPS will be used interchangeably in this section to implicate the same meaning. These studies seem applicable in Africa because they are relevant and feasible given the already available infrastructure for FCD.

- **Social trends**

Social trends may include human mobility, activities, and behaviours. Shaw, Tsou and Ye (2016) described the human dynamic as a multi-disciplinary field where researchers obtain insights from human behavioural studies. They further asserted that the widespread use of smartphones from which GPS tracked records, online social media usage, and cell phone calls, among others, create enormous data. This has enabled researchers to pursue human behavioural studies with the available computational models and simulations. Furthermore, Kong et al. (2018) noted that human activities and behaviours form complex systems that trajectory datasets can estimate. This helps urban planners to allocate available resources efficiently in the area. Also, the representation of travel links between different places could facilitate future predictions, and improve planning strategies. Guo and Karimi (2017) confirmed that understanding the spatial and temporal characteristics of the flow of people from residential areas can assist traffic engineers in understanding the traffic situation. As for transport managers, this can assist them to effectively schedule their public transport according to demand.

Renso et al. (2013) studied human travel behaviours by inferring human movement patterns. They used inductive reasoning which curtails movement pattern discovery, while deductive reasoning implies human behaviour inference. They used an implementation system called Athena to track the process. They applied this method to both traffic management and recreation patterns. The study of human behaviours is complex because of the many potential ambiguities (Kong et al., 2018). Renso et al. (2013) proposed a semantic-enriched knowledge discovery process (KDD). This process extracts the semantic and syntactic complexity of movement patterns to obtain a meaningful interpretation of human behaviours. They also provided a solution for understanding the movement patterns based on GPS trackers and encoded domain knowledge. They confirmed their findings using two scenarios; GPS datasets recording the movement of vehicles in Milan, Italy, and park visitors in the Netherlands. According to the experimental illustrations, this system proved to be robust. This favours its application elsewhere to study human behaviours and improve the urban environment.

Studying human mobility patterns is crucial for accurate traffic infrastructure planning and mitigating traffic congestion (Yao and Lin, 2016). The study of human behaviour dynamics is equivalent to traffic flow studies, thus illustrating the spatial-temporal regularities. Yao and Lin (2016) further describe GPS as a direct human spatial mobility study dataset. They studied a taxi company in south China to discover the distance distribution of human mobility. The study revealed that the mobility distance follows the power-law distribution. However, the mobility distance is affected by time and transit fare. They performed a simulation to verify the power-law distribution of human mobility and behavioural distance using a single vehicle, and incorporating the waiting time and transport charge. They compared their results with the conventional exponential distribution of mobility distance affected by various constraints.

Guo and Karimi (2017) predicted the spatial-temporal activities from latent spatial-temporal features by modelling the two entities using the Gaussian process. Not only did they consider the spatial-temporal data characteristics in a particular area, but also during a different time period with the same patterns. This rendered their approach more accurate compared to existing methodologies. They experimented on taxi trips in New York City. The results showed how the extracted latent features differentiate between neighbourhoods with distinctive characteristics. In addition, Zheng and Zhou (2017) claimed that new cities experience changes in land use and spatial facilities. This causes challenges in transportation planning and management because of the increased traffic volume. The model predicts traffic volumes based on land-use changes and newly constructed services. They, therefore, designed a transport prediction model using the scaling law and drawing on GPS records. The scaling law unearths statistical patterns of human mobility by discovering probabilistic distribution of human variables. They used correlations between visitation frequency and the locational ranking plus the locational ranking and built environment to determine the results.

Zhu et al. (2017) investigated the likelihood of sensing urban communities using streets. They used Beijing taxi trajectory data to discover urban mobility's spatial and temporal characteristics on roads. They clustered the streets into nine types based on their dynamic functions and capabilities. Their study concluded that street segments supplement areal segments. This can effectively detect urban dynamics, portray urban operations and provide an understanding of urban structures.

- **Traffic trends**

Kong et al. (2018) determined trip patterns by assigning the different modes of transport to distinct travel purposes. This enabled the extraction of origin-destination sequences. Hence, allowing for trip purpose estimation, destination prediction, route discovery, and travel mode analysis. Travel behaviour analysis allows for improved planning of urban transportation systems (Yang et al., 2016). Both studies further asserted that the traditional data collection methods such as household surveys, questionnaire administration, and telephone interviews prove inadequate for obtaining quality data. They are also expensive and time-consuming. Shen and Stopher (2013) used GPS tracking data to infer the travel purposes. However, the data available doesn’t explicitly illustrate travel purposes and modes. Nonetheless, using land use data, trip purpose detection can be established. They determined travel purpose detection by using additional trip and tour information from the National Household Travel Survey (NHTS) in the US. They claimed that the additional information could improve the accuracy of travel purpose estimation.

Gong et al. (2016) also confirmed the ability to extract travel purpose from the trajectory data. They modelled the probability of the point of interest (POI) using Bayes' rule that considers both spatial and temporal limitations. They combined the approach with Monte Carlo simulations to closely estimate residents' travel data. Their focus was on nine commonly-engaged activities mapped using POIs. They used GPS taxi trajectories to extract pick-up and drop-off points. This helped anticipate the pre- and post-travel activities. They, therefore, discovered a link between a large amount of trajectory data and trip purpose information. This contributes to improved urban transportation management if this approach is adopted. Travel demands can also be estimated, and traffic flows optimised.

Destination prediction is a significant aspect of traffic management and provides the public with traffic information about different locations in a city. Xue et al. (2013) introduced a novel sub-trajectory synthesis (SubSyn) algorithm to address the issue using taxi GPS data. First, they divided the historical trajectories into sub-trajectories and linked them into synthesized paths to predict the destination. They further proposed an end point generation method to address the issue of confidentiality in case the synthesized data reveals potential breaches of privacy. Compared to the baseline and naïve algorithm, the approach seemed effective and accurate (Xue et al., 2013).

Kong et al. (2018) asserted that route discovery is essential in the transportation system for urban planners. Yang et al. (2017) also emphasised that by obtaining information about the driving patterns of taxi drivers, the best route to support dynamic route planning can be determined. Therefore, route planning is imperative for solving some traffic problems. First, they presented a space-time trajectory cube by dividing and organising it into three dimensions; origin, time, and destination. Then, they proposed the extraction methods to acquire the details about driving habits of taxi drivers based on taxi trajectories. Afterward, they produced a condensed space-time graph by merging the drivers' driving patterns with the road network to compute the optimal routes. According to their study, the global trajectories on the road are not representative of taxi drivers' experiences in route planning or path-finding models. However, local road segments derived from data restricted to origin-destination routes more precisely imitate taxi drivers' driving experience.

Tang et al. (2016) proposed a novel time-dependent graph model to estimate the probable space-time paths and their uncertainties within a transportation network. They asserted that it is possible to map the location and timestamp trajectories from the GPS data as a space-time path. The space-time graph illustrates diverse potential routes with varying degrees of spatial and temporal distance. They concluded that their programming algorithm, when integrated with other sensor data sources, an optimal path that considers the distance measure at varying timestamps of the driving path is achievable.

There are increasingly different travel modes due to the high travel demand experienced by road users (Kong et al., 2018). They further asserted that the effect of diversified travel modes is significant. Bohte and Maat (2009) used GPS data, GIS technology, and an interactive web-based validation application to derive and validate trip purposes and travel modes. They compared their results with the Dutch travel survey, and almost all the trip purposes and modes of travel were equal, with almost more trips recorded with their method. This proves the reliability of the data collection methods employed in the study. They utilized a broad interpretation process to determine the travel mode and trip purpose. The GIS data, characteristics of responders, and GPS loggers are all combined in the rule-based algorithms. Also, the respondents validated the results during the process, hence rendering it effective.

Zheng et al. (2010) developed an approach based on supervised learning to extract the different modes of travel from raw GPS data. The forms of travel included driving, walking, bus, and riding. They employed three approaches to achieve an accurate prediction of travel mode:

- They changed the point-based segmentation method to allocate each GPS trace into separate segments of different transportation modes.
- They used the inference model, which helped to identify sets of sophisticated characteristics not affected by differing traffic conditions to classify the segments of different travel modes.
- They conducted a graph-based post-processing algorithm to reinforce the inference performance.

Yang et al. (2016) proposed a two-step method to detect trip information from personal trajectory data. The information included trip modes, mode-changing time, location, and other features. They used a machine learning algorithm-based module and critical points on GPS trajectories. Using this information, they could identify walking, riding, and driving by car or bus with the support of the GIS map. Furthermore, they applied a second module, enabling them to differentiate between personal and private vehicles, and buses. Without this step, the accuracy rates for the detection of buses and cars were below 75%. On the other hand, all four machine learning models (artificial neural networks, support vector machine, random forest, and Bayesian network) had high detection rates over 90%. Therefore, the two-step method proved accurate and consistent in performance compared to other studies conducted at the time.

The urban traffic system is an essential aspect of traffic management. Sun et al. (2016) described a traffic structure as interdependent zones with sound and adequate traffic connections between different groups.

They divided the traffic system into distinct groups according to travel demands. They adopted a group structure detection method to calculate the urban traffic structure, known as traffic zones division. They used smartcard data from the Beijing subway and GPS data from taxis in San Francisco for the study. They claimed that dividing urban traffic systems into closely-related traffic zones provides adequate grounds for regional traffic control.

Time is a significant factor in overall traffic management (Kong et al., 2018). It enables individuals to plan their trips accordingly, thus improving travel duration. Zhan et al. (2013) developed a model that assumes a possible path from each trip and then estimated the link between travel times by reducing the discrepancy between the expected travel time and the observed travel time by constructing reasonable path sets. They developed this methodology using the origin-destination (OD) trip data from taxis with installed GPS. They also determined the feasibility of estimating the network state using large-scale trajectory data with limited information. The results showed that the proposed model efficiently estimates the hourly average travel times.

Wang, Zheng and Xue (2014) proposed a city-wide and real-time model for predicting the travel time of any path based on GPS vehicle trajectories. First, they modelled different drivers' travel times on various road sections in a three-dimension tensor. Next, they used a tensor decomposition model to fill in the missing data from historical trajectories and map data. Finally, they utilised a dynamic programming solution to find the most optimal concatenation of pathways. Thus, allowing estimation of the travel time. Also, Sanaullah, Quddus and Enoch (2016) estimated the travel time for different kinds of circumstances according to the data distribution. They contended that travel time estimations are affected by several factors. Such factors include data sampling frequencies, penetration rates, and time window length. They further added that these mentioned factors are regularly not considered. They, therefore, proposed two mathematical models that incorporate the different scenarios in estimating travel times. Their results showed that the method is accurate in the case of maintaining the optimum penetration rate for a given time window length.

- **Environmental trends**

The increasing number of vehicles on the roads increases the emission of gases into the atmosphere. It is incumbent upon urban planners to ensure a clean environment by predicting the emissions and how to mitigate the social and environmental impact caused (Kong et al., 2018). Luo et al. (2017) analysed the spatial-temporal features of energy consumption and pollutant emissions mapped on GIS by using big data analysis of GPS trajectories from taxis. The results illustrated that energy consumption and emission presented a distribution of dual-core cyclic structure. The hubs identified were during the traffic rush period. These results are no surprise because of the large concentration of traffic volumes moving at low speeds and constant braking during rush hours. The fuel consumption rate on each segment was estimated based on the average driving speed. They further investigated mechanisms to improve driving behaviours like adopting electric cars and determining optimal locations for additional infrastructures in the advancement of megacities.

Chen et al. (2016) used GPS data to estimate ambient nitrogen dioxide concentrations using a non-linear optimised dispersion model (ODM). They studied the aggregated tracking of GPS-equipped vehicles (ATV) dataset and used it to approximate traffic emissions. The results were reliable and relevant for other air quality models. Al-Ali, Zualkernan and Aloul (2010) also proposed a system that incorporates a single-chip microcontroller, air pollutant sensors that detect different emissions, general packet radio service (GPRS) modem, and a GPS module. The system is a mobile, wireless data acquisition unit where a microcontroller generates a frame consisting of acquired air pollutant levels, and its position is recorded by the GPS. The pollutant level is then uploaded onto the GPRS modem, transmitted to the air pollutant server, and then to the public domain. The microcontroller chip can detect carbon monoxide CO, nitrogen dioxide NO_2, and sulphur dioxide SO_2. This enables further investigation of the pollutants emitted; allowing for mitigation plans determined by relevant authorities to improve air quality. The general public can then be informed about the status of the surrounding air in a given location, allowing them to take necessary precautions. This can reduce the environmental impact caused by greenhouse emissions.

2.3.7 Estimation of traffic congestion zones using FCD

Some studies estimate traffic congestion using different datasets besides FCD. Sun et al. (2019) estimated the congestion in city areas using traffic performance index (TPI) data. They analysed the data using a hierarchical clustering algorithm. In contrast, Zhao and Hu (2019) used traffic congestion index (TCI) data to estimate the congested zones in Beijing using a big data analytical approach. This indicates how the available data sources of a particular country are vital to the study of congestion. These studies help in the overall management of transportation systems to improve mobility. However, Sun et al. argued that combining different datasets enables the adoption of more extensive methodologies in extracting traffic congestion features.

Erdelić et al. (2021) estimated the congestion zones and travel time indexes using FCD. They mapped the probe vehicles' speeds onto the road network's links on the micro-level. Then, on the macro level, they divided the road segment into a detailed grid and represented congestion intensity in an image. Morphological closing, Monte Carlo simulation, and temporal clustering were applied to determine the spatial-temporal characteristics of congestion zones. The results indicated the viability of FCD in estimating congestion zones and travel time index compared with other state-of-the-art methods. Likewise, Rempe, Huber and Bogenberger (2016) used pre-processed FCD to estimate the congestion zones through clustering. They developed a methodology that defines areas which generally belong to the same pockets as congestion clusters. This study identified the congestion clusters, but did not explicitly indicate a particular cut-off point for congestion, as shown in Erdelić et al., who estimated congestion levels when the speed is below 30% of free-flow speed.

Other studies that use clustering of traffic congestion on a micro level to obtain information about congestion zones include that of Keler, Krisp and Ding (2017). They distinguished between recurrent and non-recurrent congestion using FCD by employing the shared nearest neighbour clustering method followed by density-based clustering. In addition, they introduced a simple method for detecting and extracting congestion events on selected rush hours. Likewise, Song et al. (2019) focused on mapping spatial-temporal patterns of traffic congestion using K means clustering and detecting the causes of congestion using geographical detectors (geo-detector). The results showed the causes of congestion in the inter and intra-regional roads of Beijing included in the study.

Other studies have attempted to estimate congestion without a learning model. For example, D'Andrea and Marcelloni (2017) utilized FCD to detect traffic congestion and other incidents. In addition, the study designed a system that could inform road users of congestion or incidents on a particular road segment. This allows commuters to make informed decisions before and during travel. On the other hand, Kan et al. (2019) proposed an approach that filters taxis-GPS data that reflects real traffic conditions to analyse congestion in greater detail over a larger area at a low cost. They used machine learning to differentiate trajectories that reflect real traffic conditions. They also proposed a system to detect turn-level congestions in multiple dimensions. Erdelić et al. (2021) also suggested machine learning to illustrate spatial-temporal patterns further.

Tišljarić, Carić, Abramović, et al. (2020) estimated traffic status using GNSS database on a city's speed transition matrix (STM) based on the centre of mass (COM) computation for every STM. Kong et al., (2016) introduced a particle swarm optimization algorithm to predict traffic congestion. A congestion status fuzzy division module converts the predicted traffic conditions into citizens' cognitive congestion status. This approach proved advantageous in terms of accuracy, instantaneity, and stability.

In a study estimating congestion in terms of travel times of a particular road section, in contrast to previous studies of specific zones, Rahmani, Koutsopoulos and Jenelius (2017) adopted a consistency path inference method.

Regarding visualizing the congestion zones, Keler, Ding and Krisp (2016) in Shanghai proposed two visualization techniques of three-dimensional and two-dimensional representations. Also, Liu et al., (2017) used ArcGIS to visualize FCD's two and three-dimensional traffic congestion patterns.

In summary, traffic congestion estimation is either performed on a link or area-wide network coverage. Also, some studies used real-time traffic, while others used historical FCD. Each study used different periods and numbers of probe vehicles. In any case, one must establish the output desired before determining the input parameters for the selected model in estimating the congestion. Different methodologies give the same result of evaluating congestion zones. Although much work is prevalent in other countries, developing countries in Africa have lagged behind in this regard.

Most congestion estimation studies using FCD don't consider a road network's level of service (LoS). Instead, they tend to identify a road network's congestion zones irrespective of the LoS. Accordingly, studies on congestion zones need to consider the type of road classes. After studying the causes of congestion in such zones, identifying the probable causes becomes crucial. A study by Liu et al. (2017) used geo-detector to identify the causes of the estimated congestion zones.

2.3.8 Applications of FCD

Each country has specific goals to achieve in the sector of transportation. There are different applications that African countries can adopt to realize their goals. This section illustrates some applications of FCD relevant for providing efficient road transport. Applications and services vary widely because applications may not emulate real-world problems. Services are generally offered by the relevant authority depending on the stakeholder's perception of the real-world issue. Therefore, various techniques are employed to solve a particular problem according to stakeholders' needs (Kong et al., 2018). Delivery of a specific service may rely on one or more applications of FCD. This section thus provides some applications to be utilized by transportation administrators in developing countries using FCD to offer improved services.

- **Road network performance analysis**

Monitoring the road network is vital for traffic engineer to evaluate its performance. It can help to redesign problematic elements of the network. For instance, an engineer may be able to identify a bottleneck in the network, allowing for analysis before and after a mitigation measure has been deployed. The studies focusing on FCD include analysis of operational assessment measures like speed, congestion measures, incident statistics, and special events. Colombaroni, Fusco and Isaenko (2020) used FCD to evaluate driver behaviour and theoretical road safety speed on the road. This is relevant to many developing countries where traffic accidents are common because of the poor roads. Therefore, analysing the FCD helps extract features in the road network that need improvement. For example, the information can be used to adjust speed limits for a particular section on the road. Also, identification of black spot areas in case of incident studies.

- **Transport planning**

Substantial evidence is needed for transport planners to pursue any improvement strategy on a road network. Therefore, transport planners must utilize FCD for infrastructure prioritization. This will depend on identifying any particular element in the road network that improves transport. For example, prioritizing congestion ratings according to road class and volumes could prove effective. Similarly, Mei et al. (2019) used the Bayesian approach to estimate the queue length on an intersection using floating cars. This could enable relevant stakeholders to predict the impact of an intersection on triggering congestion further down the road or on adjacent roads. Also, this approach renders a reactive measure for combating propagation of queues at intersections. Travel time surveys also enable route planning to be pursued.

FCD has the potential to increase the impact of new developments in the broader context of the transport planning process. Following from this, this study examines social and traffic trends to extrapolate the new development impact. Also, in terms of transportation services, transport planning enables the improvement of travellers' experiences through reducing travel time and increasing efficiency of public transport systems by providing information to commuters about transit schedules (Wang, Miwa and Morikawa, 2020).

- **Forecasting and estimation**

FCD enables studies of traffic growth to estimate and predict traffic parameters. For example, Keler, Krisp and Ding (2017) generated congestion propagation polylines. These polylines can indicate where the traffic originates. They used the shared nearest neighbour (SNN) to extract the centroids and their connection to polylines, and distinguish between recurring and non-recurring traffic to understand both events.

Non-recurrent congestion may evolve due to faulty traffic lights or temporary traffic control systems in place (An et al., 2016). This is where traffic officers contribute to such cases. Traffic officers are human beings who are prone to exhaustion and potential errors. They might distribute traffic unevenly at an intersection, hence propagating congestion on the road network. This often the case in developing countries due to lack of automated infrastructure. It therefore requires traffic engineers to understand the congestion hubs and the different stops on the road section. Stakeholders can improve the system through the estimation and prediction analyses on the road network.

An et al. (2016) used FCD to distinguish between recurrent and non-recurrent congestion to measure the recurrent progression patterns using a series of indicators. They compared their results to the real-time traffic information and field surveys proving their approach reliable. They further declared that through identification of recurrent congestion evolution patterns (RCEP), the relevant stakeholders would benefit from such information. Thus, travellers will know where traffic starts from, giving them the opportunity to decide to detour. This also allows urban planners to improve the infrastructure and traffic managers to improve the traffic control systems. These measures can be adopted in African cities to estimate the evolution of recurrent congestion to enable appropriate measures, and thus alleviating the congestion.

FCD illustrates the origin and destination relations and matrices (Vogt et al., 2019). The matrices support traffic engineers and planners in the event of infrastructure development. Vogt et al. (2019) combined FCD with detector data to produce reliable results. Also, the estimation and modelling enable route choice analysis for traffic simulations (Cohn and Bischoff, 2012). Dabbas, Fourati and Friedrich (2021) conducted a similar study on route choice modelling where they used the FCD to estimate the route choices on different spatial scales.

FCD also allows for emission modelling. The estimation and forecasting of greenhouse gas emissions in an area can help reduce the impact caused. Therefore, the implementation of necessary precautions by transport managers becomes indispensable. For example, Chen et al. (2016) estimated nitrogen dioxide concentrations as a pollutant from motor vehicles. Modelling of other emissions follows and, their results illustrate that certain areas require urgent intervention to prevent adverse effects on the health of the surrounding environment.

- **Real-time application**

FCD plays a pivotal role in the traffic management systems at control centres. It can enable adaptive signal control which allows the remote control of intersections depending on the situation. It also facilitates information dissemination to travellers in real-time; the routing details and congestion management are readily available to commuters while travelling. Moreover, the speed reductions and the increased travel times reported by probe vehicles enables traffic managers to extract information to warn travellers of expected delays in real-time. Also, D'Andrea and Marcelloni (2017) proposed a system to support traffic managers in detecting congestion and incidents in real-time, and developed a platform that broadcasts congestion updates for subscribers. This allows for appropriate decision-making for travellers when traffic jam warnings are sent or there is re-routing of traffic during an incident clearance.

Astarita et al. (2017) investigated an adaptive traffic light control using FCD. They proposed different methodologies to aid the cooperative ITS. They tested their approach using the TRITONE microscopic simulator. The results indicated that city managers can invest in the system to control traffic lights, alleviate congestion, and reduce emissions.

2.3.9 Challenges of FCD

- **Data mining techniques**

Probe vehicles report their position, time, and speed on average every minute. This indicates that the amount of data generated is enormous. Therefore there is a need for advanced technological software and computation capacities during data mining. The data also requires a high storage capacity for future analyses (Munizaga, 2019). There are various techniques applied to different traffic studies which can be adopted. However, the methods can be expensive. The burden for computational capacities is generally shouldered by private companies. Also, the software that assists in data mining might be open-source, while others require a license. The selection of a particular software will depend on theoretical reporting and consumer usage (Wang, Miwa and Morikawa, 2020). However, private companies that supply FCD have no mandate to improve infrastructure; the onus is on the city engineers and planners. Therefore, the data obtained from the private companies must be pre-processed and made usable for analysis. For cases where city administrators would like to acquire a system of collecting the probe data, the challenge of data mining will present. The institution should know which mining software to adopt and the expenses involved.

- **Privacy issues**

The issue of privacy is inevitable with geospatial data. Tracking using vehicle identification numbers is possible. Therefore this issue needs to be addressed before using the data. The assurance of privacy for individuals contributing to data collection is unquestionable. Otherwise, some vehicles would not contribute to the data collection. There are several methods of anonymising spatial data. Munizaga (2019) suggests various ways to ensure privacy. Data protection methods where individual identifiers are removed or modified make re-identification unlikely. He further indicated that the combination of anonymisation and encryption by using cryptographic techniques helps protect personal data. Also, Munizaga added that new ways of data protection require redesign due to the already reached limits of existing data protection strategies. Lastly, the standards of public and private partnership that involve data sharing must be defined to ensure that data collection aligns with legal mandates. Most African countries will obtain their data from a third party. Therefore, streamlining privacy issues is paramount. Companies should endeavour to ensure "privacy by design" to curb the privacy issue. Privacy by design is when companies consider privacy starting from the system design until the operation stage (Munizaga, 2019).

2.4 Measures to alleviate congestion

Transport authorities in many countries utilize various measures to alleviate traffic congestion. Afrin and Yodo (2020) assert that absolute elimination of congestion in cities is impossible due to the growing population. However, transportation departments continue to devise plans to minimize its effects. As discussed in the preceding sections, this study grouped the different traffic congestion measures into five categories. These measures were then refined according to the literature available and their current adoption in other countries.

2.4.1 Construction of new infrastructure

This involves increasing the roadway capacity. Operations may include; adding additional lanes, new roads, bridges, and intersection overpasses. In response, these may reduce traffic delays. However, adding infrastructure tends to scatter other city infrastructures, such as increasing walking or cycling distances to reach commuters' destinations (Litman, 2013). Therefore, the other road users should be considered before any decision in constructing new facilities is made. A study on two Norwegian cities indicated that the traffic congestion reduction experienced due to newly built facilities yielded no or only short-term benefits, according to Tennøy, Tønnesen and Gundersen, 2019. This was because of the land use sprawl. The study further encouraged assessing land-use effects on any new road projects. They also investigated the changes in modal split, travel behaviours, and commuting distances in which they concurred with Litman (2013) on the increased commuter distance to and from workplaces. Moreover, the traffic volumes increased after the new construction, causing traffic congestion. The study proved the claim that new facility construction does not contribute to congestion relief.

The approach of expanding infrastructure requires large sums of money in capital and compensation fees incurred in an already built environment. This approach is implemented in many countries and funded intensively without investigating other mitigation plans (Litman, 2013). Litman further argues that congestion evaluation measures like travel speeds tend to be biased, amplifying the need for new infrastructure. Also, during the 20th century, when motorization increased, the only option was to construct new facilities to accommodate vehicles. There was no issue with construction to meet capacity needs, given the availability of land (Litman, 2013). This option remains relevant for most developing countries where motorization has increased.

The more lanes or facilities added, the more traffic experienced. This approach tends to ignore the additional traffic generated as a result of expanded infrastructure. This approach therefore does not address the "elephant in the room" of alleviating traffic congestion, but instead wastes resources that might be more beneficial if applied to other strategies like maintenance (Transportation for America, 2020). Additionally, an evaluation of cost-benefit analysis that includes the impact on non-road users and the environment needs consideration before deciding to construct new road facilities in urban areas (OECD, 2007).

Benefits of construction of new infrastructure

- Reduces congestion in the short term on major urban arterials. However, there is expected congestion due to increased generated traffic (Litman, 2013).

Disadvantages

- High capital costs.
- Does not consider city size and growth rates since it's a short-term relief. Congestion may increase after a certain period due to other externalities.
- Increase in indirect costs like parking fees and fuel consumption due to commuters' increased likelihood of traveling because of new infrastructure.
- Increase in greenhouse gas emissions due to the increased vehicle travels.
- An increase in per capita vehicle travel due to the expansion of roadways or construction of new facilities.
- Increase in per capita traffic-related deaths.

2.4.2 Improve the existing network

This implies the efficient traffic operation of the existing road network. In the instance of identifying bottlenecks, transport authorities should devise mitigation plans. For example, improving the intersection management plan as per the demand to effectively increase the throughput and reduce the travel time experienced by commuters. Other measures which can be taken include, managing lanes during peak hours to optimize the existing infrastructure, encourage use of non-motorised transport systems, and improving land use by creating master plans for cities (Afrin and Yodo, 2020).

OECD (2007) emphasizes land use policies in different cities that advocated better utilization of existing infrastructure, thereby reducing the severity of congestion. New development causes upsurges in travel; likewise, the spatial distance between origin and destination also increases, altering travel patterns. This correlation requires attention to achieve improved coordination of long-term land use plans with respect to the transport system.

Litman (2013) concurs with the above measures in improving existing road networks. He also suggests managing lanes by applying reversible lanes and converting two-lane roads into one-ways. Litman also suggests implementing an intersection management plan involving traffic light synchronization. Additional measures in this regard include; reduced cross streets and crosswalks on major arterials, relocation of public transport stops, and provision of public transport lanes as ways of improving the existing network and increasing the roadway capacity. Furthermore, the conversion of intersection type and layout can also be included in these strategies to reduce congestion.

To deliver reliable travel times for commuters, traffic authorities should respond promptly to defective traffic signals at intersections and incidents. This can improve the traffic flow and reduce unpredictable traffic delays (OECD, 2007). Also, OECD (2007) included roadway access and parking policies to mitigate congestion. The former directly controls the physical access to the roadway, whereas the latter indirectly influences commuters to use particular roads. This is a form of lane management discussed earlier. These policies are relevant for improving the existing network as a measure for alleviating congestion; and are something that this study strongly advocates in favour of. Commuters tend to be predisposed to use particular roadways to relieve congestion on other roads. However, parking policies, which is an area-based approach to improve demand, are under-utilized by authorities in controlling congestion (OECD, 2007).

2.4.3 Mode improvement

As noted, there are different modes used in transportation besides private motor vehicles. These may include walking, cycling and public transport. These tend to be ignored in the city development plan yet play a vital role in congestion relief. Litman (2013) refers to them as space-efficient modes. The following improvements illustrate how these different modes can help alleviate congestion, as adapted from Litman (2013).

Public transport

This mode in particular impacts the effectiveness of a road network in terms of traffic congestion, safety, land use, and environment (Nguyen-Phuoc et al., 2020).

- Improved services by providing users with information and having a well-scheduled transport system.
- Ensuring safety and security.
- More routes for improved connections to allow accessibility.
- Provision of designated lanes for the transport system.

- Prioritisation of public transport at intersections.
- Easily accessible transit stations.
- Reduced transport fares and payment modes improved through incorporating innovative technology.
- Good quality vehicles to ensure comfort and safety.
- Increase in the marketing of the public transport system to encourage more users.
- Provision of frequent services for reliability purposes.

Walking

- Provision of sidewalks, crosswalks, and walking paths for commuters.
- Adoption of traffic speed reduction techniques in busy areas.
- Land use development in a compact environment to facilitate walking.
- Ensuring safety and security on the tracks, sidewalks, and crosswalks.
- Inclusion of pedestrians with disabilities in the design.
- Improved connection of paths and sidewalks.
- Providing user information on the walking paths
- Incorporating innovative technology on crosswalks to ensure safety.
- Graded separation where the pedestrians do not interact with vehicles.

Bicycling

- Provision of more paths and well-marked bike lanes.
- Provision of bike parking in the city.
- Provision of bike racks on public transport.
- Ensuring safety and security.
- Provision of user information on the bike paths and the connections.
- Establishing a funding system to purchase bicycles.
- Increase marketing and provide training to motivate commuters to adopt the mode.

These modes of transportation reduce congestion where flexible commuters can adopt one or more of them. However, this requires incentives for the realisation of the impact in many cities. Therefore, improvement measures need to be implemented for mobility management.

2.4.4 Congestion tolls

This measure is where road users pay a fee to use the road during peak hours to reduce the traffic volume (Litman, 2013). It is also a crucial tool in addressing traffic management for sustainability and achieving equity (Eby, Roskowski and Puentes, 2020). The congestion toll measure is designed to persuade commuters to travel during off-peak hours. Reducing the traffic volumes to the optimal level increases roadway efficiency because it allows more vehicles per lane. Also, as mentioned previously, studies indicate that congestion may improve for a certain period and rise. Building on the model of congestion tolls, hybrid pricing, or the pricing of a particular lane to avoid congested roadways, is also an option.

Congestion fees customarily serve to recover the capital costs, repay a debt used in construction, or execute other new projects. However, studies indicate that road tolls do not generate much income to allow for new construction projects or recover capital costs. Therefore this strategy is primarily useful for congestion reduction rather than to aid in new construction (Litman, 2013). Also, among its disadvantages, it involves high capital costs, privacy concerns, and often applies to a small portion of the road network (Litman, 2013).

Congestion pricing can be divided into two forms; cordon or corridor pricing. The former includes area-wide coverage where pricing targets a particular geographical region, usually a city centre. The latter concerns tolls on a specific road segment or lane (Eby, Roskowski andand Puentes, 2020). Both systems have advantages and disadvantages. Therefore, thorough research and recommendations are both needed to determine which system to adopt to reduce traffic congestion.

Advantages

- Reduces traffic congestion by 20-30% (OECD, 2007).
- Road users also benefit from the fees paid to use the infrastructure, like lower fuel prices (OECD, 2007).
- The revenue collected can be used for infrastructure improvement if it doesn’t go to the general national budget.

Disadvantages

- In cases of high tolls to recover the cost of construction of the infrastructure, the anticipated capacity greatly reduces if there are relatively good alternative roads and modes. Hence, less revenue is collected.

In conclusion, congestion tolls need a clear evaluation strategy before adopting this measure to alleviate congestion. Eby, Roskowski and Puentes (2020) discussed the principles any institution should apply before implementing this measure, which cut across the various stages of the development for congestion pricing. These stages include the concept, planning, and proposal phases. These principles guide the implementation of such a measure. The principles in summary include:

- Clear vision and purpose.
- A clear relationship between revenue and expenditure.
- Provision of other mobility options.
- Equitable programs.
- A strong relationship between stakeholders.
- Transparent communication.
- Building a strong foundation with a clear vision of the mechanism
- Transparency commitment with target indicators
- Limit exemptions.
- Allow for changing needs.

When addressed before implementation, these ten principle points can limit negative repercussions caused by a particular congestion toll strategy adopted.

2.4.5 Intelligent transportation system (ITS) measures

ITS, in general terms, is the application of information and communication technology (ICT) by transport service providers to meet users' desired expectations in terms of economic, social, and environmental benefits (Perallos et al., 2016). The desired expectations of users may include; reduced travel time, low emission of greenhouse gases, safety assurance, and reliability (Sumalee and Ho, 2018). ITS is generally adopted by service providers to improve the management, control, and maintenance of transport systems to satisfy the users' needs. ITS has become a common phenomenon in the industry of transportation. It falls into the smart mobility category for smart cities and their development plans (Sumalee and Ho, 2018).

Many parts of the world have highly developed ITS. In Europe and the USA, architecture frameworks for ITS deployment exist to support their easy implementation. ITS architecture is the conceptual design that illustrates the structure and performance of an integrated ITS. Countries that have adopted ITS technology in Africa include South Africa, Nigeria, and Ethiopia, among others. Africa has a functional body called Intelligent Transport Society Africa (ITS). Nigeria, South Africa, and Ethiopia formed the organization. Its primary aim is to promote and lobby for ITS strategies in Africa by creating awareness among policymakers and by hosting workshops and seminars (see http://www.its-africa.org/).

ITS measures are generally effective in cities whose infrastructure is mature and resources are available. This is because of the complexity involved in developing and deploying these systems (Perallos et al., 2016). As per the objective of this research of devising measures to alleviate traffic congestion, ITS plays a vital role in this regard. Therefore a focus on its relevance in combating congestion is included in this study. Transport authorities can generally control the ITS services in either centralized or decentralized settings called a traffic management centre (TMC) or traffic control centre (TCC). These can be physical infrastructures or remotely controlled.

ITS embodies a cooperative system where vehicle to vehicle (V2V), vehicle to infrastructure (V2I), pedestrian to infrastructure (P2I), vehicle to everything (V2X) work in unison through a communication system (Sumalee and Ho, 2018). Dedicated short range communication (DSRC) is the most widely used medium. Perallos et al. (2016) stated the characteristics of such cooperative systems. These include; vehicles, drivers, infrastructures, road users as a unique system, consideration of the operational and management needs of the entire system, the traffic safety and all participants integrated within the system, and application of technology to support the overall integration of the system. Cooperative ITS stems from the principle that all participating entities share information. The overall goal of cooperative ITS is to ensure efficient transportation of goods and services, improved traffic safety, increased passenger protection and comfort, and reduction of pollution.

Cooperative systems may include the vehicle automation and communication system (VACS) equipped in connected and autonomous vehicles (CAV). These vehicles work on the same principle of cooperative ITS (Sumalee and Ho, 2018). They improve the network performance and traffic flow efficiency. Examples of such systems may include; adaptive cruise control systems (ACC) and cooperative adaptive cruise control systems (CACC). Sumalee and Ho (2018) further argued that the increase in the use of VACS could enable the integration of ITS into a mixed vehicle environment of CAV and non-CAV. In addition, different models designed will help in the general monitoring and planning of infrastructure.

- **Traffic management centres (TMC)**

These are avenues where the decisions about traffic management systems are made (Perallos et al., 2016). They embody the ITS framework. ITS constitutes three systems that elucidate it as a broader concept. First are the communication systems which gather the information in the field. Secondly, the systems that integrate and process the field information. And finally, the systems that provide the information to the users as illustrated in figure 2. All these systems are controlled and monitored at the TMC.

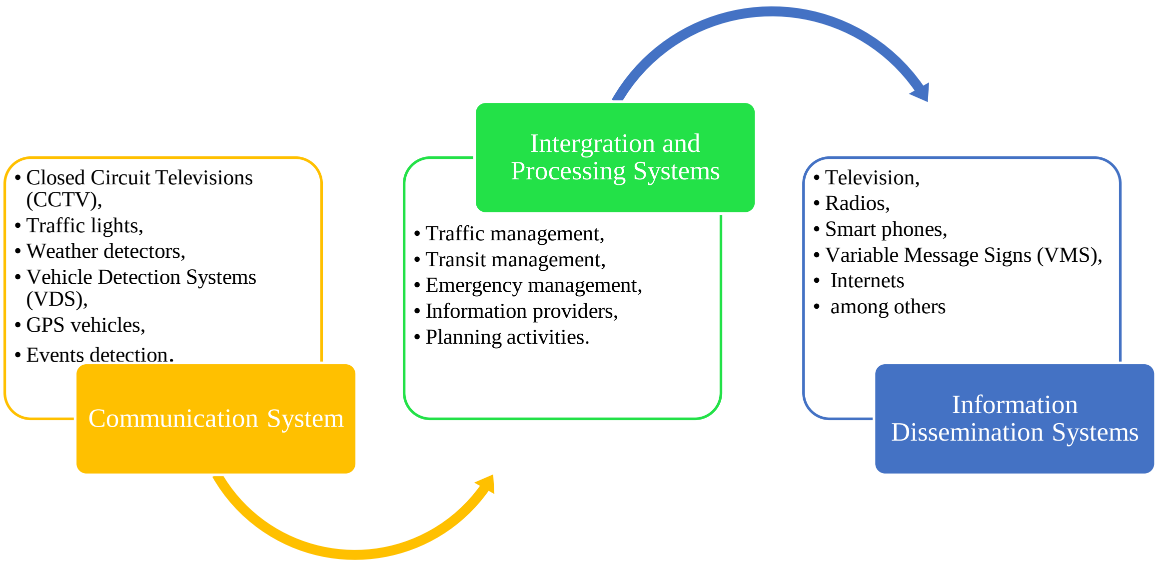

Figure 2- 2: ITS conceptual framework

TMC plays a vital role in implementing ITS infrastructure in any given country. This is because the systems are managed and controlled at a specific location. The TMC act as a traffic information hub for storing all data for roadwork's planning. The data is made available to researchers, policymakers, construction, and consultation firms attributed to the road sector (Perallos et al., 2016). There are different critical stakeholders at the TMC. They might include but are not limited to:

- **Regulator**

This is the road authority agency of a country. It is usually a government body responsible for overseeing the TMC and ensuring a certain service level is achievable. A regulator also participates in TMC consultation meetings regarding product standardization, issuing approvals, and so on. Regulators are also liable to the public regarding the safety and mobility aspects of the road network. The legal framework of the country also binds the regulator.

- **Manager**

The manager is responsible for the overall activities of the TMC. S/he coordinates all the different stakeholders in a centre's activities and supervises the operators at the TMC. S/he also chairs the meeting and is usually the final decision-maker at the centre. S/he provides information to the regulator. In addition, the manager is responsible for system repairs and maintenance of in-office and field devices.

- **Operators**

These people are responsible for achieving the objective of a particular system in place. This may include ensuring a certain level of service of roads maintained or decreasing traffic-related fatality rates. They are generally responsible for receiving, monitoring, and analysing the information from the field. They also apply the relevant course of action upon approval from the manager and other stakeholders. Operators can be private companies or government employees, according to the terms and conditions of the regulatory body.

- **Service providers**

These might include emergency units like ambulances, fire-fighters, traffic police, and breakdown services. They are responsible for executing their duties upon summon by the manager. They take action depending on the situation on the road. Operators may first analyze a scenario, and then engage the relevant stakeholders through the manager.

- **Road users**

These are the end-users in the traffic management cycle. All the efforts exerted at the TMC are to enable an accessible, safe, and reliable transport system, which is the primary concern for travelers. The road users' approval of the works from TMC is a key performance factor in the activities at the centre, implying worthwhile efforts and work well done.

❖ **Benefits of ITS**

There are several benefits of ITS technology in the transport industry. Below are some benefits adapted from a report on the benefits, costs, and potential of ITS published by the US Department of Transport (DoT). It gives an overview of how various countries have reaped the benefits of implementing ITS technology, as well as the costs involved in its implementation, and the lessons learned (US DoT, 2018).

- ITS helps inform users in cases of accidents and crash avoidance in an environment of connected vehicles. It, therefore, reduces traffic-related fatalities. Thus, the connected vehicle environment, by ensuring greater safety measures, is assumed to contribute to reducing road accidents in cases of 100% penetration.
- Installing high-intensity pedestrian-activated crosswalks (hawks) on intersections reduces accidents.
- Increases public self-reliance while traveling in cases where travel facilities are in place which enable the transit management to issue communications both visually and audibly.
- Increased ridership and revenue. In the instance of smart ticketing, the machine used will automatically deduct taxes.
- ITS serves all travellers, transport operators, and transport managers in safety, reliability, and technology awareness. This improves the road network by reducing greenhouse gas emissions and

vehicle usage, especially in cases of short travel time/distances by providing efficient public transport.

- Increased availability of data can help in future decision-making processes. For example, the data collected from the toll payments, crash reports, and FCD becomes relevant in transportation administration, policy evaluation, safety, planning, program assessment, and operations research.

❖ **Applications of ITS**

There are numerous applications of ITS in many different countries, below are the most common trends of ITS in broad terms.

1. **Advanced traffic management system (ATMS).**

Traffic planners and engineers generally employ such systems where they use real-time traffic reports to decide on improving traffic flow (Mfenjou et al., 2018). Also, Perallos et al. (2016) argued that the motivation for traffic management systems (TMS) is to efficiently manage the road network, optimise traffic flow, and maximise road users' expectations of comfort and safety. This enables planners to constantly monitor the traffic, providing an efficient traffic network (Olayode et al., 2020). TMS act as a bridge between the TMC and roadside infrastructure. This is because they incorporate elements of ITS that enable the communication, analysis, and dissemination of information.

Different traffic environments allow for specific approaches and scenarios in TMS applications. These are urban, inter-urban, and long-distance traffic environments (Perallos et al., 2016). Depending on the environment, different systems may apply; traffic signal control systems, freeway management systems (FMS), electronic toll payments, and railroad grade crossing safety (Sumalee andand Ho, 2018).

The different systems are adopted to achieve the overall purpose of the transport network of accessibility, safety, and comfort. These systems may incorporate devices to fulfil their purposes and objectives. The supporting devices may include; traffic lights, traffic counters, nomadic appliances (smartphones, on-board units [OBUs]), GPS, closed circuit television (CCTV), VMS, variable speed limits controls, automatic number plate recognition (ANPR), meteorological devices, electronic call boxes, and toll stations among others. There are some advantages linked to managing traffic as adapted from Perallos et al. (2016):

- Safety assurance through the constant monitoring of traffic flows.
- Lower average travel times are achieved by optimising the traffic flow and co-ordinating vehicle speed through variable speed limits.
- Reduced carbon emissions due to lower average travel times experienced by road users.

- Availability of on-time information to road users enables them to plan ahead for their travels, improving the overall transportation system performance.
- Provision of appropriate traffic control strategies according to travel demand.

2. **Advanced public transportation system (APTS).**

Traffic congestion results from over-dependency on private transport in urban centres. However, a paradigm shift seems inevitable if transport authorities can modify public transportation to accommodate users' expectations of safety and comfort. Also, public transportation measures tend to reduce travel time. Many measures in public transportation are aimed at increasing its reliability and effectiveness. Perallos et al. (2016) categorised the measures in public transportation systems into four categories; roadway improvement, improvement of public transport operations, administrative measures, and adaptive traffic control. However, contrary to ITS applications, roadway improvement and administrative measures can be considered in other traffic congestion measures when improving existing infrastructure and mode improvement, as discussed in sections 2.4.2 and 2.4.3, respectively. Therefore, adaptive traffic control systems qualify to be applications of ITS in public transportation systems.

Another dimension of improving public transport operations entails transit management by posting regularly updated schedules for arrival and departure times using online timetables or billboards at transit stations. This requires a public transport management centre, preferably at a TMC. Additional improvements might include smart ticketing, and vehicles with on-board access to the internet and info-tainment facilities. Regarding adaptive traffic control, public transport lanes should be given priority at traffic lights. This measure could entice travellers to utilise public transport. Adaptive traffic control with public transport priorities seems to be the most effective strategy for ITS cooperative systems (Perallos et al., 2016). This strategy works best in the existence of a scheduled timetable.

An adaptive control system works within a cooperative system of drivers, infrastructure, and vehicle systems. For example, a public transport vehicle enters a cooperative traffic zone. The detected vehicle enables the V2I communication and details are sent to the TMC. The TMC determines whether a public transport priority is necessary. If so, a strategy solution is selected, and an algorithm for signal plan changes is activated. When the public transport vehicle exits the intersection, the TMC reactivates the fixed signal timing plan. However, some cases would need special consideration in the system design. For example, in cases of multiple requests at the intersection, if two or more public transport vehicles arrive simultaneously. Furthermore, Perallos et al. (2016) illustrated the various levels of implementation for APTS measures, as shown below:

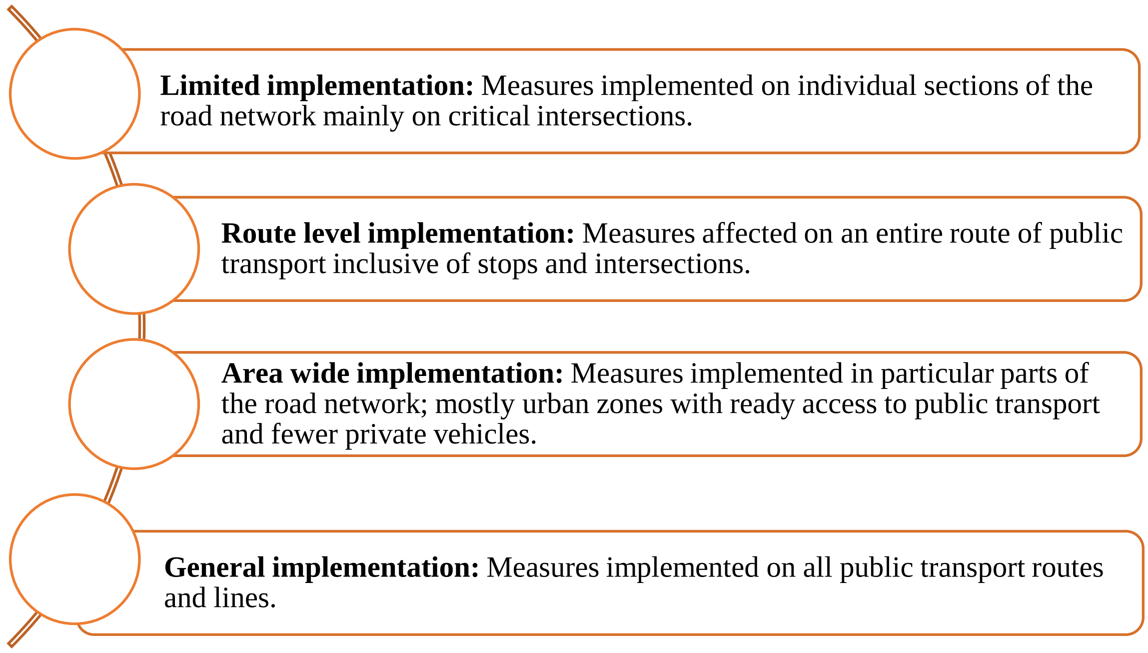

Figure 2- 3: Levels of implementation of APTS

3. **Emergency management system (EMS).**

This system deals with the overall management of road networks in cases of accidents or incidents. Sometimes, EMS is divided into incident management systems and emergency management services (Mfenjou et al., 2018). Traffic incidents are unpredictable occurrences on the road section that lead to delays at that section and other adjacent roads, often impacting the safety and efficiency of the road network (Perallos et al., 2016).

In the urban environment, incidents more adversely affect the traffic flow compared to other road networks. There are several processes EMS tend to undergo. These include; detection and verification, responding by dispatching appropriate teams on-site, incident clearance, and normal flow recovery. Detection involves identifying the spatial and temporal points of the event. This contributes to the overall efficiency of the road network due to the prompt incident clearance. Some of the events that can lead to an undesired flow of traffic include:

- Vehicle-influenced conditions like vehicle breakdowns, accidents with/without fatalities.
- Falling debris/ barriers along the road.
- Maintenance activities.

The following are the functions of EMS in an integrated ITS environment as adapted from Perallos et al. (2016):

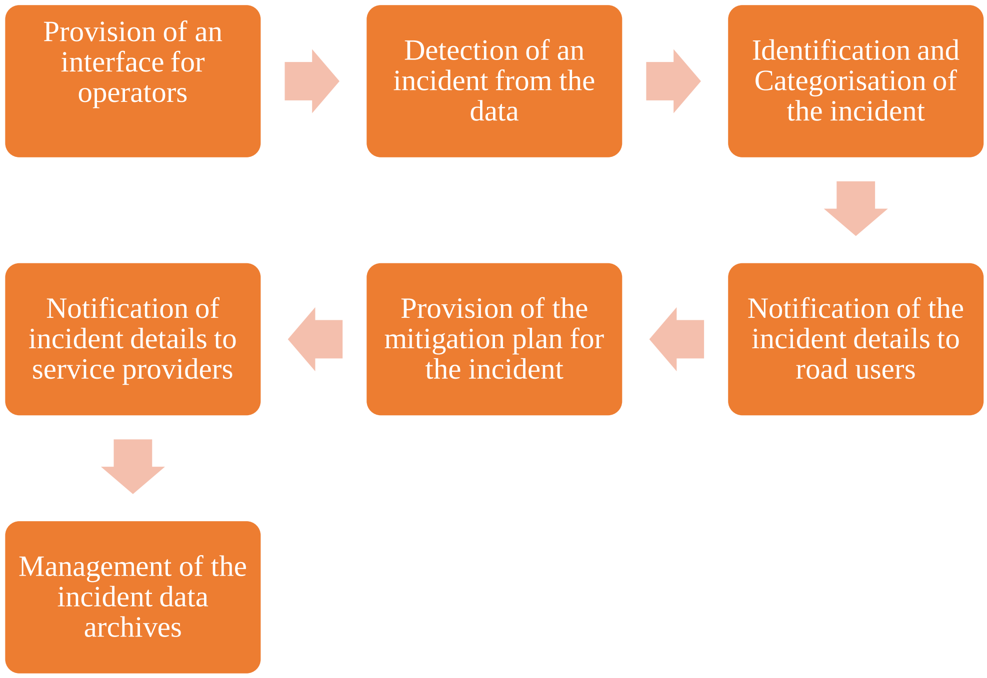

Figure 2- 4: Functions of EMS

4. Advanced traveller information system (ATIS).

These involve various systems from mobile phones, the internet (especially social media platforms, e.g. Facebook and Twitter), televisions, radios, and newspapers. Information can be collected from these sources, and disseminated to the public. The latter is especially important for issuing updates or warnings about traffic status on the roads, optimal routes, and departure times for buses (Singh and Gupta, 2015). Another advanced method is variable message signs (VMS), where information is displayed on boards to provide current road updates. This system enables users to re-route or expect a delay, thus improving the road network's traffic flow.

Perallos et al. (2016) discussed an intelligent information management system (IIMS). This system involves collecting information on the road segment, sending it to the on-board module, where it is processed and then displayed to the driver according to relevance. It prioritises ITS communication on-board. IIMS enables the collection of information via beacons on the road. The input messages consist of static and dynamic messages. The dynamic messages include VMS, variable speed limits, and data due to the changing traffic and road status. The static messages include the static road signs encapsulated in prohibitory, regulatory, and informational signs.

This system has three model phases: signal, interpretation, and representation. All the models depend on the environment, vehicle, and driver. The display information appears in the representation model through an audio or visual display device inside the vehicle. This system enables the driver to increase their alertness while driving to avoid any safety-related hazards and also not to miss out on any information displayed on VMS and other signposts.

- **Summary**

In a nutshell, ITS implementation requires architectural planning. Planning would require a clear outline in which various strategies, policies, and operations relevant to the world's different parts are considered. This study entails discussing multiple measures that suit a specific scenario. A need for a feasibility study is paramount to ascertain the cost-benefit ratios before implementing such technology (Zhankaziev et al., 2018). Similarly, various projects elsewhere could be consulted, and the success stories of such infrastructure could be considered beforehand. Also important to note is the maturity of infrastructure for the ITS development strategy; this is essential to reap the desired benefits from the system.

2.5 Conclusions

In conclusion, Litman (2013) argues that urban congestion reaches an equilibrium where there will be no increase in the delay time. Commuters tend to change their behaviours accordingly through modal shifts, alternative travel times, change of routes, and change of origin and destination points. Until congestion reduces and peak delay time normalises, behaviours also alter. This study contends that this might not be the case for countries with poor or unreliable road networks. This is because the change of routes is often impossible and traveling only during peak hours is preferable due to security reasons. However, Litman contends that congestion measures must focus on reducing the equilibrium point.

OECD (2007) indicates that congestion management in urban settings requires a multi-organisation collaboration. The organisations should ensure that the goal is well-defined and work towards achieving it from the decision-makers, technical institutions, private sector, road users, and the public. Also, it should allow for the expression of various strategies and mechanisms across the broad spectrum of actors toward controlling congestion. From the above measures discussed in section 2.4, there is no guarantee, according to the literature, that there exists a condition of no congestion. However, every city should consider its dynamics before implementing the different measures.

Congestion measures require thorough planning for effective results. Modelling is one of the elements that can be used in transport planning to enable decision-makers to reach sustainable and effective resolutions (Ortúzar and Willumsen, 2011). It is an essential component in transport planning. Therefore, before the relevant institution adopts any action to alleviate the plight of congestion, plotting models to envisage their impact is significant. On this note, this thesis develops a novel FCD model to evaluate traffic congestion to facilitate decision making.

Chapter Three

Research Design and Methodology

3.1 Introduction

This chapter discusses the research design and methodology adopted for this thesis. As per the research question, "Can FCD analysis evaluate traffic congestion zones in Kampala to propose suitable measures for alleviation?" First, the chapter describes the geographical location of the study area, Kampala. Then, it discusses the data sources for FCD, and tools used for evaluating traffic congestion and measures to alleviate it, including a consideration of the reliability and trustworthiness of the data sources. This chapter also explains the step-by-step procedures in the methodology section to justify the research design.

3.2 Research design

This study adopted a mixed-method approach for the research design, using both qualitative and quantitative methods to achieve the research objectives and respond to the research question. Specifically, this study embraced an explanatory sequential mixed-method design for the research. This type of research design firstly considers the quantitative method and then applies the output for qualitative analysis (Creswell and Creswell, 2018). It is essential to note that while the above approach was adopted, other methods can be employed to achieve the same research objectives.

Every project is unique. Therefore, this study developed the above approach based on the insights gained when compiling the literature review. The advantages of using a mixed method are clear; it enables the analysis to reveal different paradigms and encapsulates the benefits of both quantitative and qualitative, while at the same time minimizing the disadvantages of these methods (Creswell and Creswell, 2018).

For this research, traffic data expressed as travel time and speed (quantitative), led to the development of a FCD model which determined the highly congested areas. Then, a desktop study of two highly congested zones was conducted. This enabled the assessment of possible causes of congestion in the designated zones (qualitative). Finally, possible mitigation measures that relevant transport authorities can implement was compiled.

Regarding the research design, modelling and a desktop study were employed. Modelling served as the quantitative method, and the desktop study constituted the qualitative method. Both techniques provided an explanatory sequential mixed-method design approach. This study adopted these methods because they provided adequate basis to respond to the research question.

Congestion was estimated quantitatively through the FCD model. The model used the speed reduction index (SRI) and delay rate as the measures of congestion. SRI has a particular scale that eases the differentiation among zones. The delay rate was then used to easily rank the congestion zones for prioritising. This study applied these congestion measures because of the available FCD. The data consisted of the speeds and travel times during morning peak and off-peak hours (base scenario).

The qualitative method of desktop study was employed for this research due to the COVID-19 pandemic that restricted travels and engagement of certain activities. Although a site study was necessary, the desktop study was justified as an alternative to achieve the research objective.

3.2.1 Research approach

This research study utilises a straightforward, methodological approach of a FCD model to identify the congestion areas in Kampala. It abridges the traditional demand model, which is costly and time-consuming. Instead, this strategic planning model uses the FCD approach, which is cost-effective and readily available. The model discussed in this study is novel. It enables transport planners to quickly identify congested areas, prioritise them, assess the current situation, and propose suitable measures to alleviate congestion in the designated areas. Below is the systematic approach for the FCD model.

1. The case study area was the Kampala CBD. The spatial extents of the city acquired from the KCCA archives enabled the delineation of the study area. For the first objective of identifying the congestion areas from the FCD in Kampala, the PTV VISUM software was used. The software generated a model of the road network and enabled the visualisation of the congested areas in the city using speed data as the traffic parameter. The relevant areas were then clustered into no, low and high congestion intensities for different categories of road class. Meanwhile, morning peak hours were modelled, because traffic congestion is prevalent during those times (TRB, 2000).
2. The second objective was prioritising the congestion areas according to road class. This was achieved by analysing the results from the first objective. Firstly, the study utilised the delay rate congestion measure to prioritise the congestion zones using travel time as the traffic parameter. Then, the road classes were differentiated. For example, class two (major arterials) and class three (minor arterials) were placed in the same group because of their high traffic volumes compared to class four (collectors). Finally, the study ranked the zones according to their respective delay rates. This quantitative output led to the qualitative method in the third objective.
3. The third objective included identifying the causes of traffic congestion in the selected sections. A desktop study was adopted to evaluate traffic performance in these areas. Some key elements considered in the analysis included assessing the road network, adjacent infrastructure, and a

general overview of the intersections. These established possible factors causing the traffic congestion in those sections. The qualitative data obtained provided the foundation for determining possible measures to alleviate congestion per the fourth research objective.

4. This study conducted simulation modelling in PTV VISSIM software for the fourth objective, of proposing possible mitigation measures to alleviate congestion. The simulation modelling applied scenario management tools to illustrate the impact on traffic when a particular mitigation measure is implemented.

3.2.2 Design of research approach

The research followed the design approach illustrated in figure 3-1 to achieve the objectives.

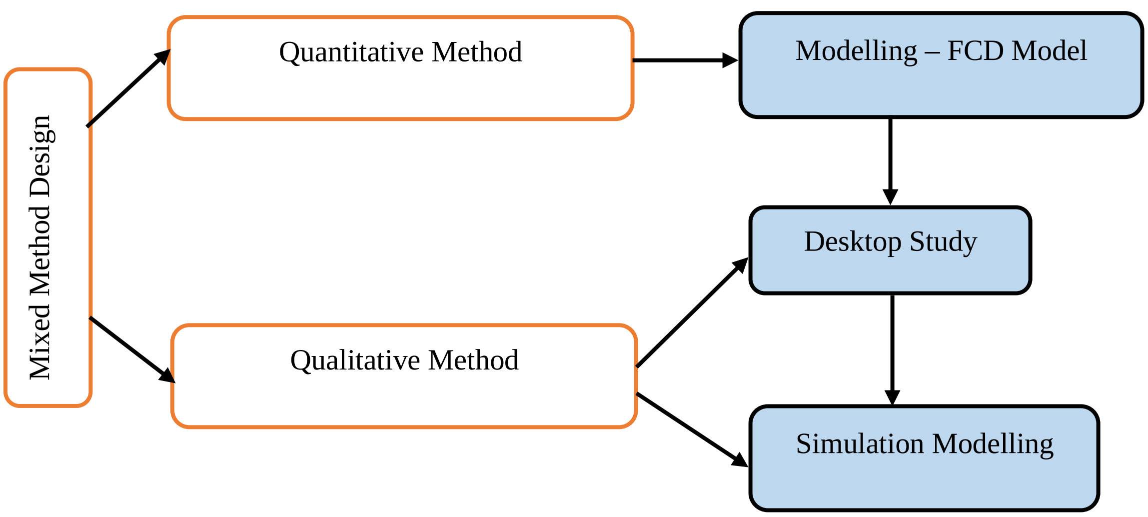

Figure 3- 1: Research approach

3.3 Geographical location of Kampala

Kampala is the capital city of Uganda, situated in East Africa. It is located at the coordinates: 0°18′ 49″ N, 32° 34′ 52″ E. The city abuts the shores of Lake Victoria, the largest lake in Africa. The city borders the Wakiso district in the west and north, and it is about 189.3 square kilometres in area. Kampala is divided into five major areas or divisions, including; Central, Kawempe, Makindye, Nakawa, and Rubaga Divisions. Kampala's Central Business District (CBD) is in the Central Division. Kampala serves as the centre of the country's administration, services, economy, education, culture, and sport (KCCA, 2019). Three major arterials that are part of the trunk, or national roads emanate from the CBD, and include; Bombo Road, Jinja Road, and Entebbe Road. These are a part of the road network, and generate high traffic volumes to and from the CBD.

Figure 3- 2: Geographical location of Uganda

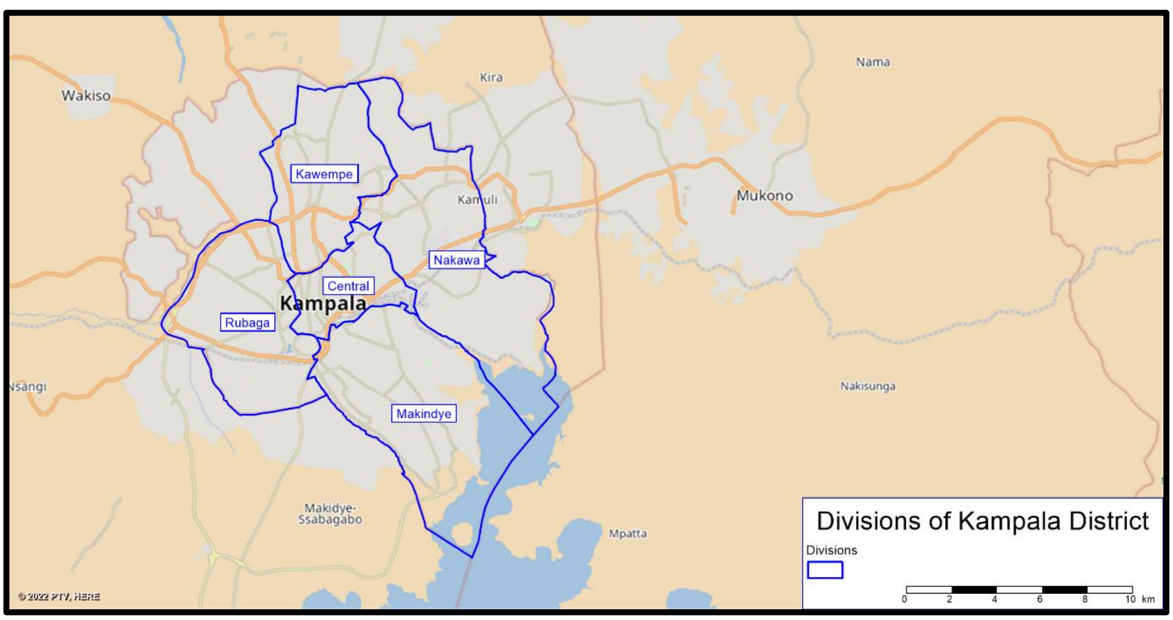

Figure 3- 3: Map showing the five Divisions of Kampala

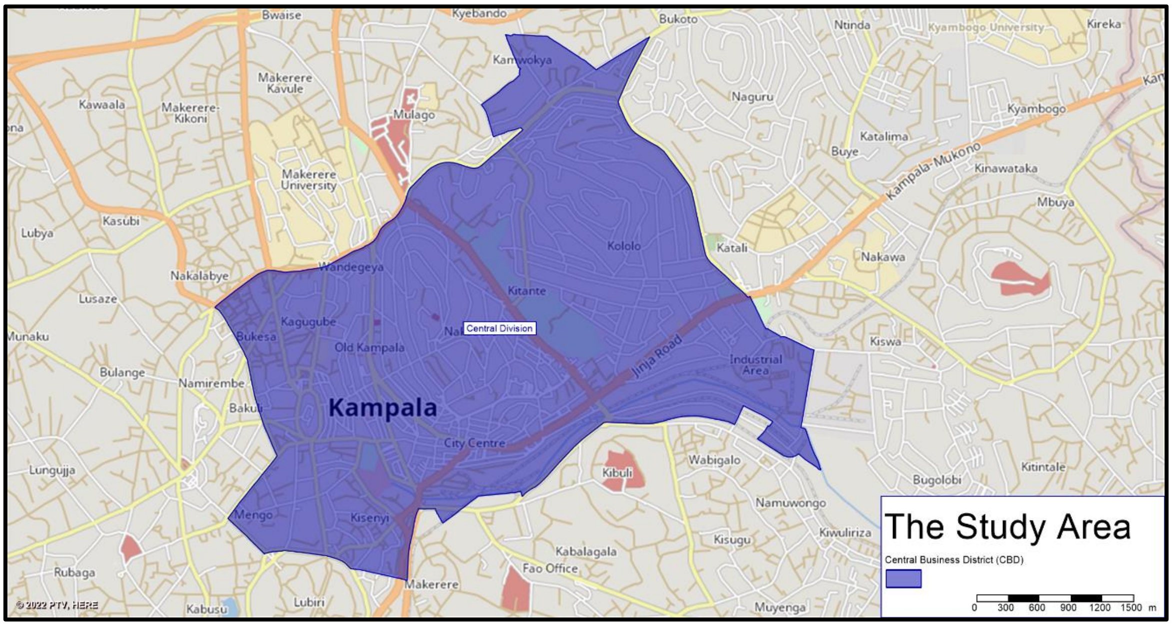

Figure 3- 4: Boundaries of the Central Business District (CBD) of Kampala City

3.4 Description of data sources and tools

This section describes the sources of data used for the traffic analysis. Also, the tools that aided the data analysis for each objective. For objectives one and two, of identifying congestion zones and prioritising them, this study used OpenStreetMap (OSM), PTV VISUM, and Google API. Google API was the source for FCD. The data from this source included the travel times and speeds for morning peak and off-peak hours. OSM provided information about the road network attributes, while PTV VISUM was used to generate a model of the road network.

The study used Google Maps and photographic images to assess the situation for objective three, of identifying traffic causes in high congestion zones.

For objective four, of proposing mitigation measures to alleviate congestion, this study used traffic volumes from UNRA in the microscopic simulation modelling in PTV VISSIM, which enabled the traffic engineering analysis.

3.4.1 Data sources

This study used the map of Uganda generated from OpenStreetMap (OSM) to PTV VISUM. The map included details of the roads in the country and their corresponding attributes. Kampala CBD was chosen as the study area. Extensive work was completed to organize the data and generate the base map. PTV VISUM proved a useful tool for generating a model of the road network. The file consisted of the nodes, links, and coordinates for the CBD's major and minor arterials, collectors, and local roads. Then, this study obtained the speed and travel time data for the morning peak and the off-peak hours on the different sections of roads from Google API.

❖ **OpenStreetMap (OSM)**

OSM is an open-access geographical database available worldwide. The primary output of OSM is the underlying geodata (Maier, 2014). OSM is, therefore, a free online software that provides a platform to create an editable map of the world (Liu et al., 2017). The advancement of inexpensive satellite navigation devices, specifically GPS, and the unavailability of map data led to the development of the OSM. Steve Coast established OSM in the UK, with more than two million users globally. The advantage of OSM is that data is readily available, and no bureaucratic procedures are involved in accessing it (Maier, 2014).

The quality of the data is reliable. Nevertheless, the respective study area for this thesis was corroborated using Google Maps. There is an added degree of accuracy since it relies on voluntary contribution. Registered users worldwide update the map's features, which are stored in the central database and made available to other users (Maier, 2014). It is, therefore, volunteered geographic information (VGI) (Mocnik, Zipf and Raifer, 2017). This study employed OSM because it has excellent quality in retrieving the street geodesy, and one can easily extract data for a particular region (Keler, Krisp andand Ding, 2017a). Maier (2014) further illustrates some uses of OSM, as discussed below:

- **Source of information**

OSM provides information on any particular point of interest in an area. It works with other servers and interfaces to retrieve data. For example, in this case, it functioned with PTV VISUM software to generate the required map and information about Kampala.

- **Geocoding and routing**

OSM contains the information obtained through a query. For example, when searching for an address, the map provides the longitude and latitude. When the coordinates are available, then a need arises to obtain the address, which is called *nominatim*. In the case of routing, it is an open access software that provides the routing path through an API. Therefore, it enables the establishment and running of routing servers.

- **Web-based application**

Licensing OSM and other related tools enables developers to use them in their applications. For instance, a researcher designing a map for a university to help individuals find different places of interest in that localised environment would use OSM as the base map and insert overlays with details of the buildings on campus. There is even a provision to switch to different floors of buildings.

As for this particular study, the researcher used OSM as a source of information to retrieve the road attributes of the Kampala city. These attributes included names of the road sections, road class, road type, number of lanes, transport systems, among others.

- **Google API**

Google APIs are application programming interfaces. These allow the exchange of information between Google and other services (Google, 2007). For example, a particular individual can use an API to extend the functionality of a service, or retrieve existing data. There are several Google APIs. In this case, the API used for this study was Google Maps to obtain the traffic data. Google Maps were also used in the desktop analysis of the different areas of Kampala with high congestion. Google Maps provides road network views, land use and locations of different infrastructure systems like banks, hospitals, and universities (Mehta, Kanani and Lande, 2019).

Google, like other companies such as TomTom and INRIX, provides open source data for a limited period and number of links and/or nodes in the network. Traffic data is also available from these companies commercially. However TomTom and INRIX do not provide the FCD for Kampala, the study obtained the data from Google API. This study utilised the open source traffic data from Google. Google provides traffic data for over 50,000 nodes without charge.

i. Accuracy of data

Google collects data from GPS-enabled vehicles and mobile phones in the traffic stream. This is a function of penetration of FCD i.e., the percentage of vehicles that act as probes. The more data aggregated for some time, the more accurate it becomes.

Yu et al. (2019) studied the accuracy of Google Maps location history data to describe human mobility. They used the data to check the health conditions due to air pollution. They discovered the accuracy of the Google Maps data in terms of mobility. Therefore, this implies that the data is accurate and valid for various studies.

ii. Trustworthiness

Google is an established company that provides other services on a global scale other than FCD. Services include email, and language translation services, among others. This contributes to the trustworthiness of the company that supplied the data.

3.4.2 Research tools

❖ **PTV VISUM software**

PTV VISUM is one of the world's most advanced and widely-used software for transport planning. It offers a wide range of transport modelling that aids decision-making (PTV Group, 2016). It is one of the products of the PTV Company, based in Germany that facilitates transport modelling. It is largely for macro-planning on a national level and meso-planning on a regional level. PTV VISUM is a demand model and data-intensive modelling software. The data used is imported from sources such as OSM, TomTom, INRIX, HERE, field data, and others.

Areas of application

The software uses data analytics and large-scale simulations to facilitate the areas of application. Some of the application areas as adapted from www.ptvgroup.com include:

- **Transport planning**

PTV VISUM provides an overview of the current road network to identify congestion, such as bottlenecks, in the system. It is ideally suited for scenario management and analysis, such as assessing the impact of additions to the road network or other localised network improvements. This influences network planning and management and applies to all modes of transport. This transport planning tool influences decision-makers in providing services according to the simulations performed to improve the transport network. For this research, PTV VISUM was emphasised. The congestion areas were identified using the road network generated in the software.

- **Public transport analysis**

Public transport may include; buses, taxis, and trains. PTV VISUM provides a detailed representation of the travel lines and stations for various modes of transport. This can help in managing, scheduling, and optimising the public system. Therefore, this serves to develop an economically feasible solution for public transport, meeting potential needs to increase the lines or add more capacity.

- **Future mobility**

As the number of vehicles increases on the roads, congestion becomes inevitable. PTV VISUM allows transport planners to adapt and make informed decisions for ongoing mobility improvement. Also, with the recent rise in availability of autonomous and electric vehicles, the automobile industry can rely increasingly on software to gauge the operations of such vehicles to shape future mobility. Additionally, the software also provides modelling in ridesharing. E-hailing companies, for instance, provide an opportunity to utilise the software application.

❖ PTV VISSIM software

PTV VISSIM is the world's most cutting-edge and flexible traffic simulation software on the microscopic and mesoscopic levels (PTV Group, 2020). PTV VISSIM is also another of the products of the PTV Group. It is a renowned software because it provides a holistic view of traffic planning to aid decision-making. It is a microscopic modelling tool for traffic engineering. Also, it enables the evaluation of different scenario cases before decision-making. It is also user-friendly and offers seamless and flexible integration of software.

Areas of application

There are different areas of application with PTV VISSIM Software. As adapted from PTV Group (2019), below are some application areas:

- **Traffic flow simulation**

PTV VISSIM provides a digital platform for modelling different scenarios and an optimum solution for alleviating traffic-related problems. This can help reduce costs related to constructing or rehabilitating road elements. The software allows for experimentation of options to study their impacts before implementation. Also, relevant traffic institutions can identify possible hotspot areas in the road network regarding the current conditions.

- **Multi-modal systems**

PTV VISSIM allows modelling for all modes of transport depending on the current needs of the area. Different areas have different needs. This software allows for incorporation of different requirements, providing a detailed traffic simulation analysis. For example, in Africa, many countries use tricycles and motor bicycles in the traffic streams; therefore, PTV VISSIM presents an opportunity for modelling such multi-modal systems.

- **Future planning**

PTV VISSIM enables detection, planning, and controlling of all necessary interventions. This may help evaluate the overall traffic flow and the decision-making process to benefit all road users.

- **Future mobility**

Future mobility is the recent advent of connected and autonomous vehicles (CAV) in the transport system. PTV VISSIM provides a platform to assess how such vehicles can interact in the traffic stream with other non-CAV on a microscopic level. Evaluating the different situations is paramount before considering the systems.

In summary, there are many software tools used for such studies. These include; simulation of urban mobility (SUMO), corridor simulation (CORSIM), AIMSUN, and others. This research utilised the PTV VISUM and VISSIM software to achieve its objectives, largely because these are readily available at Stellenbosch University in the Stellenbosch Smart Mobility Laboratory (SSML).

PTV VISUM 2022 and PTV VISSIM 2022 enabled this study to achieve its research objectives and respond to the research question. The two software components are user-friendly and require limited coding compared to other software. An added advantage is the strong support they provide customers through training and support networks.

3.5 Methodology

This research study was executed following the procedures below. The discussion illustrates how each objective was achieved in the development of the FCD model. The methodology follows the research design as explained in section 3.2.

3.5.1 Identification of congested areas.

Speed reduction index (SRI) as a congestion measure was used to identify the congested areas in the Kampala road network. SRI was calculated for each road link. SRI utilises speed data for the morning peak and off-peak periods in its calculation. Congestion intensities were visually observed on the different links in the road network using PTV VISUM. This tool allows different characteristics of the road network to be displayed. Here, SRI was displayed for each link. Another approach for clear visualisation was a zonal analysis based on a fishnet statistical approach of aggregating data. For this, the study area was divided into zones. Congestion intensities were also visualised in PTV VISUM.

3.5.2 Prioritising of congested areas

Delay rate as a congestion measure was used to rank the congested areas in the road network. Delay rate is the time loss for commuters during a road segment's congestion period. Delay rate utilises travel times for both morning peak and off-peak hours and the respective length of the road link in its calculation. The delay rate for the road links was calculated before aggregating in a zonal analysis. The results were prioritised according to the area with the highest recorded delay rate.

3.5.3 Assessment of congested areas

First, the most highly congested link was studied. Then, using Google maps data and photographs, the different features that might be the causes of congestion were analysed. At the zonal level, the same data sources of Google maps and photographs were used to determine the causes of congestion.

3.5.4 Mitigation measures

From the causes of congestion identified, measures to alleviate the congestion were proposed. This study suggested these measures based on the literature review, as well as on background knowledge in the field of engineering. Therefore, simple and practical solutions were formulated. Due to the available data for some sections of the road network, PTV VISSIM was used in the simulation modelling to test the different possible solutions suggested.

Limitations of methodology

Below are the limitations of the methodology used in this research study.

1. The FCD data used in the development of the model was obtained from a third party; Google API. Collecting this data first-hand was beyond the scope of the study.
2. The tools used for this study, PTV VISSIM and VISUM, were the readily available software at Stellenbosch University.
3. This study did not conduct a site study to assess the possible causes of congestion in specific areas. This would have been the ideal method but due to the COVID-19 pandemic, a desktop study was conducted.

Chapter Four

Data Collection

4.1 Introduction

This chapter elaborates on the data collection process. It illustrates how the FCD was obtained from Google API. The two sets of data were; travel time and speed. These datasets enabled the achievement of objectives one and two of this research study. Objective one was to identify the congestion areas, while objective two was to prioritise the congestion areas. The other data collected for objective three, which was to identify the causes of congestion, is also discussed in chapter.

4.2 Collection of the traffic data

4.2.1 Data extraction

The study utilised a map of Uganda from OSM. The map provided the road class, names, type number, and transport systems of the whole road network for Uganda. Firstly, the map was imported into PTV VISUM. Next, the mesoscopic area for Kampala was defined.

From PTV VISUM, the road network was generated for the Kampala CBD. Nodes were created which were joined through links to form a complete road network. Nodes were placed on sections where there was an intersection with another road and a change in the number of lanes. The data was stored in the link and node lists on the software.

The nodes' coordinates, as well as the name of the road containing the node, and links to and from the nodes were then imported into Microsoft Excel. The links were bi-directional i.e., representing traffic in either direction. Therefore, it was important to clearly show the uni-directional links for the other direction not to be considered in the calculation.

Two tables were organised as shown in Table 4-1 and Table 4-2. The excel sheets were saved as comma separated value (.csv) files. Through a query, traffic data was obtained for the morning peak and the off-peak hours from Google API. This study assumed 7 a.m. as the morning peak time, and 12 a.m. (midnight) as the off-peak time. The period was from January to December of 2021. The data mined was the travel times and speeds for both hours. The output was aggregated data for weekdays during the stipulated period.

Two times of the day (as a minimum) were obtained, i.e., one representative of a typical congested period, and another representative of free flow. These two situations were necessary to compare traffic conditions on links to identify congestion areas.

The tables below show the column heads needed to extract data from Google API.

Table 4- 1: Format of input data 1

Marker ID (Integer)	Marker Description (String)	Latitude Coordinates (Float)	Longitude Coordinates (Float)

The marker ID was the node number, and its description; the road name. Then the latitude and longitude coordinates as obtained from OSM were included.

Table 4- 2: Format of input data 2

Marker ID of Origin (Integer)	Marker ID of Destination (Integer)	Indication whether the pair is needed in the calculation (0 for No and 1 for Yes)

The indication of whether the pair was needed in the calculations illustrated whether both directions should be considered in the calculations. There were links on one-way roads. Here, the opposite direction with no vehicles is indicated as 0. If both directions were needed, the directions were all indicated as 1.

The traffic data was presented in the PTV VISUM software with the additional column heads of speed and travel time for both the morning peak and off-peak periods. The traffic data for each link was specified.

Table 4- 3: Extract table from PTV VISUM

From Node	To Node	Type No	Name	Length (m)	AM peak Travel Time (min)	Off peak Travel Time (min)	AM Peak Speed (km/hr)	Off Peak Speed (km/hr)	Road Class

4.3 Data collection for desktop analysis

It was necessary to conduct a field study to assess the causes of congestion. However due to the COVID-19 pandemic, a desktop analysis was conducted instead. No fieldwork was completed to obtain relevant data in analysing the causes of congestion in the selected zones of Kampala. In the research proposal, this limitation was discussed in the risk analysis subsection and a contingency plan was suggested. The contingent plan was to conduct a desktop analysis, and hire personnel in Uganda to collect data for this analysis.

Song et al. (2019) used a geo-detector to identify the causes of congestion in different zones of Beijing city. Their investigation focussed on mapping the spatial-temporal patterns and identifying the possible causes of traffic congestion with multi-source data. The use of a geo-detector is considered one of the spatial statistical analytical methods that helps identify the correlation between complex factors across diverse geographical phenomena without any assumptions. This approach serves as a substitute approach for a site study. This study did not employ the tool due to a lack of multi-source data such as satellite images, landscapes, and population sizes. This study instead used an onsite view, which provided features of the study areas from Google Maps. Personal experience was also used to assess the possible causes of congestion in the areas. The desktop analysis was then developed from three sources of information. These included photographs, Google Maps, and personal experience. Below is the discussion of the aspects considered in the desktop analysis;

- **On-site view**

On the 12th of August 2022, a hired personnel helped take photographs of the high congested area in Zone 13 of Kampala. On the 15th of August 2022, additional photographs were taken of areas reported to experience high congestion in Zone 55 of the city. In both cases, the 7 a.m. morning peak was considered. The FCD model was likewise designed based on the morning peak hour of 7 a.m. This period provided the basis for collecting information at the two sites.

The hired personnel took photographs on his mobile phone. The photographs were then sent via email. The data was uploaded on SUNScholar Data website for later use. This particular dataset helped explain the causes of traffic congestion in the zones and further provided foundation for the proposal of mitigation measures.

- **Features of the congestion areas**

Information on the physical infrastructure at and surrounding the high congestion zones was obtained using Google Maps. The data included the type of intersection, the adjacent economic activities, and road layouts in the congested areas, such as number of lanes. The boundaries of the zones were delineated using a snipping tool on the Google Maps website. The areas in the zone were studied and information gathered on the area's physical infrastructure.

This information was necessary to determine the causes of congestion and propose mitigation measures. Such findings were enumerated by zone and recorded for analysis.

- **Personal experience**

This was another form of data in the desktop analysis. Although this dataset was subjective, it nevertheless helped to reinforce the other data from photographs and Google Maps. Having lived in Kampala for over 10 years of adulthood, I am familiar with the areas that were studied and could intuitively propose traffic engineering solutions based on my experience.

4.4 Summary

This chapter discussed how the data was collected and why the particular dataset was relevant for this research study. Other data collection sources could have been used, however this study adopted the traffic data from Google API as opposed to TomTom, INRIX, or Uber movements FCD. The reason for this was that the latter companies have not yet mined the historical FCD for Kampala, hence it was not available at the time this study was undertaken. This study also discussed the different data collection methods used to assess the causes of congestion. An onsite view where a hired personnel took photographs of the selected areas was used. Also, the features of the study area were examined through Google Maps and by drawing on personal experience.

Chapter Five

Results and Discussion

5.1 Introduction

This chapter discusses the research results following the methodology stipulated in chapter three. This chapter first presents the results obtained from achieving the first and second objectives which were to identify the congestion zones/areas and prioritise them according to road class. This chapter further elaborates on the results from the desktop study to realise the third objective of assessing the causes of congestion. This is followed by a section that presents the results from the scenario management in PTV VISSIM that aimed to respond to the fourth objective, of proposing mitigation measures to relieve congestion in a selected zone. The results were produced based on simulation modelling. All the results were discussed based on a traffic engineering perspective. The knowledge obtained from the literature review is also used in this chapter to discuss the results from the data analysis.

5.2 Identification of congested areas

Firstly the study critically scrutinised the data before identifying the congestion areas. The process involved data cleaning and filtering.

5.1.1 Data cleaning and filtering

The study considered the following aspects in the process of cleaning the data.

i. Exclusion of all transport systems (TSyst) of type number 75. This type number consisted of the paths for bodabodas and pedestrians. The exclusion was because such links were discontinuous and scattered randomly in the zones.
ii. Considering all the traffic data in both directions because the data was for a specific time during the morning peak and off-peak periods (temporal). The study area was the CBD (spatial), where all directions recorded substantial differences in travel time between morning peak and off-peak periods.
iii. Counter-checking the OSM road naming with Google Maps and correcting where necessary.

5.1.2 Analysis

This study identified the congestion areas based on two approaches: link and zonal. The link approach was used to identify sections with high traffic congestion on a link. For the zonal approach, the study area was divided into 500m squares. The speed parameter was used for this implementation. Speed reduction index (SRI) was used as the congestion measure.

- **Link analysis**

The study calculated the SRI for every link in the road network following the formula below:

$$\boldsymbol{SRI} = \left[\mathbf{1} - {}^{\boldsymbol{V_c}}\!/\!_{\boldsymbol{V_{ff}}}\right] \boldsymbol{X}\ \mathbf{10}$$

V_c = Actual travel speed

V_{ff} = Free-flow speed

The actual travel and free flow speeds were the data obtained from Google API. The free flow speed was assumed to be the off-peak period at midnight which was the baseline scenario for comparison with actual travel speed. SRI is suggested as an appropriate congestion measure compared to others due to the standard limits it exhibits (Bruwer and Andersen, 2022). The SRI is based on the range of 0-10. The values were rounded off to the nearest whole number.

The results obtained on the link level recorded a SRI of five as the highest on the segments. According to Afrin and Yodo (2020), SRI of zero represents no congestion, one through four is low congestion, and five and above are high congestion. With this scale, the study area could be presumed to experience low congestion on almost all the links. Another scale was adopted based on observation and local knowledge of the congestion levels in the city. The scale from Afrin and Yodo (2020) should not be binding to all areas. Each area is unique and congestion is perceived differently. In the context of this paradigm, this study used a different scale for the links where zero represents no congestion, one through two are for low congestion, and three and above to represent high congestion. The analysis data was uploaded onto SUNScholar Data website. Below is an example of the SRI on a link level as shown in Table 5-1.

Table 5- 1: SRI on the link level

From Node	To Node	Type No	Name	Length (m)	AM peak Travel time(min)	Off peak Travel Time(min)	AM Peak Speed (Km/hr)	Off Peak Speed (Km/hr	Road Class	SRI	
94834	38809	30	Kampala Road	33	3	2	39.67	59.50	Class 2	3	High
38809	45622	30	Kampala Road	19	2	1	34.84	69.67	Class 2	5	High
45622	7558	30	Kampala Road	86	8	7	38.48	43.98	Class 2	1	Low
7558	38806	30	Bombo Road	12	1	1	42.95	42.95	Class 2	0	No
38806	294963	30	Bombo Road	165	28	19	21.27	31.35	Class 2	3	High
38806	38807	39		37	3	3	43.89	43.89	Class 2	0	No
87068	87069	30	Bombo Road	18	2	1	32.15	64.31	Class 2	5	High
87070	87071	30	Bombo Road	18	2	1	33.10	66.20	Class 2	5	High
38845	38846	60		19	2	2	34.54	34.54	Class 4	0	No
48024	7825	40	Kyagwe Road	92	8	7	41.54	47.48	Class 3	1	Low
7825	48024	40	Kyagwe Road	92	8	7	41.54	47.48	Class 3	1	Low
7825	4919	40	Kyagwe Road	51	4	4	45.82	45.82	Class 3	0	No
4919	7825	40	Kyagwe Road	51	5	4	36.66	45.82	Class 3	2	High
4919	405508	40	Kyagwe Road	95	8	7	42.80	48.91	Class 3	1	Low

All links presented SRI in the range of zero to five. There were only 15 links that presented negative values. Most class four roads' links presented zero value.

The status of the links for the morning peak hour was visualised in PTV VISUM. Figure 5-1 illustrates the congestion intensities of the links.

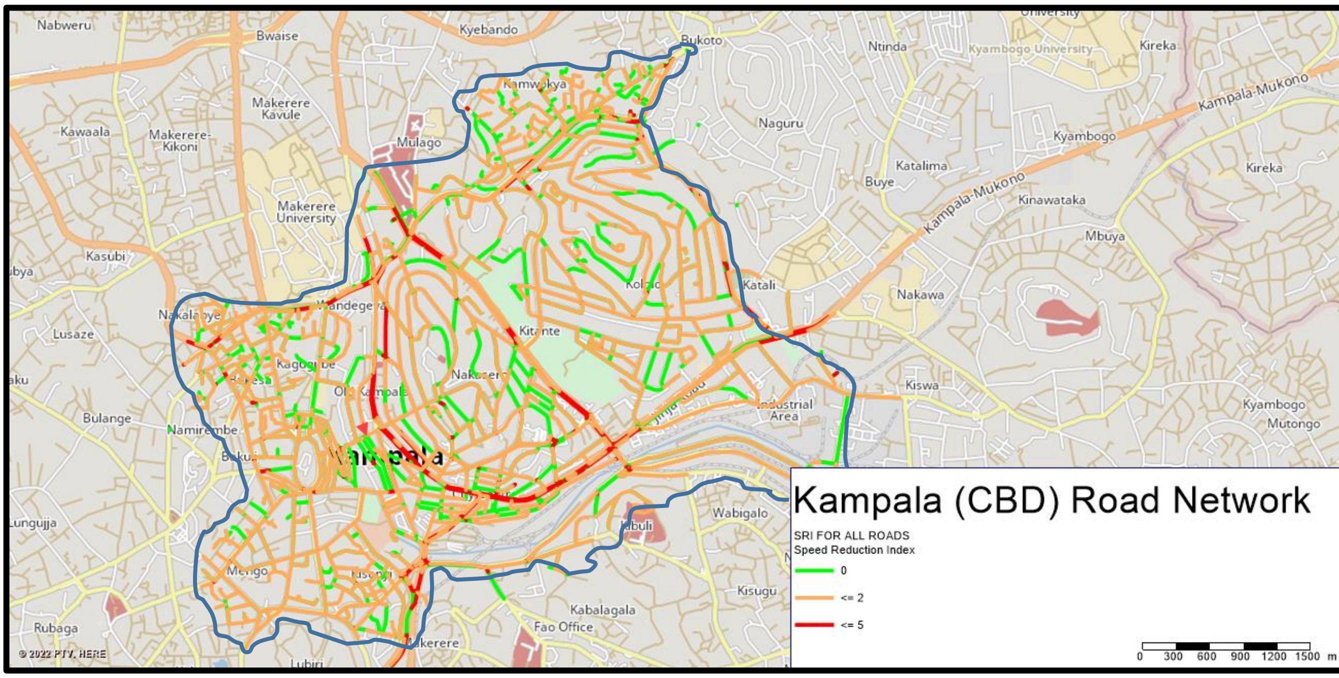

Figure 5- 1: The congestion intensities of the links

- **Zonal analysis**

The CBD area was divided into 500 m squares to enable a fishnet data analysis in PTV VISUM. Previous studies like Erdelić et al. (2021) used a similar approach of fishnet analysis by also dividing their study area into 500m squares. An et al. (2016) divided their study area into 250m squares describing their methodology in terms of grid congestion mode (GCM) to reveal the conditions of each grid. While Erdelić et al. and An et al. used created grids, Song et al. (2019) used administrative borders to identify the highly congested zones in their study. This study adopted the 500m square grids based on previous studies, and because a lack of more detailed administrative zones to aid the analysis.The 500m square grids were considered also because they provided sufficient zones with enough links to analyse.

The study created 68 zones within the boundaries of the CBD, as shown in Figure 5-2.

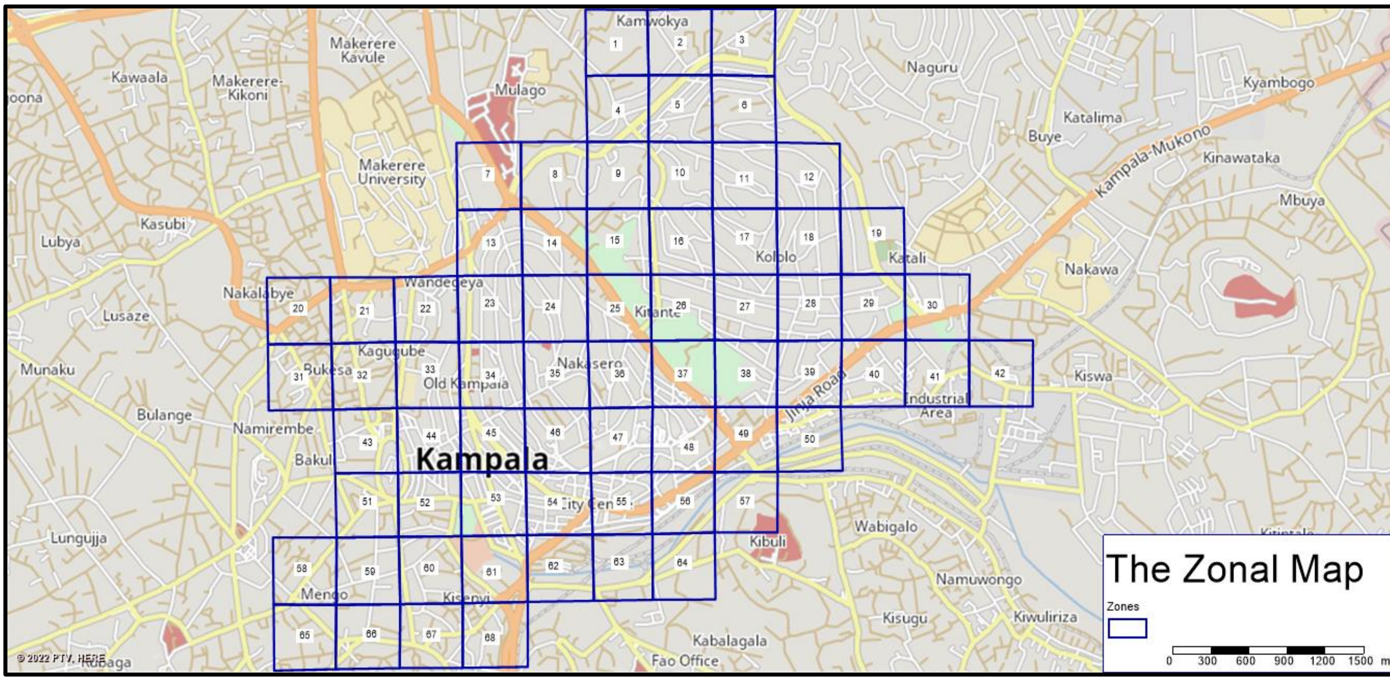

Figure 5- 2: The 500 x 500m zones of Kampala CBD

The data for each zone was imported to Microsoft Excel for further analysis. This was done link by link. Each zone was zoomed in and the corresponding data of the links in the zone was transferred into Microsoft Excel.

During the process of transferring the data to Microsoft Excel, missing links were discovered on some road sections in the different zones. These missing links were few, so they did not noticeably affect the data analysis. In general terms, most roads had complete links with data. Some roads with missing links included:

- Spring Road to Africana Roundabout
- Wampeewo Avenue to Africana Roundabout
- Nile Avenue to Shimoni Roundabout
- Luwum Street to Entebbe Road
- Bank Rise to Kampala Road
- Kira Road Junction with Lugogo by-pass from Bukoto
- Kenneth Dale drive to Old Kira Road
- Katanga Road
- Nkinzi Road
- Colville Street to Kampala Road
- Kafu Road to Yusuf Lule Road
- Shimoni Road to Yusuf Lule Road

- Corydon Road to Yusuf Lule Road
- K.A.R Drive
- K.A.R Road
- Ben Kiwanuka to Kampala Road
- Wilson Road from Ben Kiwanuka Road
- Princess Avenue to Nehru Avenue
- George Street to Square 2 Road
- George Street to Speke Road.

Twenty links were missing in the analysed link total of 4,208 of the road network. As noted, this number is negligible and did not affect the results of the study. Therefore the results obtained were satisfactory despite these missing links. Additionally, the missing links appeared scattered in different zones of the network, which further supports its negligible impact on the results.

During the data transfer two assumptions were made. When two or more zones shared a link, that link was selected at random for a particular zone, or each zone shared the link's attributes depending on the link's length. The other assumption was considering both directions of the link, taking note of one-way link routes. This was because both directions were contributing to the traffic congestion; as noted, the study area was the CBD where all directions of traffic matter.

The study aggregated SRI for each link in the zone to obtain the zonal SRI. The data was analysed in Microsoft Excel, as shown in Table 5-2 below.

Table 5- 2: SRI on a zonal level

Zone 9										
From Node	To Node	Type No	Name	Length (m)	AM peak Travel time(min)	Off peak Travel Time(min)	AM Peak Speed (Km/hr)	Off Peak Speed (Km/hr)	Road Class	SRI
2254	2255	70	Katego Road	221	21	21	37.80	37.80	Class 4	0
2255	2254	70	Katego Road	221	22	21	36.09	37.80	Class 4	0
2255	40897	70		14	1	1	48.66	48.66	Class 4	0
40897	2255	70		14	1	1	48.66	48.66	Class 4	0
3350	40897	30	Kira Road	46	4	3	41.43	55.24	Class 2	2
40897	18358	30	Kira Road	76	6	5	45.71	54.85	Class 2	2
18358	407597	30	Kira Road	190	26	20	26.27	34.16	Class 2	2
407421	70496	30	Kira Road	254	30	26	30.84	35.59	Class 2	1
70496	2255	30	Kira Road	76	7	6	39.33	45.89	Class 2	1
2255	39235	30	Kira Road	47	5	4	33.62	42.02	Class 2	2
18358	70496	70		14	1	1	49.46	49.46	Class 4	0
70496	18358	70		14	1	1	49.46	49.46	Class 4	0
18357	18358	70	Lincoln Lane	225	22	20	36.89	40.58	Class 4	1
18358	18357	70	Lincoln Lane	225	22	22	36.89	36.89	Class 4	0
3350	39235	70		12	1	1	44.93	44.93	Class 4	0
39235	3350	70		12	1	1	44.93	44.93	Class 4	0
3350	91257	70	Windsor Loop	20	2	2	36.66	36.66	Class 4	0
91257	3350	70	Windsor Loop	20	2	2	36.66	36.66	Class 4	0
3351	91257	70	Windsor Loop	247	25	22	35.59	40.45	Class 4	1
91257	3351	70	Windsor Loop	247	23	22	38.69	40.45	Class 4	0
3351	436984	40	Acacia Avenue	66	7	5	33.88	47.43	Class 3	3
436984	3351	40	Acacia Avenue	66	6	6	39.52	39.52	Class 3	0
46171	710947	70		140	14	13	35.92	38.68	Class 4	1
710947	46171	70		140	14	13	35.92	38.68	Class 4	1
									AVERAGE	1

The results from the zonal SRI analysis are shown below for all zones.

Table 5- 3: Zonal SRI results for all classes

Zone	Speed Reduction Index (SRI)	Classification	Zone	Speed Reduction Index (SRI)	Classification	Zone	Speed Reduction Index (SRI)	Classification
1	1	Low	24	1	Low	47	1	Low
2	1	Low	25	1	Low	48	1	Low
3	1	Low	26	1	Low	49	1	Low
4	1	Low	27	1	Low	50	1	Low
5	1	Low	28	1	Low	51	1	Low
6	1	Low	29	1	Low	52	1	Low
7	0	No	30	2	High	53	1	Low
8	1	Low	31	1	Low	54	1	Low
9	1	Low	32	1	Low	55	1	Low
10	0	No	33	0	No	56	1	Low
11	1	Low	34	1	Low	57	1	Low
12	1	Low	35	0	No	58	1	Low
13	1	Low	36	1	Low	59	1	Low
14	1	Low	37	1	Low	60	1	Low
15	1	Low	38	1	Low	61	1	Low
16	1	Low	39	0	No	62	1	Low
17	1	Low	40	1	Low	63	1	Low
18	1	Low	41	1	Low	64	1	Low
19	1	Low	42	1	Low	65	1	Low
20	1	Low	43	1	Low	66	1	Low
21	1	Low	44	1	Low	67	1	Low
22	1	Low	45	1	Low	68	1	Low
23	1	Low	46	1	Low			

The status of the zones for the morning peak hour was visualised in PTV VISUM. Figure 5-3 illustrates the congestion intensities of the zones for all classes of the road network.

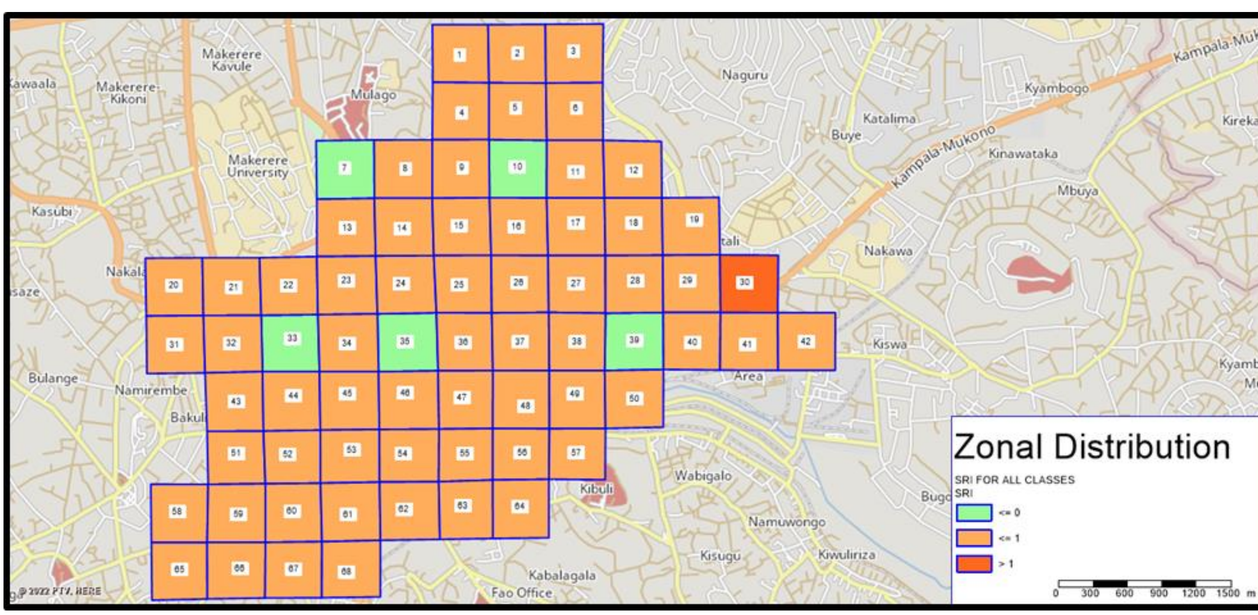

Figure 5- 3: Congestion intensities for all road classes

As shown in the results obtained above, almost all zones presented low congestion on the scale of zero for no congestion, one for low congestion and two for high congestion. This was attributed to the number of class four links in zones that always presented SRI of zero. In Figure 5-4 shows the proportion of congestion intensities.

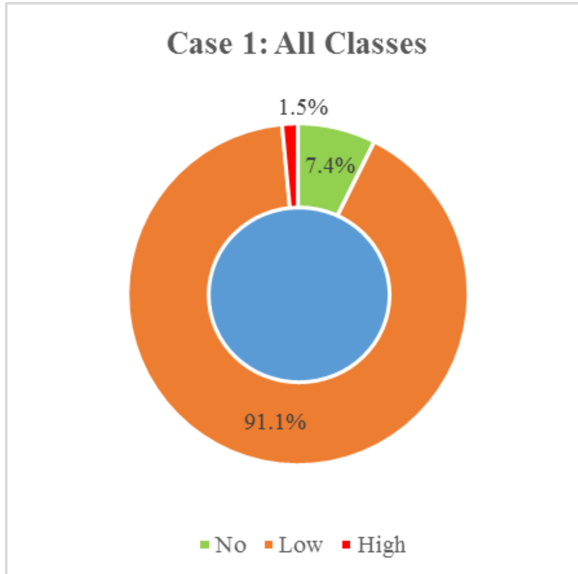

Figure 5- 4: Proportion of congestion intensities for all classes

This study devised another approach to eliminate the effect of class four roads. In this regard, a second case was considered for only classes two and three. Classes two and three were grouped together because they are the arterials in the Kampala road network. Class two are major arterials and class are minor arterials. These arterials reported substantial SRI that indicate traffic congestion in the area.

The 68 zones were then copied in another sheet in Microsoft Excel. All the zones were then examined by eliminating all class four links in the respective zones. An example using zone nine as in Table 5-2. When the class four links were eliminated, the zonal SRI changed from one to two. The results are shown in Table 5-4 below.

Table 5- 4: SRI on a zonal level for only arterials

Zone 9										
From Node	To Node	Type No	Name	Length (m)	AM peak Travel time(min)	Off peak Travel Time(min)	AM Peak Speed (Km/hr)	Off Peak Speed (Km/hr)	Road Class	SRI
3350	40897	30	Kira Road	46	4	3	41.43	55.24	Class 2	2
40897	18358	30	Kira Road	76	6	5	45.71	54.85	Class 2	2
18358	407597	30	Kira Road	190	26	20	26.27	34.16	Class 2	2
407421	70496	30	Kira Road	254	30	26	30.84	35.59	Class 2	1
70496	2255	30	Kira Road	76	7	6	39.33	45.89	Class 2	1
2255	39235	30	Kira Road	47	5	4	33.62	42.02	Class 2	2
3351	436984	40	Acacia Avenue	66	7	5	33.88	47.43	Class 3	3
436984	3351	40	Acacia Avenue	66	6	6	39.52	39.52	Class 3	0
									AVERAGE	2

The results for all zones in this case of only arterials are shown in Table 5-5.

Table 5- 5: Zonal SRI results for arterials

Zone	Speed Reduction Index (SRI)	Classification	Zone	Speed Reduction Index (SRI)	Classification	Zone	Speed Reduction Index (SRI)	Classification
1	0	No	24	1	Low	47	2	High
2	1	Low	25	1	Low	48	1	Low
3	1	Low	26	1	Low	49	1	Low
4	1	Low	27	2	High	50	1	Low
5	2	High	28	1	Low	51	1	Low
6	1	Low	29	2	High	52	1	Low
7	1	Low	30	2	High	53	1	Low
8	1	Low	31	1	Low	54	1	Low
9	2	High	32	1	Low	55	2	High
10	1	Low	33	0	No	56	2	High
11	0	No	34	2	High	57	1	Low
12	0	No	35	0	No	58	1	Low
13	2	High	36	2	High	59	1	Low
14	2	High	37	2	High	60	1	Low
15	2	High	38	0	No	61	1	Low
16	1	Low	39	1	Low	62	1	Low
17	0	No	40	1	Low	63	1	Low
18	0	No	41	1	Low	64	2	High
19	1	Low	42	1	Low	65	1	Low
20	1	Low	43	1	Low	66	1	Low
21	1	Low	44	1	Low	67	1	Low
22	1	Low	45	1	Low	68	1	Low
23	2	High	46	1	Low			

The zonal SRI was in the range of zero to two for the two cases. The zonal SRI were imported into PTV VISUM. The traffic status of the zones for the morning peak hour was visualised in the software. Figure 5-5 illustrates the congestion intensities of the zones for only arterials of the road network.

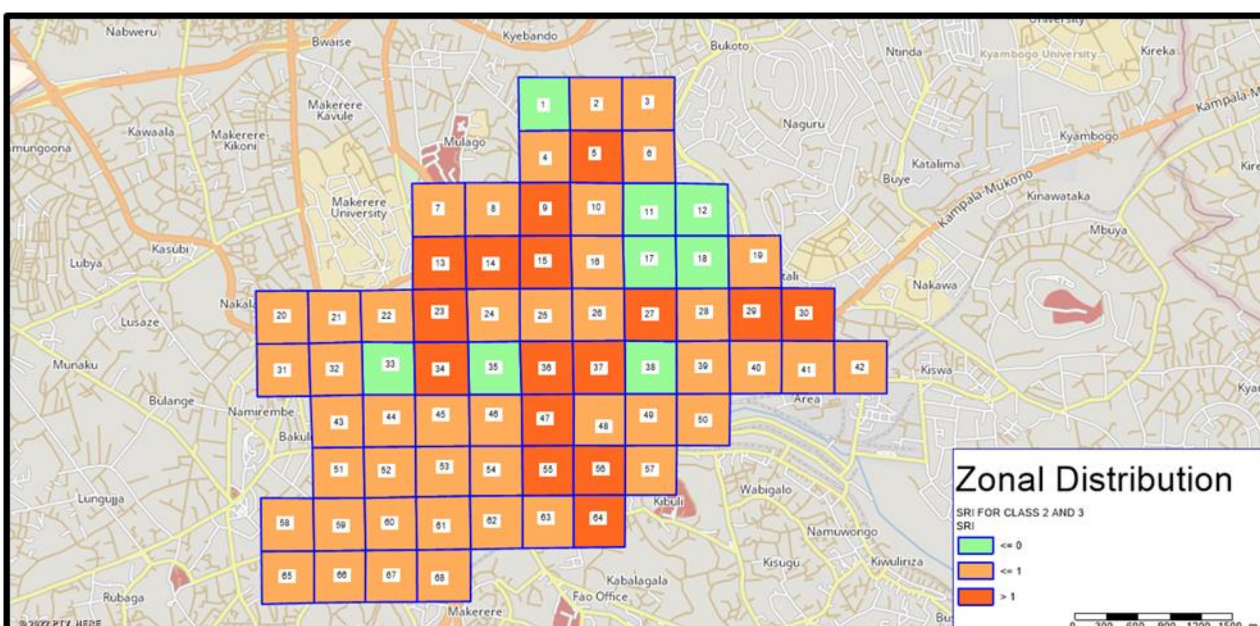

Figure 5- 5: Congestion intensities for only arterials

The second case changed the dynamics of the previously obtained results in case one. It indicated many more zones with high congestion than previously observed in case one. This clearly illustrates a reasonable congestion distribution in the CBD. In the inner most region, there is high congestion. At the periphery of the CBD, high congestion is experienced in all directions apart from the west end. The proportion of congestion intensities for only the arterials is shown in Figure 5-6.

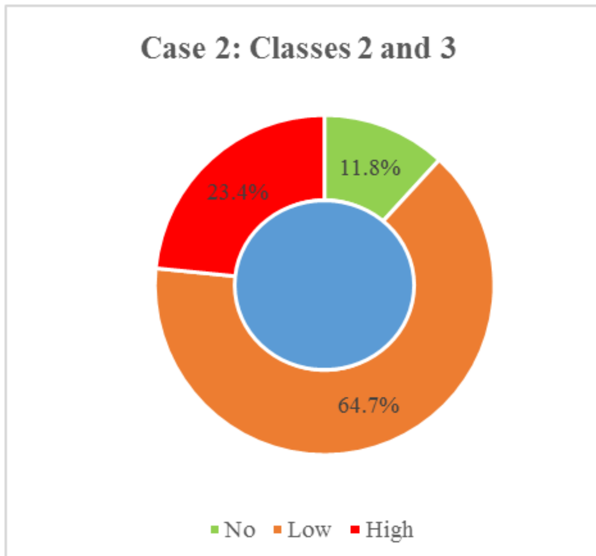

Figure 5- 6: Proportion of congestion intensities for only arterials

5.1.3 Discussion of Results

To identify congestion areas, this study presented two approaches, link and zonal analysis. The link analysis illustrated the congestion intensities with SRI as the congestion measure on every link of the road segment. The zonal analysis aggregated the SRI of the links in a zone.

For the link analysis, the negative values indicated that the off-peak speed was less than the morning peak speed, which is impossible realistically. Therefore, the study considered such results as outliers. Most class four links presented an SRI of zero, implying no congestion because these were collectors, indicating that the off-peak speed was the same as the peak hour speed. This is representative because class four links carry low volumes, which cannot reduce travel speeds during peak hours.

The class two and three links reported having high SRI, which shows the congestion levels of such links due to high traffic volumes on some road links. In contrast, the low SRI values indicate less congestion during the morning peak.

It can be observed in Figure 5-1 how the congestion was distributed along the major arterials into the CBD, and on the outskirts of the boundaries and the inner CBD. Most other areas in the CBD recorded low congestion. Therefore, such links provide indications for where to improve in the transport network.

This study considered two cases in the zonal analysis. The first case reflected the congestion zones for all road classes, that is, class two (major arterials), class three (minor arterials), and class four (collectors). The second case revealed the congestion intensities for only arterials classes two and three. The negative values reported for link roads, although referred to as outliers, were used in calculating the average SRI for the zones.

In the first case of all road classes, most zones indicated an SRI value of one, insinuating low congestion. Only one zone was reported with an index of two, implying highly congested, as illustrated in Figure 5- 2. However, this didn't resonate with the current state of the roads during that time. The class four links in zones reported with value zero, shrouded the actual congestion state in the zones. Class four links underestimated the extent of congestion in the zones after aggregation. In order to reduce the effect of class four roads reported to experience no congestion, the second case of only arterials was considered. Therefore this study incorporated the distinction for better results.

The second case of only classes two and three reflected higher congestion zones because it included only roads with high traffic volumes minus the collectors. The high congestion zones were indicative of the true status on the ground based on real-life experience of the areas. The high congestion zones also formed a stream of connection because of a major arterial traversing across them. These factors also rendered the results reliable. In this case, the zones reported with no congestion did not possess any major or minor arterials.

Generally, this study noted that the outskirts and the innermost areas in the CBD experienced high congestion. The outskirt areas contain the major roads carrying a lot of traffic volumes towards the CBD. For instance, in the north west of Kampala, is Bombo Road and in the north east is Jinja Road, both of which are major arterials.

In summary, this step of identifying the congestion zones/segments in an area could be a way of realizing the FCD model as the strategic planning tool of a given transport body. This is because the method presented here enables the identification of areas that need prioritisation in terms of allocating resources to provide for an efficient transport system, thereby achieving the objectives and goals of the transport body. Since the SRI could only identify the classification of zones into no, low and high congestion zones, a ranking measure was vital for prioritisation.

5.3 Prioritisation of zones

For the second objective of prioritising the congestion zones according to road class, this study employed the delay rate as a congestion measure. The delay rate was calculated using the travel time data obtained from Google API. This study utilised this measure because it takes into consideration the effect of link length. The purpose of this was to rank the links and zones to depict the highly congested areas.

- **Link analysis**

This study used the delay rate calculated from travel time to emphasize the congestion experienced on the corresponding road segment by speed, as illustrated in the SRI calculation. Ter Huurne and Andersen (2014) assert that travel rate is perceived by travellers when the speeds reduce by 60 – 70% of free flow speed. This cannot be calculated directly from commercial FCD (Bruwer and Andersen, 2022). However, the delay rate used in this approach was for ranking the link segments. Therefore, the acceptable travel rate was calculated using off peak travel times. The travel speed at off peak times would be considered the acceptable speed at any given time, while keeping other factors constant. In addition, this measure demonstrated the waiting time on the link per km. The calculation was as below:

$$\boldsymbol{Delay\,rate\ = TR_A - TR_{AC}}$$

TR_A = Actual travel rate (min/km) – morning peak

TR_{AC} = Accepted travel rate (min/km) – midnight off-peak

$$\boldsymbol{TR = {}^{T_t}/_{L_s}}$$

T_t = Travel time (min)

L_s = Segment length (km)

Table 5-6 below shows the results of the delay rate for each link.

Table 5- 6: The delay rate on each link

From Node	To Node	Type No	Name	Length (m)	AM peak Travel time(min)	Off peak Travel Time(min)	AM Peak Speed (Km/hr)	Off Peak Speed (Km/hr)	Road Class	Actual Travel Rate (min/km)	Acceptable Travel Rate (min/km)	Delay Rate
94834	38809	30	Kampala Road	33	3	2	39.67	59.50	Class 2	91	61	30
38809	45622	30	Kampala Road	19	2	1	34.84	69.67	Class 2	105	53	53
45622	7558	30	Kampala Road	86	8	7	38.48	43.98	Class 2	93	81	12
7558	38806	30	Bombo Road	12	1	1	42.95	42.95	Class 2	83	83	0
38806	294963	30	Bombo Road	165	28	19	21.27	31.35	Class 2	170	115	55
38806	38807	39		37	3	3	43.89	43.89	Class 2	81	81	0
87068	87069	30	Bombo Road	18	2	1	32.15	64.31	Class 2	111	56	56
87070	87071	30	Bombo Road	18	2	1	33.10	66.20	Class 2	111	56	56
38845	38846	60		19	2	2	34.54	34.54	Class 4	105	105	0
48024	7825	40	Kyagwe Road	92	8	7	41.54	47.48	Class 3	87	76	11
7825	48024	40	Kyagwe Road	92	8	7	41.54	47.48	Class 3	87	76	11
7825	4919	40	Kyagwe Road	51	4	4	45.82	45.82	Class 3	78	78	0
4919	7825	40	Kyagwe Road	51	5	4	36.66	45.82	Class 3	98	78	20
4919	405508	40	Kyagwe Road	95	8	7	42.80	48.91	Class 3	84	74	11

All links presented the delay rate in the range of 0 -133min/km. There were only fifteen links that presented negative values. Most class four roads' links presented zero value. Bombo Road recorded the link with the highest delay rate of 133min/km. This insinuates the time lost on that link is more than two hours per kilometer.

- **Zonal analysis**

Using the link data which was transferred into Microsoft Excel when identifying the congestion zones discussed in section 5.2, the zonal delay rate was also calculated. This analysis involved two cases; case one for all road classes and case two for only arterials. Examples of the results of the zonal delay rate for case one are shown in Table 5-7. Table 5-8 illustrates the zonal delay rate ranking for all road classes.

Table 5- 7: Zonal delay rate analysis for all classes

Zone 14												
From Node	To Node	Type No	Name	Length (m)	AM peak Travel time(min)	Off peak Travel Time(min)	AM Peak Speed (Km/hr)	Off Peak Speed (Km/hr)	Road Class	Actual Travel Rate (min/km)	Acceptable Travel Rate (min/km)	Delay Rate (min/km)
148659	3363	30	Yusuf Lule Road	41	4	3	36.57	48.76	Class 2	98	73	24
3363	6731	30	Yusuf Lule Road	174	16	12	39.37	52.49	Class 2	92	69	23
6731	410233	30	Yusuf Lule Road	55	5	4	39.32	49.14	Class 2	91	73	18
410233	46170	30	Yusuf Lule Road	133	11	11	43.98	43.98	Class 2	83	83	0
46170	148711	30	Yusuf Lule Road	18	2	1	31.95	63.89	Class 2	111	56	56
148711	3364	30	Yusuf Lule Road	233	19	15	44.14	55.91	Class 2	82	64	17
3365	148712	30	Yusuf Lule Road	232	21	16	39.53	51.88	Class 2	91	69	22
148712	3348	30	Yusuf Lule Road	128	12	10	38.45	46.14	Class 2	94	78	16
3348	6732	30	Yusuf Lule Road	76	7	6	39.32	45.88	Class 2	92	79	13
6732	3362	30	Yusuf Lule Road	175	19	14	33.63	45.64	Class 2	109	80	29
3362	148660	30	Yusuf Lule Road	40	3	3	47.70	47.70	Class 2	75	75	0
148659	148660	39		13	1	1	45.89	45.89	Class 2	77	77	0
148660	148659	39		13	1	1	45.89	45.89	Class 2	77	77	0
3362	3363	39		13	1	1	47.34	47.34	Class 2	77	77	0
3363	3362	39		13	1	1	47.34	47.34	Class 2	77	77	0
6731	6732	39		12	1	1	44.50	44.50	Class 2	83	83	0
6732	6731	39		12	1	1	44.50	44.50	Class 2	83	83	0
148711	148712	75		14	1	1	50.11	50.11	Class 4	71	71	0
148712	148711	75		14	1	1	50.11	50.11	Class 4	71	71	0
3361	3360	70	Kitante Close	415	42	37	35.57	40.37	Class 4	101	89	12
3360	3361	70	Kitante Close	415	42	37	35.57	40.37	Class 4	101	89	12
3360	410233	70	Kitante Close	29	3	3	34.88	34.88	Class 4	103	103	0
410233	3360	70	Kitante Close	29	3	3	34.88	34.88	Class 4	103	103	0
73273	46170	70	Kitante Lane	222	24	22	33.26	36.29	Class 4	108	99	9
46170	73273	70	Kitante Lane	222	23	22	34.71	36.29	Class 4	104	99	5
3349	3348	70		53	6	5	31.91	38.29	Class 4	113	94	19
3348	3349	70		53	6	6	31.91	31.91	Class 4	113	113	0
4561	3349	70	Lourdel Road	425	46	44	33.23	34.74	Class 4	108	104	5
3349	4561	70	Lourdel Road	425	42	41	36.40	37.29	Class 4	99	96	2
3349	42102	70	Muwafu Road	268	26	24	37.08	40.17	Class 4	97	90	7
42102	3349	70	Muwafu Road	268	28	28	34.43	34.43	Class 4	104	104	0
313	42102	40	Kyadondo Road	529	82	66	23.13	28.74	Class 3	155	125	30
42102	313	40	Kyadondo Road	529	72	59	26.34	32.15	Class 3	136	112	25
42102	405339	40	Kyadondo Road	17	2	1	30.14	60.28	Class 3	118	59	59
405339	42102	40	Kyadondo Road	17	2	1	30.14	60.28	Class 3	118	59	59
42104	42103	50	Akii Bua Road	554	59	54	33.78	36.91	Class 4	106	97	9
42103	42104	50	Akii Bua Road	554	62	57	32.14	34.96	Class 4	112	103	9
									AVERAGE			13

Table 5- 8: Results of the delay rate rankings for all classes

Zone	Delay Rate (min/km)	Ranking	Zone	Delay Rate (min/km)	Ranking	Zone	Delay Rate (min/km)	Ranking
30	21	1	51	9	23	26	7	38
13	18	2	63	9	23	43	7	38
34	15	3	65	9	23	44	7	38
45	15	3	4	8	27	46	7	38
29	14	5	9	8	27	58	7	38
41	14	5	20	8	27	60	7	38
49	14	5	27	8	27	64	7	38
14	13	8	32	8	27	67	7	38
57	13	8	37	8	27	68	7	38
47	12	10	40	8	27	2	6	56
23	11	11	42	8	27	6	6	56
50	11	11	48	8	27	8	6	56
66	11	11	52	8	27	18	6	56
17	10	14	59	8	27	24	6	56
25	10	14	3	7	38	1	5	61
28	10	14	5	7	38	10	5	61
53	10	14	7	7	38	12	5	61
54	10	14	11	7	38	33	5	61
55	10	14	15	7	38	36	5	61
56	10	14	16	7	38	38	5	61
61	10	14	19	7	38	35	4	67
62	10	14	21	7	38	39	4	67
31	9	23	22	7	38			

The zones presented the delay rate in the range of 4 - 21min/km. Zone 30 ranked number one, making it the most highly congested zone with a delay rate of 21min/km.

The results of the zonal delay rate calculation changed when case two was considered, involving only arterials, as shown in Table 5-9.

Table 5- 9: Zonal Delay rate for arterials only

Zone 14												
From Node	To Node	Type No	Name	Length (m)	AM peak Travel time(min)	Off peak Travel Time(min)	AM Peak Speed (Km/hr)	Off Peak Speed (Km/hr)	Road Class	Actual Travel Rate (min/km)	Acceptable Travel Rate (min/km)	Delay Rate (min/km)
148659	3363	30	Yusuf Lule Road	41	4	3	36.57	48.76	Class 2	98	73	24
3363	6731	30	Yusuf Lule Road	174	16	12	39.37	52.49	Class 2	92	69	23
6731	410233	30	Yusuf Lule Road	55	5	4	39.32	49.14	Class 2	91	73	18
410233	46170	30	Yusuf Lule Road	133	11	11	43.98	43.98	Class 2	83	83	0
46170	148711	30	Yusuf Lule Road	18	2	1	31.95	63.89	Class 2	111	56	56
148711	3364	30	Yusuf Lule Road	233	19	15	44.14	55.91	Class 2	82	64	17
3365	148712	30	Yusuf Lule Road	232	21	16	39.53	51.88	Class 2	91	69	22
148712	3348	30	Yusuf Lule Road	128	12	10	38.45	46.14	Class 2	94	78	16
3348	6732	30	Yusuf Lule Road	76	7	6	39.32	45.88	Class 2	92	79	13
6732	3362	30	Yusuf Lule Road	175	19	14	33.63	45.64	Class 2	109	80	29
3362	148660	30	Yusuf Lule Road	40	3	3	47.70	47.70	Class 2	75	75	0
313	42102	40	Kyadondo Road	529	82	66	23.13	28.74	Class 3	155	125	30
42102	313	40	Kyadondo Road	529	72	59	26.34	32.15	Class 3	136	112	25
42102	405339	40	Kyadondo Road	17	2	1	30.14	60.28	Class 3	118	59	59
405339	42102	40	Kyadondo Road	17	2	1	30.14	60.28	Class 3	118	59	59
									AVERAGE			26

The ranking of results for case two (only arterials) are shown in Table 5-10.

Table 5- 10: The results of the zonal delay rate ranking for only arterials

Zone	Delay Rate (min/km)	Ranking	Zone	Delay Rate (min/km)	Ranking	Zone	Delay Rate (min/km)	Ranking
55	35	1	2	13	24	63	10	24
13	31	2	16	13	24	8	9	25
14	26	3	26	13	24	22	9	25
30	21	4	31	13	24	24	9	25
15	20	5	42	13	24	58	9	25
27	20	5	50	13	24	59	9	25
29	20	5	60	13	24	3	8	30
5	19	8	62	13	24	19	8	30
34	19	8	65	13	24	43	8	30
54	19	8	4	12	33	39	7	33
9	18	11	25	12	33	44	7	33
23	18	11	40	12	33	68	7	33
37	18	11	46	12	33	10	5	36
41	18	11	67	12	33	57	5	36
45	18	11	6	11	38	35	3	38
64	18	11	32	11	38	1	0	39
52	17	17	48	11	38	11	0	39
20	16	18	51	11	38	12	0	39
47	16	18	61	11	38	17	0	39
28	15	20	66	11	38	18	0	39
49	15	20	7	10	44	33	0	39
36	14	22	21	10	44	38	0	39
56	14	22	53	10	44			

The zones had a delay rate in the range of 0 - 35min/km. Zone 55 ranked number one, the most highly congested zone with a delay rate of 35min/km.

5.3.1 Discussion of results

After identifying the congestion areas using the SRI measure, the delay rate congestion measure was used to rank the zones and segments. The delay rate ranged from 0-133 min/km for all links in the study area, except fifteen links that presented a negative value. Most class four links maintained a delay rate of 0min/km. This is realistic because class four links generally carry low volumes, and their travel times can therefore remain constant. The negative values indicated that the off-peak travel time was greater than the peak travel time, which is not realistically possible. Therefore, such results could be considered outliers. However, they were considered in calculating the zone's average delay rate.

In the link analysis, a link on Bombo Road presented a high delay rate of 133min/km. This link is located on the northwest periphery of Kampala's CBD. The road is a major arterial that carries a lot of traffic to the city from the northern suburbs. This explains the high delay rate experienced in that area.

In the first case of zonal analysis, where all road classes were considered, the delay rate was 4-21min/km. In the second case, for only arterials, the delay rate was 0-35min/km. The second case conveyed different ranking from case one. This was ascribed to the class four links whose delay rates were low, hindering the accuracy of the exact delay rates in zones.

According to the zonal analysis, in the first case of all road classes, the range obtained indicated less waiting time in different zones in the study area. The results indicate that commuters usually wait for less than 30 minutes per kilometre during the morning peak. However, when only classes two and three were considered for the analysis, the delay rate increased drastically in some areas, registering the delay rate of more than 30 minutes per kilometre. This substantial change demonstrated the impact of minor and major arterials in the road network when experiencing high traffic volumes. The zones that indicated zero delay rate were those only composed of class four links. Hence, no congestion was reported for such zones in case two.

Case one ranked zone 30 and 13 in the first and second positions, whereas case two recorded zone 55 and 13 in that order. The common zone for both cases is in need of attention to address the congestion levels. The recorded link with the highest delay rate was also situated in zone 13, which ranked second in both cases of the zonal analysis. An investigation of the causes of congestion in zone 13 is discussed in the next section 5.4.

Zone 30 which ranked first in case one, was number four in case two. This indicates that its congestion level is also dire. This zone recorded 21 minutes per km delay rate in both cases, which implies that it does not contain any class four links; it also maintained the same delay rate with only arterials. On the other hand, zone 55, which ranked first in case two, was in position fourteen in case one. It recorded a delay rate of 35 minutes per kilometre in case two and 10 minutes per km in case one. This implies that it contained many links of class four, which presented a delay rate of zero, so the delay rate was low on aggregation. All these need to be considered when assessing the causes of congestion in each area.

In summary, ranking the zones according to their delay rate can be a tool for prioritizing projects to enable transport institutions in ensuring an efficient road network that is accessible, safe, and reliable. In addition, the prioritisation step in the FCD model lists the congestion areas according to their effects on travel time that results into traffic congestion. The causes of congestion in the highly ranked zones was further assessed using case two, as discussed in the next section. This study considered only two zones due to time constraints.

5.4 Causes of traffic congestion

This study conducted a desktop study to ascertain the causes of traffic congestion in the most highly ranked zones. Only two zones were ultimately considered for the assessment due to time constraints. Firstly, Google Map was used to locate the relevant features in the zones and adjacent areas. As a result, the road network and traffic control systems utilised in the area were easily identifiable.

Personal experience was also used to enhance the study. I have lived in Kampala for more than ten years of my adult life. This approach helped confirm that the highly-ranked zones were realistic and representative of the actual congestion intensities. A site study would have best assessed the causes of traffic congestion to identify traffic behaviours and the road network conclusively. However, the desktop study was adopted due to COVID-19 pandemic that severely restricted travels.

An alternative approach was hiring a personnel to take photographs of the particular sections under investigation. The interpretation of the photographs formed part of the desktop study. In addition, the photos provided additional insight into the present status of the road during the morning peak of 7 a.m. This glimpse of the conditions of the road section enabled the composition of more detailed suggestions about the possible causes of traffic congestion in the relevant areas.

- **Zone 55**

This zone ranked number one in case two, where the study considered class two and three roads, and number fourteen in case one for all road classes. The reason is that zone contains many links on class four roads with low traffic volumes, hence lower delay rates, which tend to reduce the overall delay rate for the zone. Since the study eliminated class four in case two, the actual situation of the zone was reflected. The only class two road in the zone was Kampala/Jinja Road, a dual carriageway. The OSM indicated it as Kampala Road, and Google Maps as Kampala/Jinja road; however, it is Jinja Road on the ground. Therefore all the naming on the sources were correct.

The location of Kampala/Jinja Road is in the middle of the city. It has five junctions running to and from the main road. The zone recorded a delay rate of 35minutes per kilometre. The zone's boundaries are shown in Figure 5-7. The zone includes some of the features of the zones and the road network.

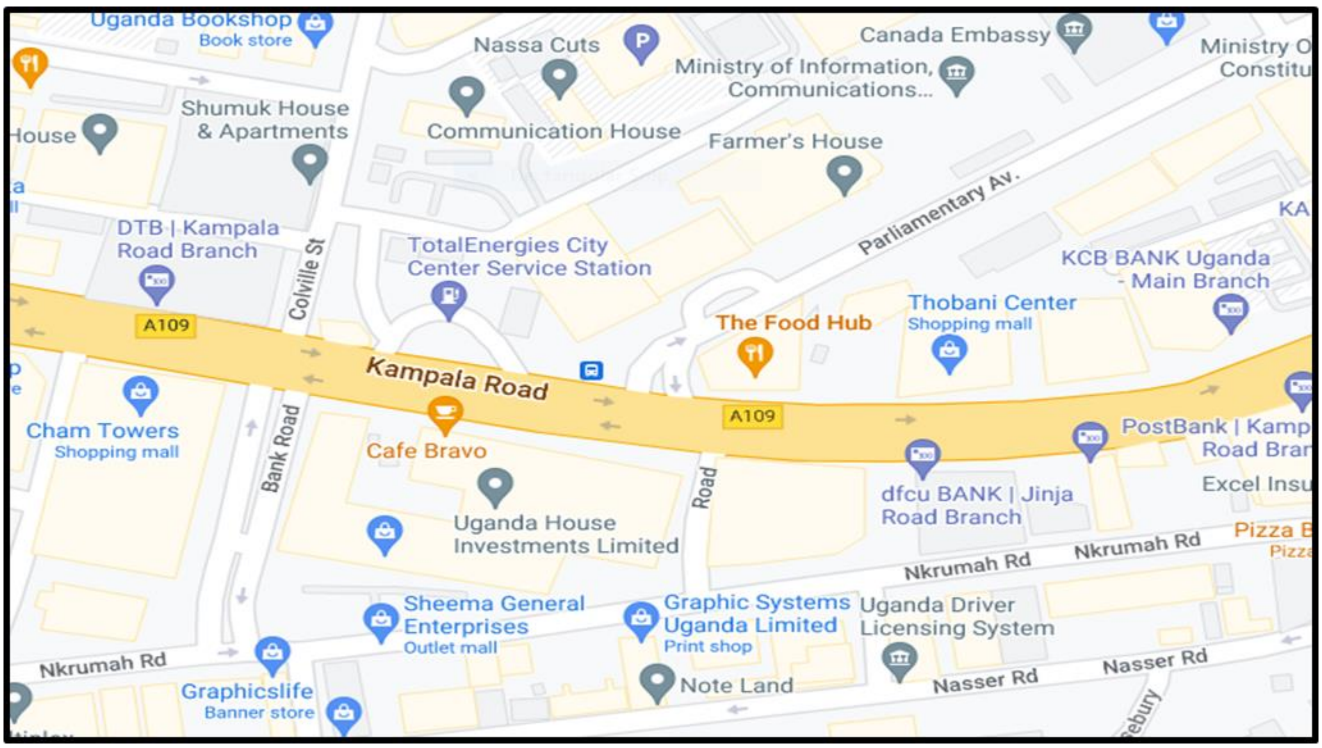

Figure 5- 7: Boundaries of zone 55 and road network

The preceding zone 54 includes a major T intersection of Kampala and Entebbe Road, which both carry high volumes; this explains the high delay rate in zone 55. Zone 54's boundaries are shown in Figure 5-8 including some of its features and the road network.

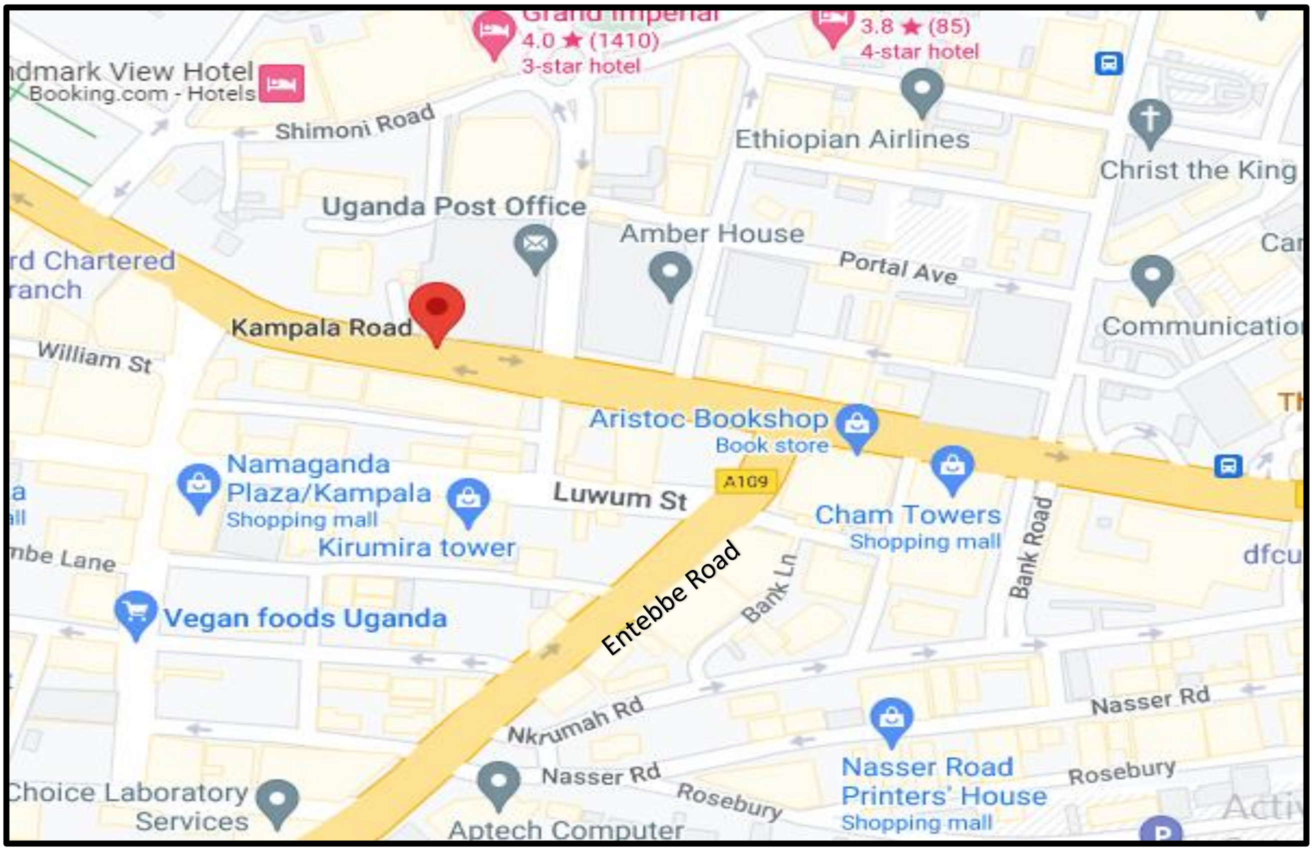

Figure 5- 8: Zone 54 with a T intersection adjacent to Zone 55.

The adjoining roads to Kampala/Jinja road in zone 55 include: Colville Street, Parliament Avenue, Bussel Road, Bank Boad, and an unnamed road. The other roads in the zone not connected to Kampala/Jinja Road are Nkrumah Road, Nasser Road, Kimathi Road, and Portal Road. There are two junctions in the westbound direction on the Kampala/Jinja Road adjoining Colville Street and Parliamentary Avenue. Also, on the eastbound to the CBD, there are three junctions with the other roads. All the junctions merge with or have branching areas on Kampala Road in the section. In addition, all the intersections are uncontrolled. There are no stop signs or traffic lights. All these factors contribute to the delays experienced in the zone. A schematic drawing is shown in Figure 5-9 of the conditions in the area.

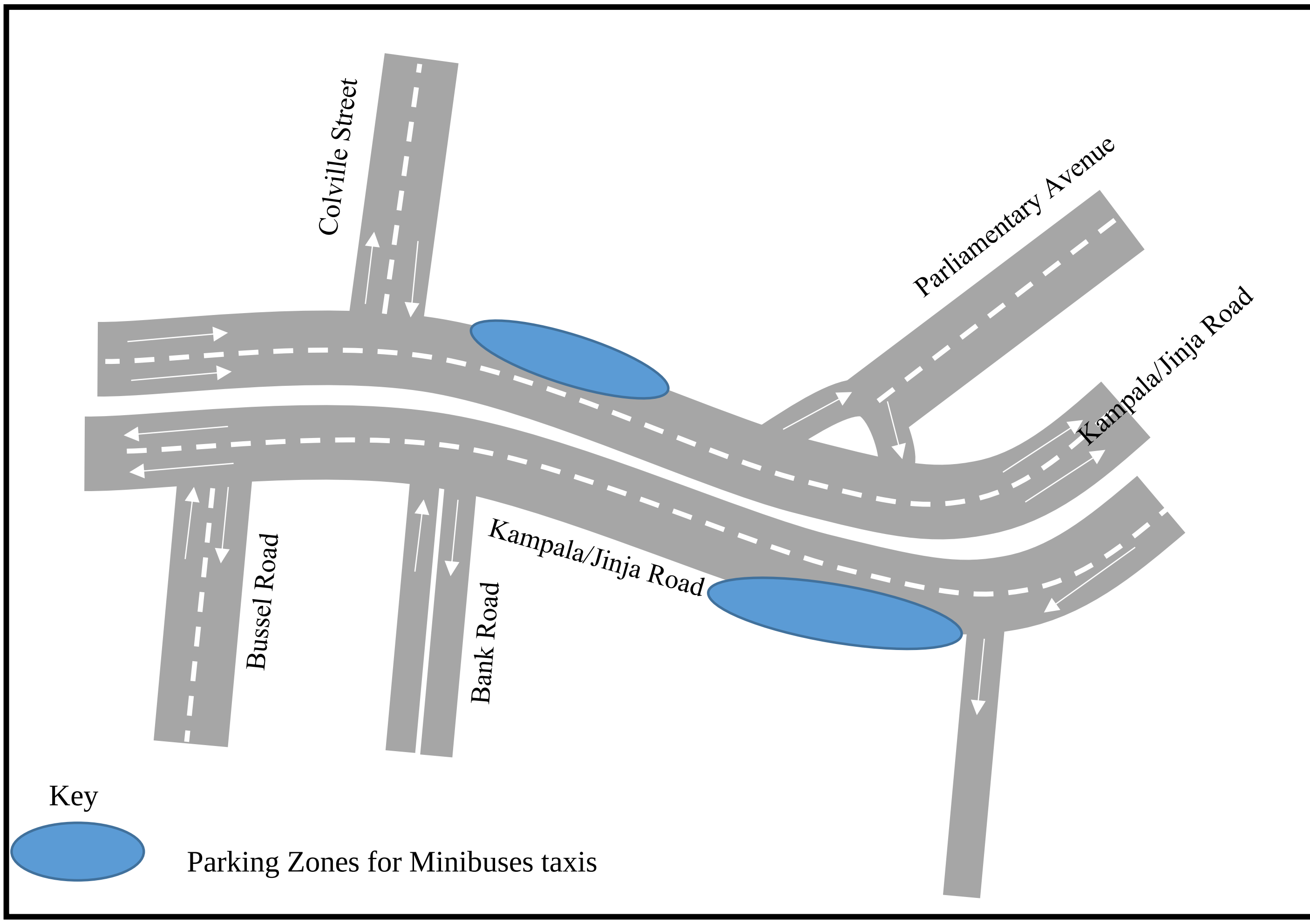

Figure 5- 9: Schematic drawing of Kampala/Jinja road area in Zone 55

Zone 55 includes the main routes into the upper CBD, where there are corporate offices and several government ministries. The zone also provides access to the lower CBD, where there are shopping arcades and taxi ranks. There is also an high-rise buildings area, with various corporate business offices, as seen on Google Maps. These indicate the possibility of workers possessing cars. Also, this zone includes a section of Parliamentary Avenue, which leads straight to the Ugandan Parliament. Therefore, it can be deduced that high traffic volumes are experienced in the zone.

In my personal experience as a road user in Kampala, bus stops in either direction of Kampala/Jinja road are not clearly demarcated. As a result, minibuses for boarding and disembarking passengers park on the main road as shown in Figure 5-9. This causes a bottleneck where the two lanes become one lane. Another constraining factor is the movement of bodabodas. These are numerous during the morning peak, implying low speeds for vehicle traffic due to sharing a road that is already narrow.

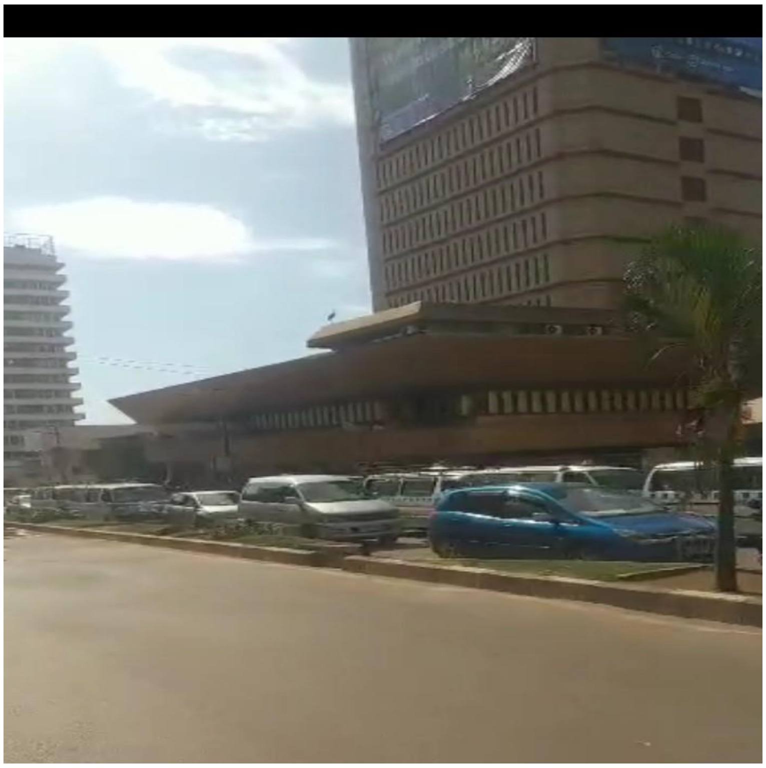

Figure 5- 10: Traffic congestion along Kampala/Jinja road around Bussel Road

Figure 5- 11: The Bodabodas mix in with vehicles along Kampala/Jinja Road

Besides the uncontrolled junctions along Kampala/Jinja Road in zone 55, the concentration of businesses also causes traffic congestion, as observed in Figure 5-7. The capacity of the road is often exceeded, which increases the waiting time in the zone. The bottleneck caused in the network constricts traffic flow, reducing the throughput at the junctions. All these causes of congestion in the zone are related; mitigating a particular cause may help to reduce the waiting time in the zone.

- **Zone 13**

This zone is situated in a very busy area with an intersection with approaches of class two (major arterials). Bombo Road serves as the major arterial from the northwest of Kampala, emanating from Kawempe, one of the divisions of the city, as seen on the map of Kampala. It is the main route into the city from the suburbs of the Kawempe Division. The area includes Wandegeya Market and is also adjacent to Makerere University. There are also many businesses, banks, and hotels in the area. Bombo Road and Makerere Hill Road serve Makerere University both either sides; this points to the expected traffic congestion during the morning peak. For Hajji Musa Kasule Road, its traffic is served by Kira Road, a major arterial in the northeast of Kampala. This study observed that several of the roads in zone 13 are major arterials which carry high traffic volumes and based on their classes and physical appearances. The features of zone 13 are elaborated in the map from Google Maps below.

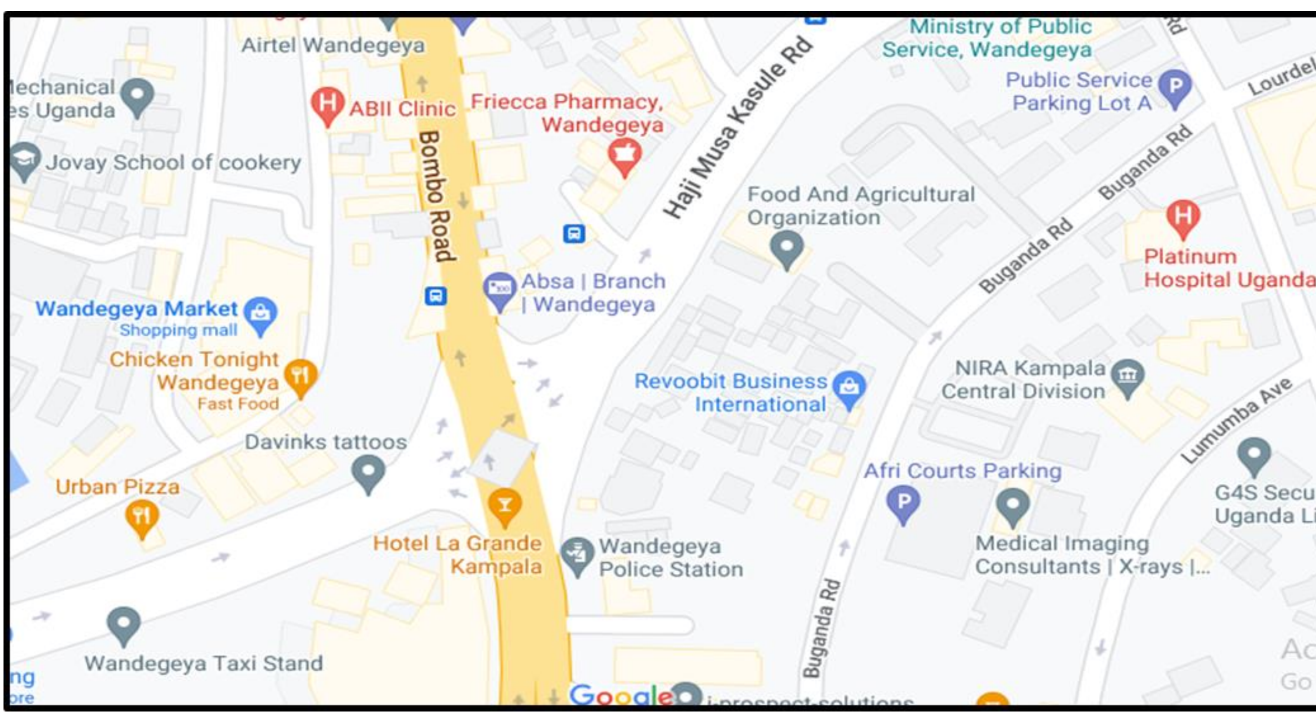

Figure 5- 12: Features of zone 13 from Google Maps

Zone 13 contains other class three roads regarded as minor arterials served by the major arterials. Minor arterials help reduce traffic on the major arterials to access the city centre. However, the minor arterials have considerable delay rates, although the rates are below the average of 31 minutes per kilometre. The minor arterials include; Lumumba Avenue, Kyaddondo Road, Nakasero Hill Road, and Buganda Road. These are alternative routes when avoiding the main road heading into the city centre.

Zone 13 includes a four-way intersection with a signalised traffic control system. The intersection consists of Bombo Road in northbound (NB) and southbound (SB) directions, Makerere Hill Road in the westbound (WB), and Hajji Musa Kasule road in the eastbound (EB) direction. The schematic layout of the intersection is shown below in Figure 5-13. This is also the section that records the link with the highest delay rate. This study focussed on this particular section due to its propagation of traffic congestion to other zones.

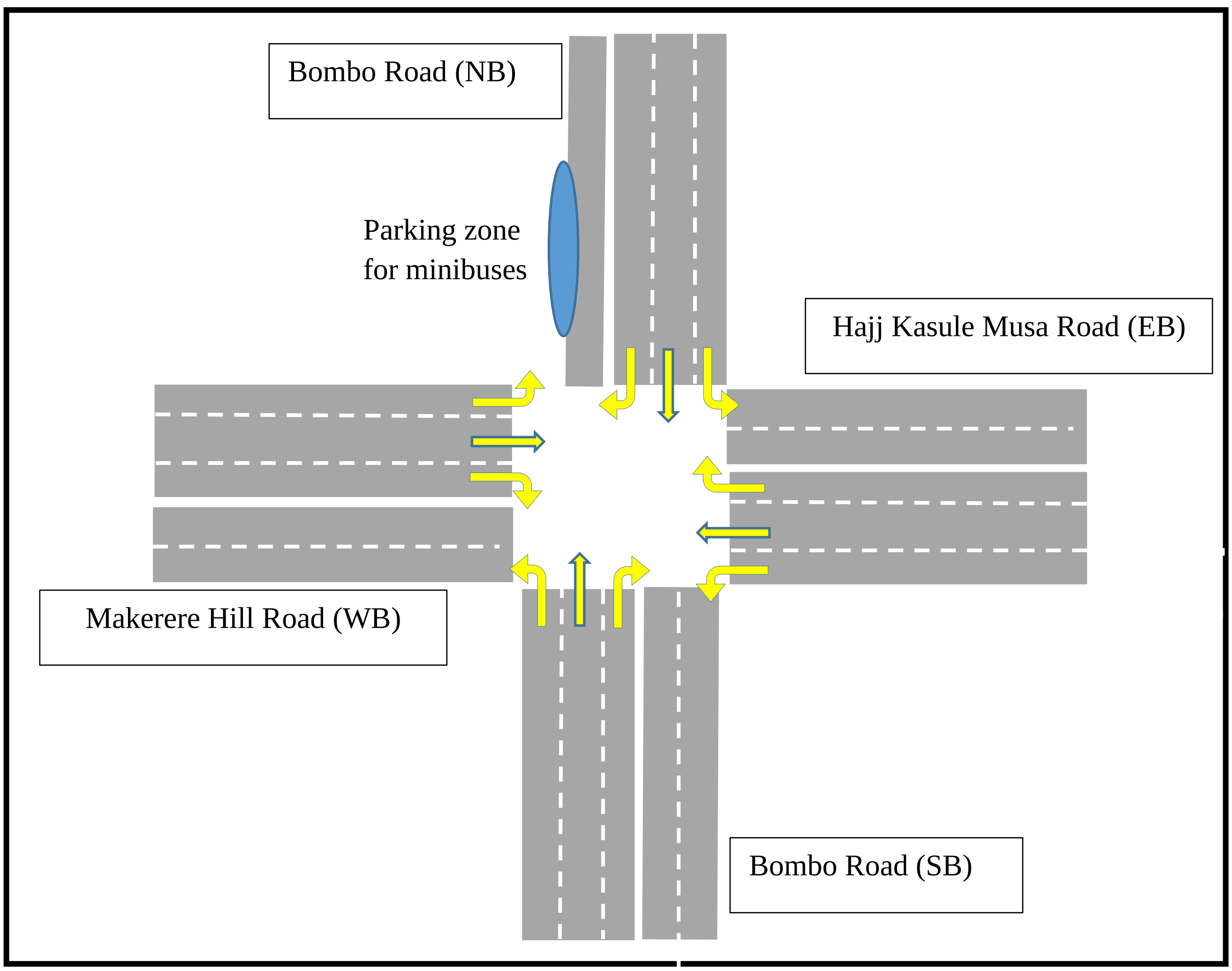

Figure 5- 13: Schematic layout of the intersection in zone 13

On the ground, the intersection is often controlled by traffic officers during peak hours, despite the existence of traffic lights. This is because the traffic lights have fixed time signals (as opposed to sensors). Because of this, during peak hours they are not efficient, which explains the need for intervention by traffic officers.

There is also a problem with bodabodas in Kampala, as mentioned in the discussion of zone 55. Bodabodas appear at the front of lanes at the intersection. In other words, when the traffic on either side begins to move, they cut to the front of the queue and move first. This tends to reduce the throughput of vehicles at the intersection, contributing to the long waiting times. There is also a single lane in the northbound direction on Bombo Road, embedded with parking slots on the main road. This contributes to long waiting times when there are no movements in the lane due to slow speeds.

On the 12th of August 2022, when a hired personnel helped to take pictures at this intersection, the traffic lights were not working. The traffic officers directed the traffic at the intersection. If this is regularly the case, the relevant authority needs to implement measures to mitigate the congestion in this area by ensuring that the traffic lights work all the time throughout the day to ensure the smooth flow of traffic. Below are a selection of photographs showing the conditions of the area in the morning peak hour of 7 a.m.

Figure 5- 14: Photo showing bodabodas at the front of the approach lane on Makerere Hill Road

Figure 5- 15: Photo showing the non-functioning traffic lights and traffic police

Figure 5- 16: Photo showing the congestion and vehicle composition on Bombo Road (NB)

The intersection in zone 13 serving major arterials explains the high congestion in the area. Also, the surrounding environment contributes to the lower speeds that increase the travel time in the surrounding zones. The traffic officers controlling the throughput of the vehicles in the intersection may be prone to bias due to human nature, which leads to a much longer waiting time than the fixed time signals.

The causes of congestion in this zone are all interrelated; the area's density and major arterial roads contribute to lower speeds with high volumes; hence traffic congestion is inevitable. Besides these two factors, the bodabodas also impact the throughput. Suppose the traffic managers in the city could utilise the traffic signals already in place, and educate the road users about the importance of not ignoring the traffic lights for preventing blockages in the intersections. These blockages lead to low throughput of vehicles at the intersection during green lights. Therefore, the factor of driver behaviours needs urgent attention.

In conclusion, a site visit was needed to study the areas. The desktop study could only discuss the available resources. However, the latter was sufficient, considering the situation and timing of the research study, during the COVID-19 pandemic. To improve the traffic flow in Kampala, the relevant traffic authorities need to pursue a thorough investigation to provide much-needed relief from congestion.

5.5 Mitigation measures

The last objective of this research study is to propose appropriate measures to alleviate congestion in highly congested areas of Kampala. The approach adopted to achieve this was simulation modelling. This modelling allows engineers and managers to evaluate the present conditions and suggest measures in an imitation environment. Due to the lack of traffic volumes for Kampala/Jinja road in zone 55, no modelling was performed for the zone. Instead, the study discussed possible mitigation measures from a theoretical point of view. Whereas for zone 13, the traffic volume data for Bombo Road, as explained in chapter 3 section 3.5.5, was available; therefore, this study conducted a scenario management for the zone. This section discussed the mitigation measures of traffic congestion for the zones studied. For zone 55, the study applied the knowledge from the literature review to suggest mitigation measures, and for zone 13, a simulation model was conducted.

5.5.1 Zone 55

The bus stops should be designated off the two lanes of Kampala/Jinja Road so that traffic does not constrict, leading to a bottleneck in the section. This measure could be a part of improving the existing infrastructure to alleviate traffic congestion. Also, since the locality of the road section is a busy area, the parking slots on the road could be relocated to less busy streets.

The merging traffic should have clear roadway markings to allow safe entry to the main road. Also, the vehicles on the main road should not be affected by the traffic merging by lowering their speeds. There are no road markings or stop signs at the junctions serving the main road. Therefore, drivers are not under any restriction to access the main road. Sufficient markings and signs contribute to the orderly movement of cars compared to when there are no markings or stop signs; these measures also help prevent accidents.

Besides road markings, the junction would be more effective with traffic lights. This could also enable the connection of Colville Street and Bussel Road to increase the accessibility of the area. The traffic lights would help to control traffic to at least a minimum level.

Zone 54, adjacent to the study zone also needs consideration. Although zone 54 recorded low congestion, it contains an intersection which may be part of the cause of high delay rates in zone 55, it is essential to consider it.

5.5.2 Zone 13

- **Procedure for Scenario Management in PTV VISSIM**

Scenario management in PTV VISSIM was conducted for only one zone ranked second; Zone 13. This was because the traffic data was only available for the major arterial of Bombo road. The data was obtained through an engineer at Uganda National Roads Authority (UNRA). The traffic data was, however, for roads beyond KCCA's jurisdiction. The data for the road section under analysis was therefore extrapolated. The availability of the annual average daily traffic (AADT) data enabled a smooth simulation analysis. The zone includes a signalised intersection which eased the analysis.

According to the results, zone 55 ranked the most highly congested in the Kampala CBD. However, it was not analysed using the scenario management tool in PTV VISSIM because no data was available for the roads in the zone.

- **Setting the base model**

The intersection in zone 55 was located using the network editor in PTV VISSIM 2022. The links at approximately 100m in all directions were allocated. The network objects, like connectors and reduced speed areas, were positioned at the intersection. The traffic composition was 50% private vehicles, 40% minibuses and 10% heavy goods vehicles (HGV). Figure 5-17 illustrates the road network and the network objects used.

Figure 5- 17: Intersection layout-base model

Traffic volumes were assigned through the vehicle inputs parameter according to the vehicle route attributes. The zone includes Bombo Road at the periphery of the CBD. The AADT data reported for Kampala-Kawempe Road (Bombo Road) was 4,453 vehicles per day.

Assumptions

This study assumed the design hourly volume (DHV) at 10% of AADT.

$$DHV = \frac{10}{100} * AADT$$

The design volume during peak hours was 445 vehicles per hour. Since the volume was for both directions, the study assumed the direction factor at 60% in the northbound (NB) direction on Bombo Road. The NB traffic heads to the CBD, and since the consideration was for the morning peak, this seemed realistic. From those distributed percentages, 20% of traffic took a left turn, 20% traffic took a right turn, and 60% of traffic volume was through traffic.

The other roads at the intersection were also class two, the same as Bombo Road. 50% of the peak traffic volume on Bombo Road was assumed as well as the peak traffic volume on Hajji Musa Kasule road-Eastbound direction (EB) and Makerere Hill road-Westbound (WB). These followed the distribution of 60% onto Bombo Road to CBD and 20% each in other directions.

Table 5- 11: Traffic distribution at Zone 13 intersection

Roads	Total Traffic	Direction	Traffic Volumes
Bombo Road (NB)	0.6*445 = 267	Through traffic	0.6*267 = 161
		Left turn	0.2*267 = 53
		Right turn	0.2*267 = 53
Bombo Road (SB)	0.4*445 = 178	Through traffic	0.6*178 = 106
		Left turn	0.2*178 = 36
		Right turn	0.2*178 = 36
Makerere Hill Road (WB)	0.5*445 = 223	Through traffic	0.2*223 = 45
		Left turn	0.2*223 = 45
		Right turn	0.6*224 = 133
Hajji Musa Kasule Road (EB)	0.5*445 = 222	Through traffic	0.2*223 = 45
		Left turn	0.6*222 = 134
		Right turn	0.2*222 = 45

Signal control system

The signal control data was set using the signal control dialog box. Since no data were available for the traffic signals in zone 13, this study assumed a fixed-time type of signalised intersection. The fixed-time followed a two-phase control system where a particular road permits all movements during the green light (TRB, 2000). The control system allocated 60 seconds per cycle time. Each direction was allocated a green light time of ten seconds with five seconds for interchange time. The signal heads were placed on the respective approaches. The simulation was run using the node evaluation. Finally, the results for the vehicle delay in the respective movements were obtained.

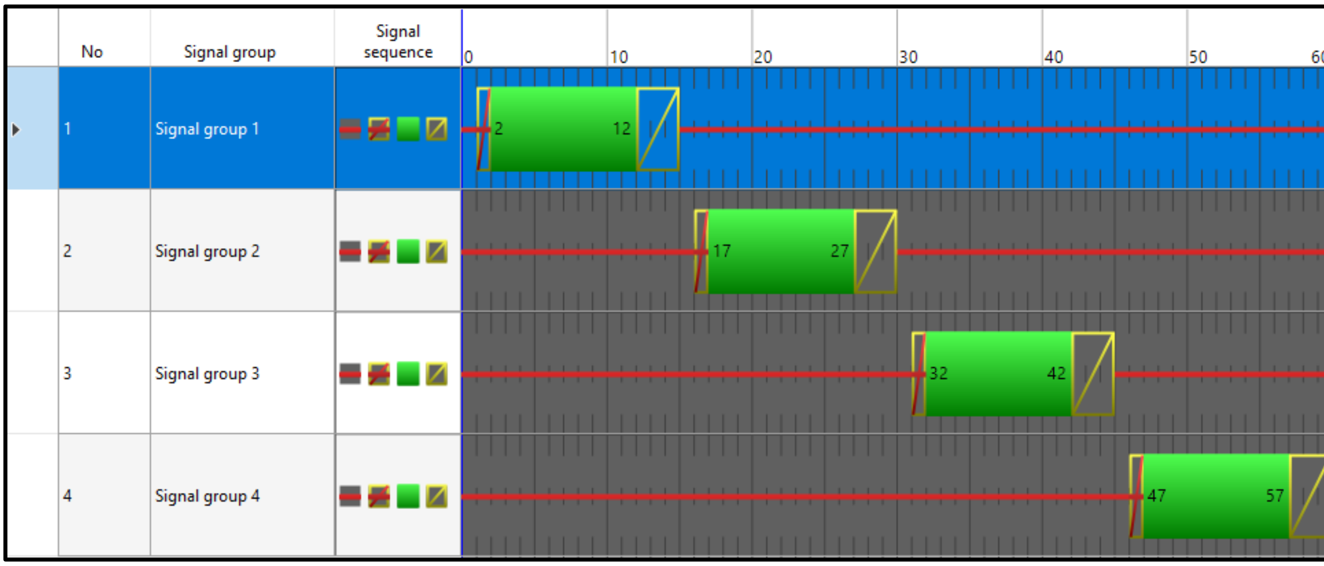

Figure 5- 18: Signal control system-base case

- **Setting scenario cases**

There are two different approaches to running scenario management in PTV VISSIM; implicit and constructive. The latter involves creating and editing modifications and then building scenarios from these modifications, whereas the former requires editing scenarios directly. There are a variety of cases such as:

- Geometry variants;
- Signalisation variants;
- Demand variants;
- Any combination of variants;
- Modifying any attributes of any object.

For this study, the approach adopted was the implicit method, where the scenarios are directly edited. The implicit approach was appropriate for this study because the number of scenarios considered for this case was few. Customarily, a constructive approach is recommendable where there are numerous modifications. The two modifications made and two scenarios executed were:

1. Modification one: adding a second lane along Bombo Road (NB) after the intersection (geometry variant).

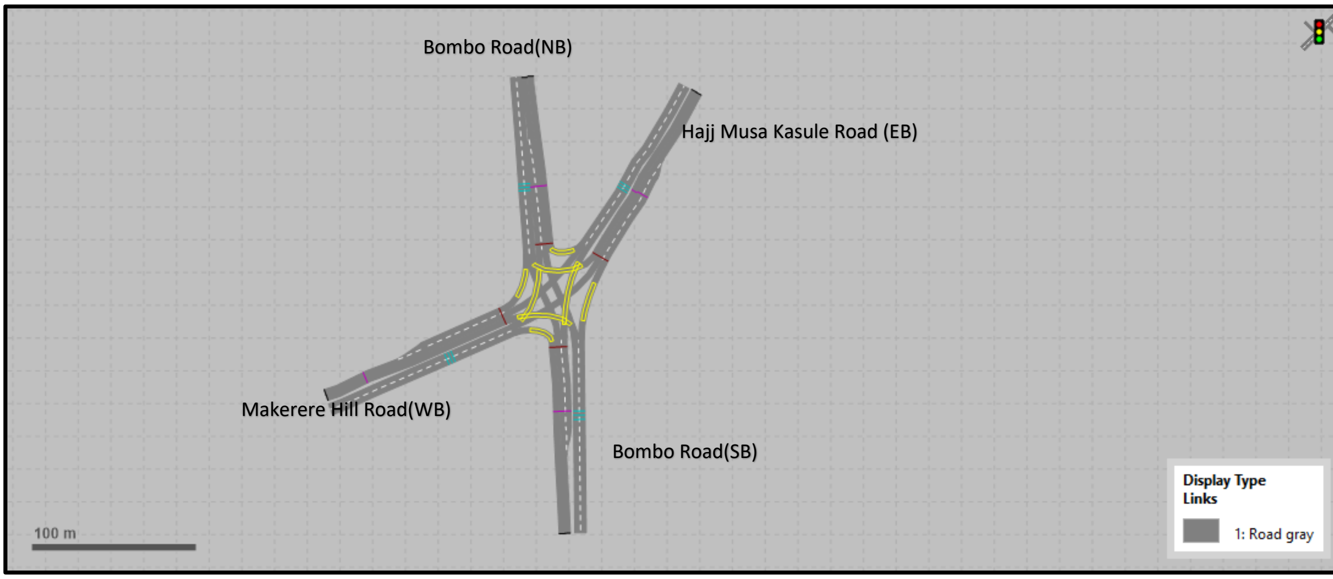

Figure 5- 19: Modification 1 - addition of lane

2. Modification two: altering the signal timing on Bombo Road by increasing the green light time to 15 seconds (signalisation variants)

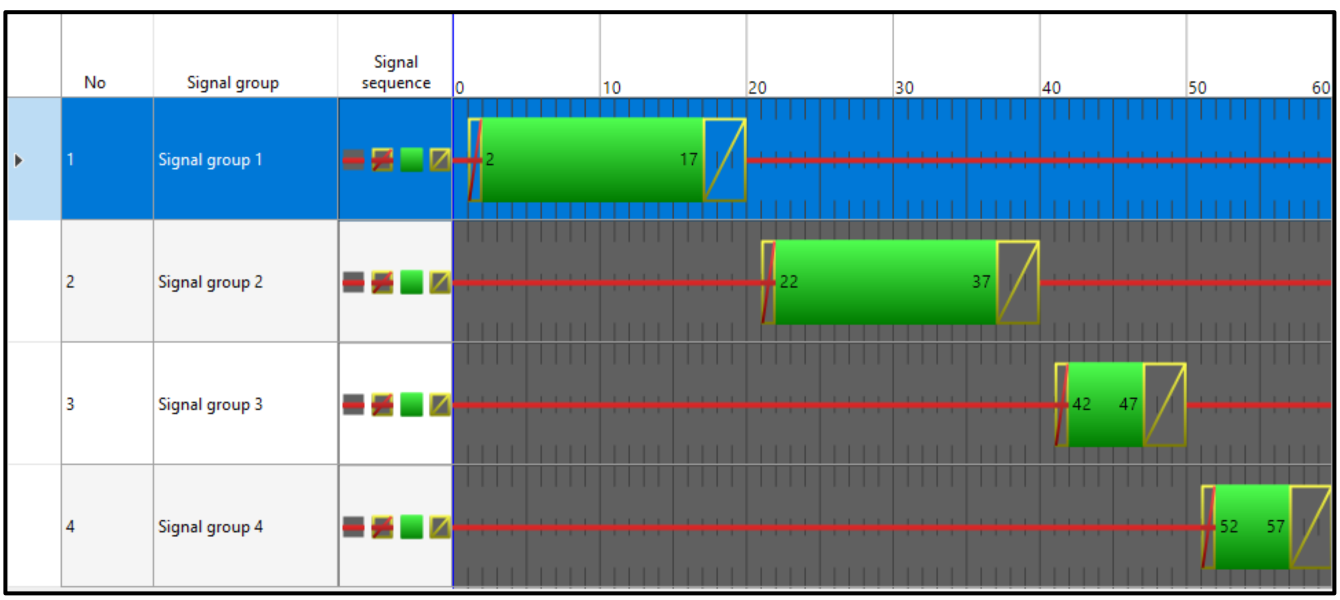

Figure 5- 20: Modification 2: signal control system

Simulation runs were performed with scenario one using the first modification and scenario two with both modifications one and two. The results for comparison were then obtained.

❖ **Results and discussion**

This study performed a simulation in PTV VISSIM on zone 13 with the available data. The data allowed for further assumptions of other traffic volumes on the approaches at the intersection in this zone. The base case was considered the current layout of the intersection. This base case was then compared to two more scenarios. For scenario one, adding a lane on the north of Bombo Road after the intersection, and scenario two combined the lane addition modification and the altered signal timings. The simulation results were obtained after aggregating three runs for each scenario case. The vehicle delays in seconds are shown in Table 5-12 below. The graphic representation shown in Figure 5-21 provided the basis for comparison and discussion.

Table 5- 12: Vehicle delay analysis on movement directions

Movement Directions	Vehicle Delays(seconds)			Remarks	
	Base Case	Scenario 1	Scenario 2	Comparison between Scenario 2 and Base Case (%)	
Makerere Hill Road (WB)- Bombo Road (SB)	25.5	25.5	62.6	145	↑
Makerere Hill Road (WB)- Bombo Road (NB)	19.8	19.8	24.5	24	↑
Makerere Hill Road (WB)- Hajji Musa Kasule Road (EB)	23.4	23.4	22.6	-3	↓
Bombo Road (SB) - Bombo Road (NB)	26.0	26.0	22.5	-14	↓
Bombo Road (SB) - Hajji Musa Kasule Road (EB)	20.9	20.9	16.8	-19	↓
Hajji Musa Kasule Road (EB) - Makerere Hill Road (WB)	29.8	29.8	49.7	67	↑
Hajji Musa Kasule Road (EB) - Bombo Road (SB)	28.7	28.7	59.1	106	↑
Hajji Musa Kasule Road (EB) - Bombo Road (NB)	19.1	19.1	29.1	53	↑
Bombo Road (NB) - Hajji Musa Kasule Road (EB)	27.9	27.9	22.0	-21	↓
Bombo Road (NB)- Makerere Hill Road (WB)	54.3	54.3	23.1	-58	↓
Bombo Road (NB) - Bombo Road (SB)	44.6	44.6	23.9	-46	↓
Bombo Road (SB) - Makerere Hill Road (WB)	19.0	19.0	18.0	-5	↓

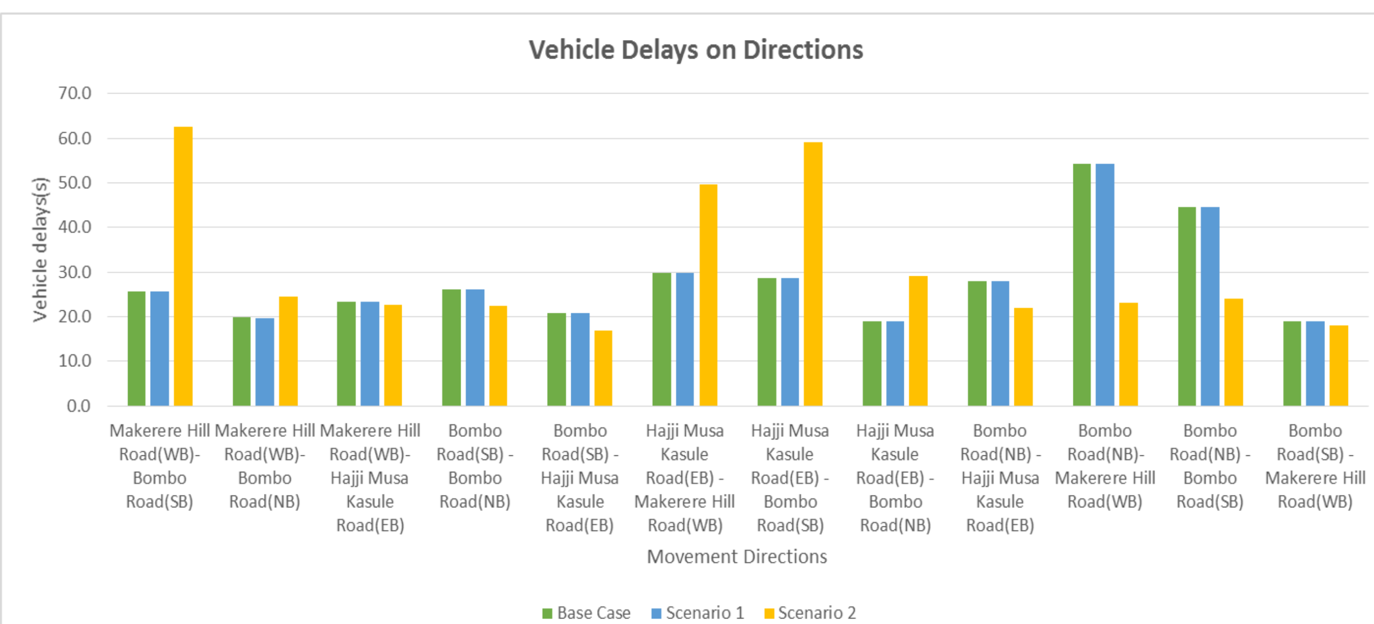

Figure 5- 21: Comparison analysis of vehicle delays in Zone 13

The results indicate a difference in the scenarios suggested. Scenario one, of adding a lane on Bombo Road in the north direction after the intersection, yielded no difference compared with the base case. The addition of a lane was suggested in this case since this direction has only one lane. The one lane served the left turning vehicles from Makerere Hill Road, right turn vehicles from Hajji Musa Kasule Road, and the through traffic from the southbound of Bombo Road. This implies a slow movement in the cars, causing congestion. However, the simulation run proved adding a lane to be inappropriate, and did not improve the vehicle delays on all movements in the morning peak. Results might be different for the evening peak hours.

This study also considered adding a lane, since all other roads possessed two lanes, increasing the throughput. Also, the relevant traffic bodies could easily implement this measure because the space is available in the area in question. The traffic authority should precisely demarcate the lanes to show how the traffic movements should follow the path. This measure also seems achievable by preventing roadside parking in this area, which would allow for more efficient vehicle movement.

Scenario two of altering the signal control system showed promising results. The previous signal timings of 10 seconds for each approach towards the intersection were changed to 15 seconds for Bombo Road approaches and 5 seconds for Makerere Hill Road and Hajji Musa Kasule Road. However, the delay increased enormously on Makerere Hill Road and Hajji Musa Kasule Road by over half compared to the previous delay. By contrast, there was a huge reduction in the delay for Bombo Road northbound by an average of 42% of initial delay. There was also a slight decline in the delay on the southbound of Bombo Road. The former is particularly important to note because there is generally more traffic on the northbound of Bombo Road heading to the CBD. This reduction in delay proved to be of great benefit, improving the overall efficiency of the intersection. The other approaches, of Makerere Hill Road and Hajji Musa Kasule Road would be affected by this measure, but since they carry less traffic, their delay might be justifiable.

This study performed only those two scenarios to allow for reliable, easily explainable results. Different researchers might suggest other techniques. Further modelling would allow for the possibility of improving congested zones by reducing the delays experienced by vehicles. This would aid in finding an optimal solution where all lane approaches are served effectively. Also, due to the lack of on-the-ground data on the signal control system in the base case, it was important to discuss the approach adopted in alleviating congestion. In the base scenario, the study assumed that the signal control system was in use, to provide adequate foundation for analysis.

❖ **Steps taken to ensure a credible simulation model**

Law (2008) discusses several aspects required for a simulation model to be credible and valid depending on the study. Below are some of those aspects and how each one was logically considered.

- **Formulation of the problem**

One of the research objectives was to minimize traffic congestion in significant sections of the Kampala CBD. All the aspects considered aimed to alleviate the congestion of the existing road network in the city. The problem also entailed responding to the second part of the research question by pinpointing mitigation measures. Simulation modelling was used to propose measures to alleviate traffic congestion. However, due to the project's scope, the model design did not involve any stakeholders.

- **Collection of the required data and construction of the assumption document**

The quantitative data used for this study was the traffic volumes. The data collection process was established before using it in the analysis. The other data source was qualitative, gathered through a desktop study of the city section in question. This data represented both the existing system and augmented the model development, rendering it credible and valid. The assumptions of the study, as well as the data analysis were clearly illustrated in section 3.6.3, stipulating the step-by-step procedure for simulation modelling in PTV VISSIM.

- **Is the assumption document valid?**

The steps presented by the PTV VISSIM software training manual were followed. In addition, assumptions made thereof were also noted during the model development. These assumptions were reasonable according to the field practice.

- **Programming the model**

The the model for this study was developed using computer-aided software PTV VISSIM, a product of PTV Group, as discussed in section 3.4.2. The modelling was performed on a licensed software program. Therefore, the model was credible.

- **Is the programmed model valid?**

The model was compared with the existing traffic system in Kampala to validate the former's output results. The software enabled running comparison patterns based on the current traffic system. This provided information on the model developed. The = the developed model was further discussed with the supervisor for this research to check whether the results were plausible.

- **Design, conduct, analyse experiments**

The design, conduction, and analysis of results were conducted depending on run iterations. The independent variables and their implications were then analysed. For this study, the simulation modelling was not complex with intricate variables. The only dependent variable investigated was the vehicle delays at the specified intersection.

- **Document and present the results**

The results were presented and discussed accordingly in chapter four of this thesis. This research study at the time of submission was also in the process of publication. This study will also be presented to the KCCA, because Kampala was the case study area. The presentation will include information about the model developed, the software used, and explaining the scope and assumptions made while developing the model.

5.6 Summary

In conclusion, this chapter has described and discussed the results of developing a FCD model to evaluate traffic congestion in Kampala, Uganda. The results arose from the traffic congestion zone visualisation using a SRI measure. Then the zones, were ranked according to severity of their respective delay rates. After that, the possible causes of congestion in the two highly ranked areas were discussed. This was followed by a discussion of possible measures to alleviate congestion in the specified zones.

Due to a lack of data, the study investigated only zone 13 of the Kampala CBD using simulation modelling to affirm whether the suggested measures could potentially solve the zone's congestion problems. Two scenarios performed, were scenario one which did not alter the base case scenario. When the study subjected the intersection to the further modifications of a lane addition and changing the signal control system, there was a huge difference in congestion alleviation. This study has provided a framework that different stakeholders can follow in any given urban area to determine the highly congested zones and find ways of mitigating the problem using FCD.

Chapter Six

Application of the FCD Model

6.1 Introduction

This chapter presents a summary of the study in the form of suggestion for application. It provides a step-by-step approach to the FCD model that can be replicated in other cities of developing countries. It generally describes the procedure followed in analysing the data. This chapter also describes how necessary data can be obtained. Then how the data can be manipulated to identify congestion areas and prioritize them is discussed. The various ways to determine the possible causes of congestion in high-priority areas are also explained. Lastly, an overview of the procedure for proposing different mitigation measures is provided.

6.2 Step-by-step approach

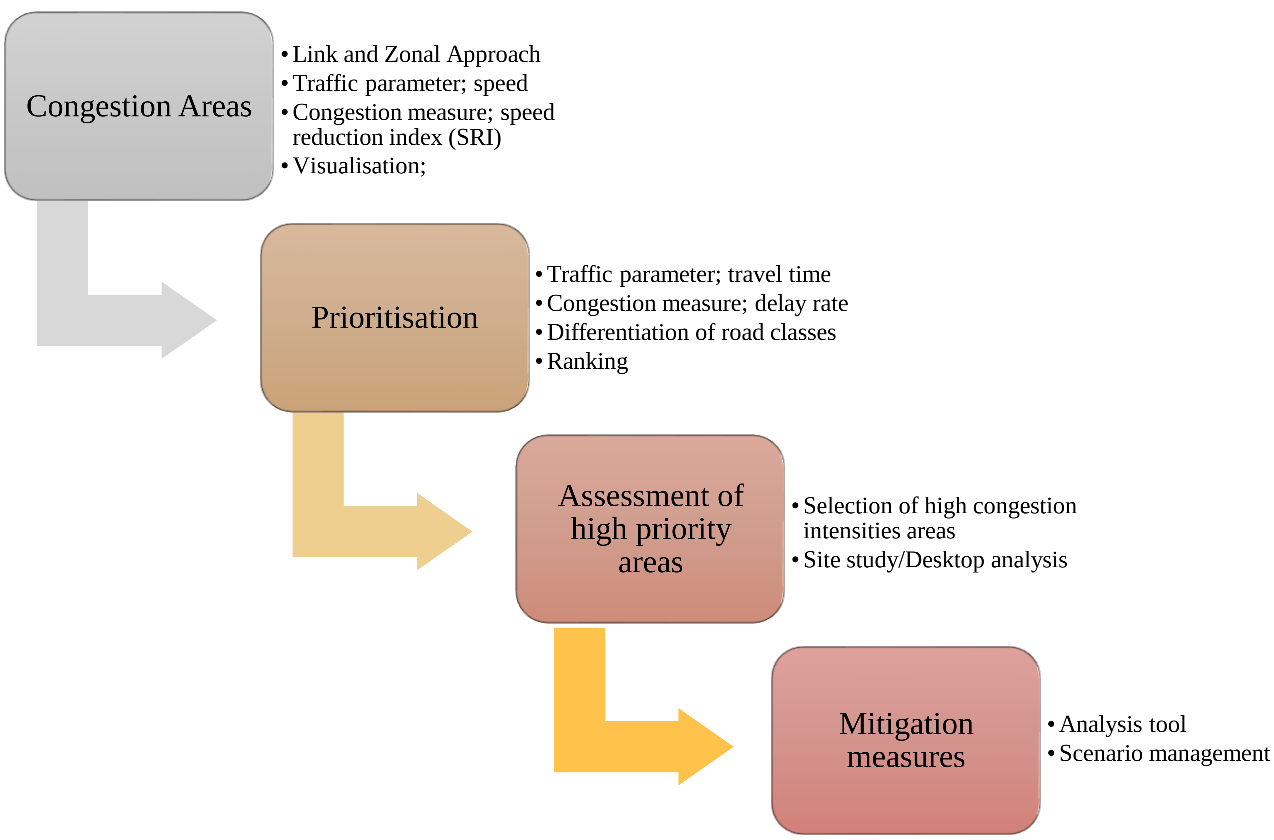

Figure 6- 1: Step-by-Step Approach

6.3 Data acquisition

Like any other transport planning technique, traffic data is vital. There are different ways of acquiring data, as was discussed in chapter two section 2.3.2. Although this study used FCD from Google API, data from other companies like TomTom, INRIX, and Uber Movements, when acquired satisfy the FCD model discussed in this study.

The road attributes, which are part of the data acquisition, can be obtained from websites such as OSM (www.openstreetmap.org) or HERE (www.here.com)

The data should be obtained for a specific area for a particular period, focusing on peak hours and off-peak hours. The period may vary accordingly, such as one week, one month, six months or a year. Researchers have used varying periods when evaluating traffic-related problems with FCD. The peak hour(s) to be used should be representative of congested periods. For instance, In Kampala 7 a.m. is the morning peak, and 5 p.m. the evening peak; or an average of 7-9 a.m. morning peak and 4-6 p.m. evening peak. Also, any follow-up analysis needs to consider the off-peak period to provide the baseline scenario of free flow traffic conditions. The congestion should be evaluated against the free flow conditions. Depending on the city, the off-peak period may be 12 a.m., or within the range of 12 a.m. – 4 a.m. Indeed, the longer the data collection period, the more accurate the results.

FCD typically includes the speeds and travelling times of the probe vehicles in the transport network. This is the data which was evaluated in the FCD model using the novel approach presented in this thesis. The data obtained for road links is composed of nodes with distinct coordinates. Each dataset, which is explicit, has corresponding links in the road network. It has already been mined from the traffic stream by the companies that provide FCD.

6.4 Application procedure

This study had a set of objectives to be achieved, as mentioned in chapter one. There were four guiding objectives from which this application procedure emerged. These objectives included; identifying the congestion areas in the network, prioritising the congestion areas, assessing the causes of congestion, and proposing mitigation measures to alleviate congestion. This chapter describes these objectives in a generalized manner, as a flexible application to allow almost any city in a developing country to apply them.

6.4.1 Identification of congestion zones

After obtaining the data from sources that supply it, as discussed above, in this case, a road network needs to be delineated using the PTV VISUM software. Then the speed reduction index (SRI) must be calculated using the speed parameter for each road link. The results should then be categorized into a uniform scale to enable consistent visualisation. The results can be classified into no, low, and high congestion. Finally, the software can be used to visualise the congestion areas using SRI.

Another analysis approach that can be adopted is the zonal analysis. For this, the study area is divided into equal squares, say 500m x 500m squares or 250m x250m squares or other sizes, depending on the level of detail required. Using a detailed grid system will lead to better results. This depends on the time available and scope of the study to allow analysis of more grids.

In the zonal analysis, each zone is treated differently by obtaining the average SRI of the links in a particular zone. The results should also be classified into no, low and high congestion intensities. PTV VISUM enables the visualisation of the average SRI of designated zones.

Identifying the congestion zones may require the consideration of different road classes. This is possible by only taking the average values for a particular road class in a given zone. It enables the identification of the different trends of congestion on a specific class of road. Each class can be evaluated separately depending on the objective of the research.

6.4.2 Ranking of congestion zones

Ranking of zones helps to identify the high-priority zones within the study area. The first step of identifying congestion areas is to group zones according to no, low, and high congestion categories. This doesn't help to identify the most affected zones emphatically. Therefore, a prioritisation step is necessary. The delay rate is another suggested measure in this thesis because it illustrates the amount of time lost while navigating on a particular link or zone in a given road network. The delay rate utilises the travel time parameter and is expressed as minutes per kilometre.

On the link analysis, the delay rate should be calculated for each link, and the high delay rate is considered the highly congested area.

The same principle is applied with the zonal analysis, as seen in the identification of congestion zones. The zones can be analysed according to different road class levels. Then, the average delay rates for each link in the zone should be obtained. In any case, the zone with the highest delay rate is ranked number one, and others follow. This ranking enables the identification of the most affected area(s). It also eases the process of determining the factors affecting the area that lead to high congestion.

6.4.3 Determining the causes of congestion

The process of determining the causes of congestion is best achieved through a site study. A site study enables researchers to collect first-hand information on the performance of the road section or city zone in question, including details about the traffic flows and operations, intersection layouts, and adjacent areas. A site study can also facilitate traffic counting in the designated area to obtain the traffic volumes. This data may assist in modelling the area and also enable obtaining its LoS.

Other methods in assessing the causes of traffic on a particular road link or in a specific zone can be pursued. For example, desktop analysis can be used. This is performed from the comfort of any workstation, using only a computer. Sites like Google Maps or OSM can be used to study the features of high-congestion zones and identify possible causes of traffic congestion for a given area. This method can be backed up by personal knowledge of and experience in the relevant city or area. Also, on-site photographs can provide additional insight into the traffic status during the period under investigation.

Another approach that can be employed is a geo-detector. This method focusses on mapping the spatial-temporal patterns and using multi-source data to determine the causes of congestion (Song et al., 2019). The data may include satellite images, landscapes, and/or population details.

6.4.4 Mitigation measures

These involve proposing different measures to alleviate traffic congestion in high-priority zones. This step is enabled by the previous phase of determining the possible causes of congestion. With that background, the measures to mitigate traffic congestion can be determined with knowledge of the status of the road section under analysis.

Depending on the available data, mitigation measures can be proposed through different avenues. One approach can be to apply qualitative strategies. Of course, this approach is subjective, although the reasons are justifiable. For instance, qualitative studies give often more meaningfully account for human nature. Another approach is performing simulation modelling by using any traffic management simulation tool. This method also allows for any modifications that must be applied to the base scenario, and also allows for comparison results.

Simulation modelling is a useful resource because it maps the effect of any proposed measure and shows how the traffic flows will readjust according to the proposed solution. There are different simulation tools like PTV VISSIM, AIMSUN, SUMO, and CORSIM, among others.

6.5 Summary

This section described the step-by-step procedure for developing a FCD model. FCD models are a simple and cost-effective transport planning approach that transport authorities can adopt. The main aim of transport authorities is to provide an efficient, reliable, and safe transport network for road users. This model can help to monitor the performance of the road network and contribute to alleviating traffic congestion. The step-by-step application procedure described here allows for replication in other cities. The process included; obtaining the FCD, identifying congestion areas using the SRI, ranking the areas utilising the delay rates, assessing the high priority areas to detect the possible causes of congestion, and proposing measures to alleviate congestion in the road network.

Chapter Seven

Conclusion and Recommendations

7.1 Introduction

This chapter presents the conclusions deduced from this research study and the recommendations. The conclusion summarises the response to the research question, the hypothesis proved, and the aim fulfilled. It also reviews the results from the objectives of the research. For the recommendations, suggestions for further research works that can follow in line with this particular study are provided. Finally, this chapter also offers some suggestions for undertakings to relevant stakeholders in the transport industry who strive to alleviate traffic congestion in major cities.

7.2 Conclusion

7.2.1 General

The research responded to the question, "Can FCD evaluate traffic congestion in Kampala to propose suitable measures for alleviation?" This study affirmatively answered this question, as shown in the results of the research. A model developed from FCD proved satisfactory for identifying congestion areas in Kampala. This dataset has been utilised in different parts of the world for various traffic-related problems. However, in Uganda, which is considered a developing country, there is some reluctance to adopt technological avenues to analyse situations in the traffic environment. Therefore, the study used Kampala, an understudied city in terms of alleviation of traffic congestion, as a case study.

Kampala, under KCCA as an institution liable for an efficient, safe, and accessible city, at the time this thesis was submitted was still using an online survey to gauge the state of the road network. The survey targets commuters from different parts of the city. Respondents are required to estimate their travel times in the morning and evening out of the city. However, this survey may be subjective and prone to human error, thus unreliable results are expected. Therefore, to bridge the gap between the unavailability of traffic statistics and the need to improve the road network, this study presented FCD as a traffic dataset to evaluate traffic congestion in cities through a designed model.

This research proved the alternative hypothesis of the study, which stated that FCD can evaluate traffic congestion in Kampala. This hypothesis was based on the research statement developed for the study. The argument relied upon the different studies conducted using FCD. FCD is therefore a feasible means to develop a model to evaluate city traffic congestion. Furthermore, these hypotheses guided this study to streamline its main focus, and the results ultimately upheld both hypotheses.

This study fulfilled the research's aim which was to develop a novel FCD model. The model can be used to monitor and evaluate city traffic congestion in other contexts beyond Uganda. The aim, as previously mentioned, targeted KCCA because the case study was Kampala. The goal was to contribute toward alleviating traffic congestion by providing a reliable and cost-effective traffic statistics database and to develop a widely-applicable model for use in other cities. Therefore, relevant bodies can use the database of FCD to evaluate traffic congestion zones, propose mitigation measures to the identified high congestion areas, and perform monitoring evaluations before and after a mitigation measure.

7.2.2 Findings

This study developed a novel FCD model. The model can be used to identify and monitor traffic performance in the road network. The model was designed with the help of structured objectives, the first of which was to identify the traffic congestion areas for Kampala using FCD. The speeds during the off-peak hour (midnight) and morning peak hour (7:00 am) served as the data for analysis. The data was analysed using two approaches, namely a link and a zonal analysis. Using the SRI as the congestion measure, each link was evaluated for its congestion intensity on a scale of zero for no congestion, one to two for low congestion, and above two for high congestion.

The geographical area was divided into 500 x 500 square metres for the zonal analysis to enable a spatial analysis. Next, the study analysed the zones based on the average SRI calculated on the links of the roads. The zones presented SRI in the range of zero to two. A different scale was used for clear visualisation in the PTV VISUM software. The latter indicated zero for no congestion, one for low congestion, and two for high congestion zones.

The zones were further divided into two cases; case one included all the road classes (two, three, and four), and case two comprised only classes two and three (major and minor arterials). This was to differentiate the congestion intensities across different road classes. The classification enabled a precise observation of the impact of road classes in different zones as per the visualisation. For example, class four roads, which are collectors, generally had an SRI of zero. When mixed with other classes, the effect of congestion seemed distorted. However, the congestion intensities were clear and distinctive, with classes two and three being the major and minor arterials considered.

The second objective was to prioritise the areas according to road classes. The zones were ranked appropriately to account for the highly congested areas. Travel time was used as a traffic factor for measuring congestion. The congestion measure used was delay rates. The delay rates indicated the amount of time lost on a particular road segment or zone. The zones or links were ranked according to the highest delay rate, starting with the number one most congested zone/link, followed by others with declining delay rates.

The third objective of this study was addressed by assessing the causes of congestion in high-priority areas through a desktop study. Although a site study would have been more practical, a desktop study seemed ideal at the time the research was carried out, because of the COVID-19 pandemic. The desktop study involved studying the geographical areas in the zones, adjacent environment, intersection types, and layout through Google Maps, photographs, and personal knowledge.

The link that ranked number one in the link analysis was located in zone 55, which also ranked among the first two highly congested zones. Therefore, the causes of congestion in that zone were discussed in greater detail. Two zones ranked the first and second most highly congested from the second case were considered for the assessment. These were zone 55 and 13, with delay rates of 35min/km and 31min/km, respectively. The contributing cause of high congestion in the zones was determined to be the major serving arterials of class two contained in the zones. The arterials are in different directions towards the city centre. Also, the intersection types and layouts were contributing factors, along with adjacent social and economic hubs, and the presence of traffic officers managing the intersection in zone 13.

Finally, the study achieved the fourth objective of proposing appropriate measures to alleviate traffic congestion through simulation modelling for zone 13. The arterial in zone 13, reported to be the second most highly congested zone, was located in the outer areas of KCCA jurisdiction. The sections beyond the boundaries of the Kampala metropolitan area are under the jurisdiction of UNRA. Therefore, the data was obtained from UNRA for the average annual daily traffic (AADT) for 2014 on this particular road and then extrapolated. This data was used in the simulation analysis using PTV VISSIM to suggest remedies that can improve travel delays in the zones under study. For zone 55, there was no available data about traffic volumes. Therefore, the measures were proposed theoretically from a literature review point of view.

7.2.3 Final remarks

Evaluating traffic congestion requires diverse means of measure. Traffic congestion varies in different geographical areas. Therefore, it is inevitable for countries to require their own measuring scale for assessing congestion which is not dependent on universal global scale values. In this thesis, the researcher noted that using the SRI, road links in Kampala indicated values equal to or less than five. According to the zonal analysis, the average was between zero and two. On a global scale, the value zero indicates no congestion, and below four indicates low congestion, whereas beyond five is high congestion (Afrin and Yodo, 2020). Basing the results obtained on the latter scale, it would suggest that Kampala generally experiences low congestion on almost all the roads. However, this is not accurate in comparison to the situation on the ground. This would indicate a bias in the results. Therefore, a need to have different scales on which to measure congestion in different areas becomes necessary.

The FCD model developed in this study is a cost-effective method that can be used for transport planning. Transport planners and engineers require a tool for decision-making. The traditional trip-based and activity-based models are complex and costly. In addition, these models require a lot of data and are time-consuming. Therefore, this study proposed an FCD model to bridge the gap between transport stakeholders needing to improve the road network, and a lack of decision-making tools like traditional four-step models. The model presented here provides information on where traffic congestion is experienced in the cities. The relevant authorities, upon locating such areas, can decide how to improve the condition. The model also ranks the areas according to severity, hence enabling prioritisation.

The FCD model developed in this study does not replace the traditional trip-based and activity-based models. These models play an important overall role in traffic management systems. They consider not only traffic but also land use and population sizes. They are complex and used for different purposes in the country. They are also used as prediction tools. In contrast the FCD model developed in this study is unilateral. It focusses on traffic congestion as one of the problems of cities. Its main aim is to identify the cities' congestion areas and prioritize them. It also monitors performance after implementing a mitigation action.

In Uganda where this study was conducted, KCCA at the time this thesis was submitted was still using an online survey to monitor traffic congestion in the city. This study designed a model using FCD that serves the same purpose of monitoring congestion areas in the city. This study, therefore, contributes to alleviating traffic congestion in Kampala. It provides an alternative to KCCA's data collection system. The approach suggested here allows for determining the possible causes of congestion in the city. Upon identifying such areas, mitigation plans can be sought. The method used for mitigation measures of simulation modelling provides an appropriate action tested in a simulation process.

The FCD model can be applied in other cities, as discussed in chapter six where the study elucidated a step-by-step approach. It is an inexpensive method because it utilises already available FCD supplied by different companies. The world is becoming more digitalised. Transport planners and engineers should embrace digital traffic statistics to pace with the modern phenomenon of smart technology. In this case a FCD was developed to monitor and identify city traffic congestion.

7.3 Recommendations

This study deduced some recommendations from the literature review and analysis of the results. Also, these recommendations were posed to different areas in the transport field, including fellow researchers and transport authorities in other cities. Fellow researchers may include scholars or independent consultants who want to focus on traffic management and traffic-related problems in busy cities.

- **Researchers**

This study recommends further investigations on traffic problems using FCD. Many studies have adopted FCD in analysing traffic-related problems in other parts of the world, but Africa is still underrepresented. There is a great deal of potential for various studies using this convenient, available, and reliable dataset. Further studies would allow transport authorities to gain more confidence in using similar datasets to solve the various problems in the road network. It could also act as a knowledge bank for FCD in Africa. According to this study, the researcher noted some studies using FCD in South Africa and one in Ghana. This should motivate other countries to engage with the dataset and study problems affecting our transport systems like safety issues.

Through the analysis of the results, the need to study the efficiency of roundabouts (traffic circles) and signalised intersections on busy junctions is apparent. This was discovered when establishing the zones of Kampala for the study area. Since the zones might contain existing type of traffic control systems, future studies could derive conclusions about one zone based on the efficiency of another. This methodology could ease the ways of justifying the suitability of a traffic control system.

- **Transport authorities**

Transport authorities should strictly define the ranges for different measures of congestion in their cities. Different traffic congestion measures are available; however, many cities do not have definite ranges for clarifying the exact conditions of traffic congestion. Traffic congestion implicitly varies in different cities. Therefore, what could seem like congestion in a particular city might not appear so in another. Utilising particular standard units will allow for clear proposed mitigation measures to effectively reduce congestion and increase travel time according to the situation's circumstances. For example, through FHWA, the USA uses congestion time, travel time index, and planning time index (FHWA, 2019), whereas China uses the speed performance index (SPI) to determine congested areas (He et al., 2016)

Relevant transport authorities should discuss developing their data collection protocols. This will allow them to collect their data more effectively, mined using advanced technology and ready to be used to evaluate traffic problems. Furthermore, the relevant authorities should pursue their governments to motivate the general public to use GNSS that transfers data to their control centres in exchange for better traffic management. By doing this, the traffic managers could pursue different mitigation measures upon receiving this information. After that, performance evaluations could follow to gauge the improvement in the system. However, the authorities must also reassure the public of the measures taken for confidentiality since this data is prone to individual privacy issues.

The relevant transport authorities seeking to mitigate traffic congestion should adopt a zoning system to analyse different parameters in their cities. Traffic analysis zones (TZA) are used when conducting traditional transport planning models. However, some countries lack this zoning system. Therefore, transport authorities should have a uniform zonal system for more accurate studies. In this study, the researcher divided Kampala into zones of 500 x 500 square metres. This demonstrates that a well-zoned system would be much more effective for traffic management.

FCD provides both real-time and historical data; the real-time is suitable for re-routing dynamics and real-time management. In contrast, historical data is useful for transport planning where monitoring and evaluation occur. Transport authorities should look forward to obtaining decentralized traffic management centres to better manage transport systems. There is a general lack of TMCs in many African countries save a few; such as South Africa, Nigeria and Ghana though situated in one or two cities in the country. This information could provide a database for an inexpensive, decentralized system compared to a centralised TMC. The decentralised system could work in such a way that different bodies adapt unique platforms suited to their city's needs to provide an efficient transport system. For instance, this could be in the form of a FCD analyst working with the signal controllers in different areas. Also, the ITS has not evolved in many cities due to immature infrastructure. Therefore, this data could bridge the gap by controlling the road network as they progress with improved systems which incorporate ITS.

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