UNIVERSITY OF RWANDA
COLLEGE OF SCIENCE AND TECHNOLOGY
AFRICAN CENTER OF EXCELLENCE IN INTERNET OF THINGS

TOWARDS IMPROVED ROAD TRAFFIC SAFETY: A MODELLING AND IoT INTEGRATION APPROACH

PhD Thesis submitted in the fulfilment of requirements of award of PhD Degree in Internet of Things - Wireless Intelligent Sensor Networking

Gatera Antoine

July 2022

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GATERA Antoine
(Student ID: 218015825)

Thesis Supervisor: Prof. Chomora MIKEKA
Thesis Co-Supervisors: Dr. Gaurav BAJPAI and Dr. András VALKÓ

July 2022

Approval

Antoine GATERA, a Ph.D. student of UR-ACEIoT student ID 218015825, successfully defended the thesis entitled "*TOWARDS IMPROVED ROAD TRAFFIC SAFETY: A MODELLING AND IoT INTEGRATION APPROACH*", which he prepared after fulfilling the requirements specified in the associated legislations, before the thesis examination members whose signatures are below.

Thesis Supervisor:

Prof. Chomora MIKEKA
Directorate of Science, Technology and Innovation ----------------------------
Ministry of Education
Lilongwe-Malawi

Thesis Co-Supervisors:

Dr. Gaurav BAJPAI -----------------------------------

Dr. András VALKÓ -----------------------------------

Viva Voce Members:

Prof. Jules DEGILA (External)
University of Abomey Calavi, Benin Republic -----------------------------------

Prof. Haci Ilhan (External)
Yildiz Technical University, Istanbul, Turkey -----------------------------------

Prof. Charles Kabiri (Chair) -----------------------------------
University of Rwanda

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Declaration

I hereby declare that the thesis entitled "*Towards improved road traffic safety: A modelling and IoT integration approach*" to be submitted for the Degree of Doctor of Philosophy is my original work and the thesis has not formed the basis for the award of any degree, diploma, associateship, or fellowship of similar other titles. It has not been submitted to any other University or Institution for the award of any degree or diploma. Where other people's work either from a printed source, internet or any other source has been used and this has been properly acknowledged and referenced in accordance with the University of Rwanda's anti plagiarism policy.

Gatera Antoine

To my spouse and children,

Acknowledgement

First, I would like to extend my gratitude to God for his love, life, protection, and providence, by which this journey has been possible.

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July 2022 Gatera Antoine

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Abbreviations

ACC	: Adaptive Cruise Control
ADAS	: Adaptive Driving Assistance System
ASE	: Automated Speed Enforcement
EAC	: East African Community
GPRS	: General Packet Radio Services
GPS	: Global Positioning System
GSM	: Global System for Mobile
HI	: High Income
ICT	: Information and Communications Technology
IoT	: Internet of Things
ISA	: Intelligent Speed Adaptation
ITS	: Intelligent Transportation System
LMI	: Low and Middle Income
MLR	: Multiple Linear Regression
MOSFET	: Metal-Oxide-Semiconductor Field-Effect Transistor
QoS	: Quality of Service
RF	: Random Forest
RSU	: Road Side Unit
TSR	: Traffic Sign Recognition
VANET	: Vehicular Ad hoc Network
V2I	: Vehicle to Infrastructure
V2V	: Vehicle to Vehicle
V2X	: Vehicle to Everything

List of Symbols

S_r	Sensor
T_r	Traffic light
λ	The arrival rate of cars at the intersection
μ	Service rate of single traffic light
c	The capacity of the facility
δ	Intersection utilization
P_0	Probability of having no car in the queue
L	The average number of cars at the intersection
L_q	The average number of cars in a queue at a time
ω	The average time spent in the queue at the intersection
ω_q	The average time spent in a queue by a car

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Summary

Every year, the lives of millions of people are cut short due to road traffic crashes. Millions of people suffer non-fatal injuries, leading to lifetime disability. Traffic accidents are caused by many factors including reckless driving, inappropriate speeding, drunkenness, violation of traffic lights, and dangerous manoeuvres. Speed has been one of the leading causes and a fundamental risk factor for road traffic injury problems. Excessive speed is a crucial risk factor for road traffic collisions, deaths, and injuries. Cars become more difficult to manoeuvre at higher speeds, especially on curves or where evasive action is necessary. The forces experienced by the human body in a collision also increase as the speed increases. In low- and middle-income (LMI) countries, this proportion is likely high, given the higher proportion of deaths among vulnerable road users. On Rwanda's roads, speeding is among the significant causes of accidents.

Several approaches have emerged to support road safety towards reducing fatalities and severe impairment outcomes. Therefore, speed and management are at the core of a safe road system. There is a need to look for all ways of curbing the accident rate caused by inappropriate speeding by preventing people from being exposed to risk. Besides this, there is a need to know the details of the cars, like current location, and speed to gain details when an accident occurs. The Global Positioning System (GPS) advancement and the Internet of Things (IoT) have opened new systems to limit a maximum speed to a safe speed with no effect on the regular operation of vehicles. The whole process will be accomplished based on GPS technology and sensing technology to maintain the appropriate speed.

This thesis aims to evaluate how to reduce inappropriate speed caused by road accidents towards a safer traffic system. The thesis comprises three scientific papers that summarize this work's main contributions. Hence, the focus of this research is an architectural framework for vehicle monitoring, designing an intelligent electronic speed governing system for the maximum speed of the vehicle to be automatically limited to the local speed limit. The system inside the car will be able to control the vehicle's current speed to the required maximum speed in a particular speed zone.

In Paper I, we investigated the readiness for intelligent transportation systems (ITS), existing technologies, and transportation applications in Rwanda as the majority are not familiar with the concept. An IoT based conceptual framework was proposed to improve the transportation system. In Paper II, structural speed control and IoT based online monitoring system was developed to monitor vehicle data continuously. Multiple linear regression (MLR) and random forest (RF) models were evaluated to find the best model to estimate the required voltage to be supplied to the motors. Based on the coefficient of determination, the RF performs better than the MLR. In Paper III, we proposed a multi-server queueing model for traffic signal optimization to strengthen the sustainability of urban mobility systems. A numerical algorithm was successfully developed and discussed to compute steady-state performance measures.

***Keywords**: Traffic safety, speed adaptation, intelligent transportation, traffic flow, traffic congestion, queuing theory, internet of things, electric vehicles.*

CHAPTER 1: INTRODUCTION

This thesis investigates how IoT-based systems and ITS might contribute to the reduction of over speeding caused accidents. Intelligent speed adaptation (ISA) systems have different characteristics and requirements. The relevant literature on various intelligent transportation countermeasures was reviewed. The framework to conceptualize intelligent mobility was proposed. An IoT system and the process of limiting the electric vehicle from exceeding the required speed limit were presented. Communication system analysis for a centralized intersection coordination scheme using traffic flow data was proposed to improve the quality of service (QoS) delivery while enhancing road safety. Section 1.1 presents the background information on road accidents and discusses practices to reduce road accidents. Section 1.2 provides a detailed problem statement. Section 1.3 includes the research objectives and questions. In section 1.4, we discuss the significance of the study. Research contributions are highlighted in Section 1.5. Finally, the thesis outline is in Section 1.6. The three research publications are an integral part of this thesis.

1.1 Background of study

The research reported in this thesis attempts to contribute to understanding of a range of issues pertinent to the implementation of IoT-based intelligent mobility for road safety and management. Over the past decades, the number of deaths and injuries resulting from road crashes has remained a worldwide concern. A vehicle moving at high speed has a more significant impact during the crash. The ability to judge the forthcoming events also gets reduced while driving faster, which causes error in judgment and finally a crash. Methods such as law enforcement, engineering, and technological solutions have been proposed to reduce the extent of road accidents. Advancements in technology have allowed the development of methods for reducing driver speed. We propose and evaluate a solution to the road safety problem associated with exceeding the maximum lawful speed.

The rate of road accidents that keeps increasing is the most critical health and social concern. According to the World Health Organization (WHO), every year approximately 1.3 million people die in road traffic crashes. Between 20 and 50 million people remain suffering non-fatal injuries [1]. According to the global health estimates of 2019, road injuries caused deaths were estimated to be 16.7 deaths per 100,000 population from 16.96 deaths per 100,000 population (2015) [2]. The report shows that road traffic injury was ranked 10^{th} in the leading global causes of death in LMI countries (after diabetes mellitus) and 7^{th} leading cause of death among all age groups in low-income countries (after malaria). In addition, road traffic injuries are the leading cause of death for children and young adults aged 5-29 years [3]. Africa has the highest road traffic injury death rate in the world. In terms of road safety, Africa accounted for the highest road-traffic mortality rate of 26.69 deaths per 100,000 inhabitants in 2019. The LMI countries where most African countries belong account for more than 90% of all fatal road traffic accidents. The average death rate per 100,000 population in LMI countries is 27.5, while 8.3 deaths per 100,000 in high income (HI) countries.
Table *1* depicts the mortality rate worldwide by sex and World Bank (WB) income group. Figure 1 shows the fatality rate for all ages and gender.

Table 1. Mortality rate in 2019 by gender per 100,000 inhabitants.

Gender	Low income	Lower-middle income	Upper-middle income	High income
Male	39.8	25.5	25.7	12.4
Female	17	8.9	7.9	4.4

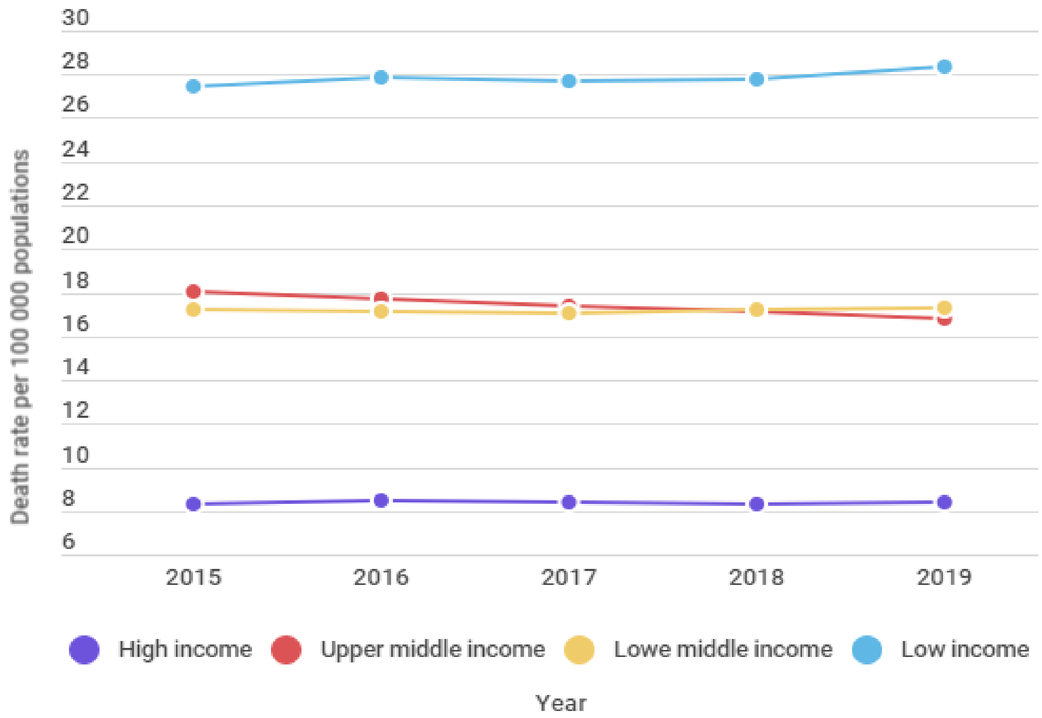


Figure 1 Road fatalities rate by World Bank region per 100,000 inhabitants.

The European Union (EU) road safety policy framework aims to reduce accidents on EU roads to zero deaths and zero serious injuries by 2050 [4]. The 2019 EU strategic action plan on road safety encourages the requirement for road traffic management systems to limit speeds [5]. The WHO targets to halve road traffic deaths and injuries by 2030 [6]. Though road fatalities keep increasing in the East African Community (EAC), some countries like Rwanda and Uganda are taking measures such as setting maximum speed limits and the use of road speed limiters systems to reduce the road accident rate [7].

However, for some other EAC countries, a regional intergovernmental organization consisting of seven member states (Rwanda, Uganda, Tanzania, Burundi, Kenya, South Sudan, and Democratic Republic of the Congo (DRC)), the death rate caused by road accidents keeps increasing. Figure 2 shows the death rate per 100,000 inhabitants for every member state in the past 5 years. In 2019, Rwanda's death rate per 100,000 inhabitants was 29.45, Uganda's 29.39, Tanzania's 31.12, Burundi's 35.46, Kenya's 29.39, South Sudan's 36.73, and DRC's 34.86 respectively.

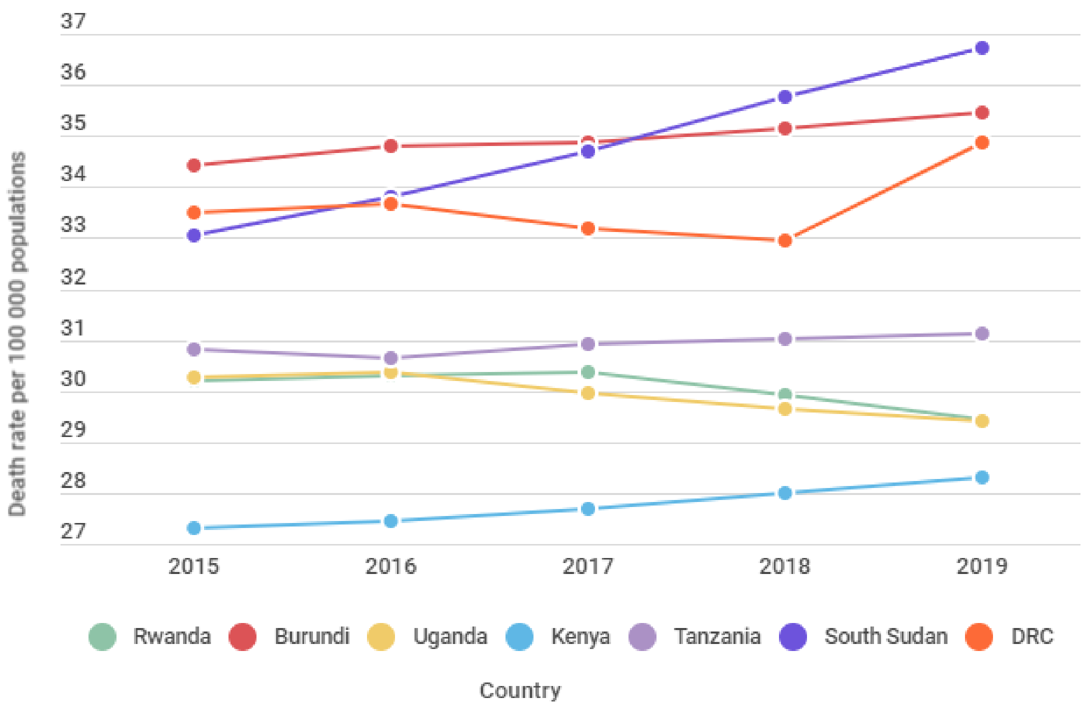


Figure 2 EAC countries fatalities per 100,000 inhabitants.

Road traffic deaths decreased from 30.21 (2015) to 29.45 (2019) per 100,000 inhabitants in Rwanda. However, the rate of both minor and property damage accident cases decreased, on the other side, the rate of both fatal and severe injuries increased. Figure 3 shows the variation of accidents by category in Rwanda over the past four years.

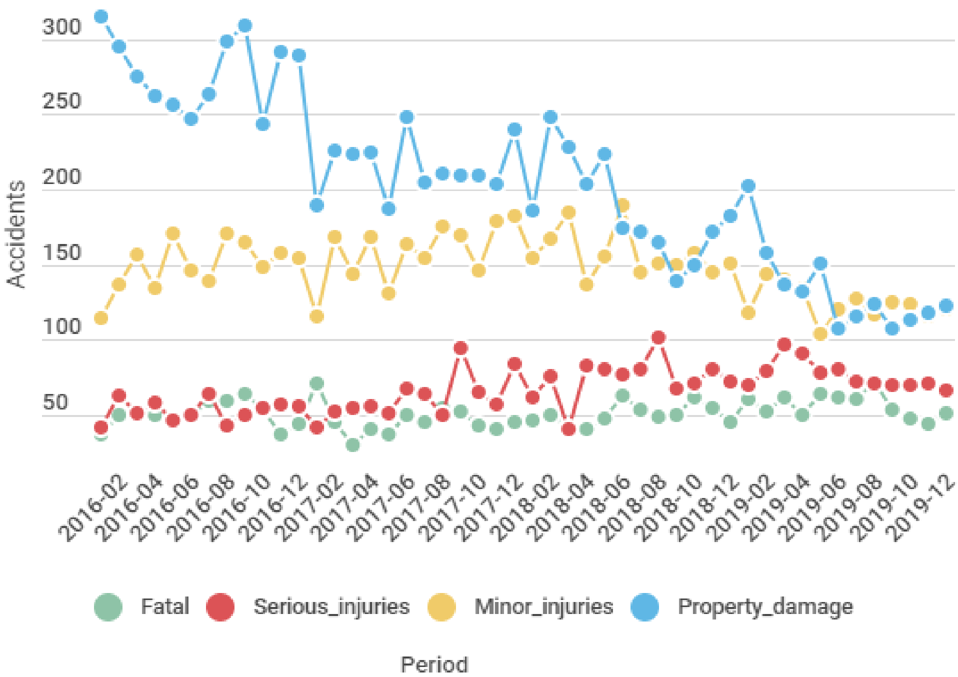


Figure 3 Variation of accidents by category in Rwanda (2016-2019).

According to statistics, reckless driving, wrong manoeuvring, and excessive speeding have been the leading causes of traffic accidents between 2016-2019. They account for 32.64%, 25.36%, and 13%

of the total traffic accident cases. Figure 4 depicts the causing factors in their respective cases for the past 4 years.

Figure 4 Road traffic accidents by causing factors (2016-2019).

Looking at the leading causes, speed-related cases increased every year from 7.1% (2016), 10.6% (2017), 15.1% (2018) and 21.8% (2019) respectively. Figure 5 depicts the variation of speed-caused cases by month over the past 4 years.

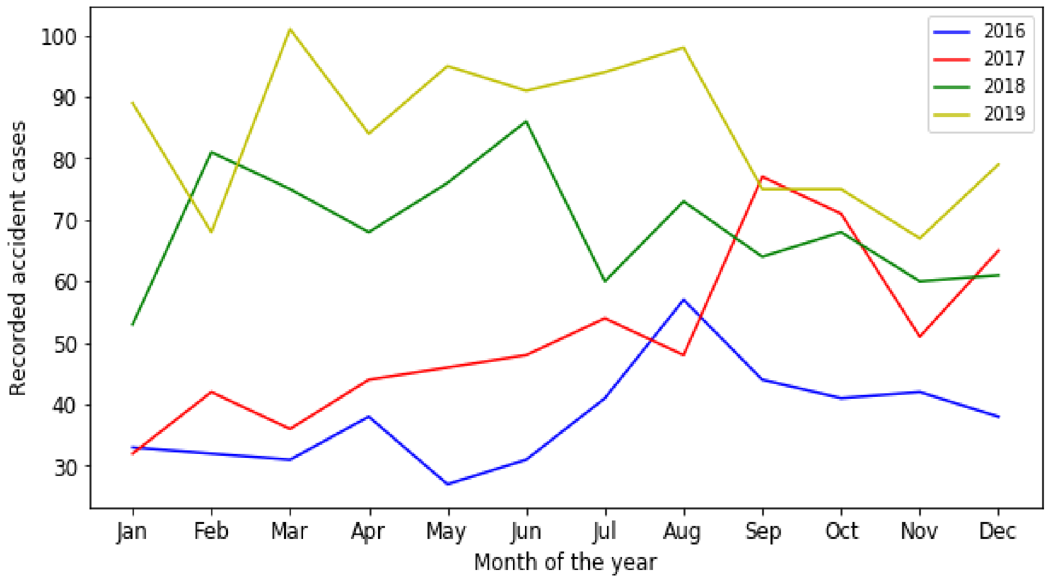


Figure 5 Over speeding caused accidents in Rwanda (2016-2019).

The Government of Rwanda (GoR) thus emphasizes various government initiatives including the use of speed governors, speed limit cameras detectors and road safety campaigns towards reducing the increase of both fatal and non-fatal traffic accidents. Road accident reduction is an urgent issue to be addressed by all governments, more particularly in LMI countries, as it brings high costs to their economies. Although the social costs of road crashes in LMI countries are reported to be underreported, every year road accidents cost these countries between 3% to 5% of their gross domestic product (GDP) on average [8], [9], [10]. Speed and its role in causing crashes and more severe crash outcomes have a clear economic impact. To address this financial and public health issue, the United Nations (UN) has proposed the global goals for sustainable development and a decade of activity for street safety initiatives to extend awareness across diverse nations [11].

The WHO collaborates with the member states to support road safety planning, implementation, and evaluation. A system that can provide the driver with the road environment information and appropriate feedback is required. ISA systems with a function that attempts to limit the speedometer speed to a stable speed [12]. Currently, there are several technical options for the feedback method to be used as a basis for an ISA system. However, not all those options can be used in each motor vehicle due to their technical characteristics. The countries are copying emerging technological solutions from developed countries. Motivated by the challenges mentioned above, context-specific solutions and proper interventions are required to decrease road-related risks, heavy losses of human resources, and socioeconomic costs. Traffic management includes traffic safety management, such as optimization, traffic state estimation and prediction. ITSs are an essential means of making road safety less dependent on the individual choices of road users. Some researchers have shown that ITSs may lead to 40% fewer fatalities and injuries [13], [14]. By considering the immense potential of ITS and the power of the IoT, there is a gap between research and practice concerning developing intelligent systems to reduce road traffic accidents.

1.2 Problem statement

Although several attempts such as direct police action, license to drive together with road safety policies have been implemented for a long time in EAC countries, the accident rate continues to be alarming. Speed has been reported to be at the core of road accidents. Setting proper speed limits, improving traffic flow homogeneity, and reducing speed are all aspects of speed management. Speed and speed regulation are key factors to improve road safety. Exceeding the speed limits has been a concern for road safety. Hence, there is a need for adopting systems that support drivers to follow the legal speed limits. Lower speeds have safety benefits, including reducing negative consequences. However, speed affects safety as stopping the vehicle during an emergency is difficult, leading to accidents and crashes occurrences [15], [16], [17], [18], [19]. Therefore, a speed management strategy that encompasses a range of measures to balance the safety and efficiency of vehicle speeds is required. Speed management aims to reduce the number of road traffic crashes and the severe injury and death that can result from driving too fast for the prevailing conditions and maximize compliance with speed limits. Numerous practices have been implemented in urban areas to reduce speeds, as it has been recognized as one of the primary measures for improving traffic safety for all types of road users [20]. It is vital to take measures against accident-causing factors to reduce accidents. This is done by developing solutions to reduce accidents and optimize road traffic safety. The use of the ISA system to aid the driver in maintaining the appropriate speed is one of the potential solutions [21], [22]. However, such systems can be used to set a maximum speed above the required maximum speed, ISA systems require enabling conditions in their implementation. In this regard, there is a need for a good design and conceptualizing a controlling ISA that automatically limits the maximum speed of the vehicle to the speed limit to address road traffic safety [23]. This is to be done while considering the country's context to avoid systems and application failures in implementing initiatives or reduce the risk of not getting the benefits of Information Technology Communication (ICT) penetration. An intelligent speed management strategy could reduce the frequency and severity of speeding-related crashes. It is well recognized that ICT functions like the nerve system of the transport chain. Hence, transport operators and users should benefit from its benefits including but not limited to providing real-time visibility, efficient data exchange, and better flexibility during transport operations.

1.3 Aim, research questions, and objectives

This thesis aims to contribute to intelligent mobility implementation and research toward improving mobility and road safety in the least developed countries. It presents the importance of data and data collection methods, which is the key support tool for developing evidence-based road safety policies. The research presented in this thesis identifies the strategy to reduce the vehicle's speed to the maximum lawful speed. Most of the time, accidents are much more likely to occur when the lawful speed in a particular zone is exceeded and when complex situations such as road junctions. Therefore, the appropriate schedule and traffic flow optimization is required at signal-controlled junctions. The main objective of junction design is to reduce the number and severity of potential conflicts between different types of road users. This thesis attempts to answer the following central question:

"How to reduce the extent of speed-related accidents?"

Intending to address this question, the solutions proposed in this work aim to address the identified research questions listed below:

1. Which suitable IoT model can be developed to improve road safety?
2. How can a practical IoT based intervention be designed to support road safety?
3. Which IoT technology is to be adopted in EAC countries?

As an emerging platform based on IoT, ITS is promising for applications in traffic management and road safety. The main objective of this research is to design adaptive speed assistance based on speed signs, meaning to prevent traffic road accidents that are due to absolute speeding. Nowadays, the system-on-chip paradigm allows hardware and software co-design by integrating hardware components and programming software modules. The main objective in this thesis will be fulfilled through specific purposes including:

1. To analyse IoT Technologies in supporting continuous road safety.
2. To design, develop and evaluate a prototype to ensure the speeding limit.
3. To propose an IoT based model for the integration of smart devices.

1.4 Significance of the research

This research employed both modelling and IoT integration approaches to propose solutions for improving road safety. Specifically, the focus of this research was addressing the road accidents that are caused by exceeding the imposed speed by limiting the driver not speed beyond the legal maximum speed at which vehicles may travel on a given stretch of road. The solutions suggested in this work are relevant for countries struggling with improved transportation systems. This is by highlighting the process to achieve intelligent mobility. To achieve the objectives of this work, both qualitative, quantitative, and experimental approaches were combined. These three approaches complemented each other to achieve the objectives presented in this thesis.

The literature presents various existing speed-reducing measures, ranging from road-based measures to technological and engineering-based solutions. Developing countries have adopted modern ICT-based solutions from the developed towards adequate transportation. However, these solutions are associated with various requirements for their implementations. This thesis identifies social-technical needs in the ITS implementation process. The insights on the performance of speed management are brought out and ways to pinpoint them were presented. The proposed solutions will undoubtedly contribute to the road transport safety sector inadequately developing systems and applications for road safety.

1.5 Overview of the significant contributions

This thesis provides a comprehensive literature review on integrating IoT in road transport to ensure road safety and management. The contributions are summarized as follows: A comprehensive literature review and an investigation of the process to achieve effective mobility practices were conducted. We analysed the impact of ITS systems and applications to optimize road traffic safety. The framework to conceptualize intelligent mobility was proposed. We presented an IoT system and the process of limiting the electric vehicle from exceeding the required speed limit. Communication system analysis for a centralized intersection coordination scheme using traffic flow data was proposed to improve the QoS delivery while enhancing safety.

Specific contributions are:

Paper I: The research explored the process for achieving intelligent transport initiatives, opportunities, and challenges to achieving ITS in developing countries like Rwanda. Practitioners' and decision makers' perceptions of ITS were assessed since they are ITS influencers. The IoT-based ITS platform was proposed to improve road transport. An ITS platform stimulated by advances in ICT, access to mobile technologies, the internet and other technological advances will enhance transport safety. The findings presented an interesting perspective on training industry professionals and policymakers to be aware of technical requirements for intelligent mobility. To understand smart transportation's complex concept requires breaking the process into goals, components, and process enablers.

Paper II: The research proposed a strategy to control the speed of a moving vehicle and an IoT-based online monitoring system for continuous monitoring of vehicle data. Data acquisition and a communication system based on a global system for mobile/general packet radio service (GSM/GPRS) were presented. The design and the execution, for which voltage measures were analysed to control the speed. Synchronization between software applications and hardware features has been programmed. The transmission synchronization tests conducted demonstrated that the GSM/GPRS-based on real-time monitoring was successful. The speed control model suggested for control based on IoT indicates that the system can be applied to both other systems for parameter monitoring.

Paper III: The research provided a comprehensive IoT-based traffic flow and signal scheduling mechanism, as minor and property damage accidents are much more likely to occur at high speeds and in complex situations. An analytical queuing model to analyse traffic flows and delays for one phase from the four-phase intersection control of intersection at Latitude 1°57'39.36", Longitude 30°7'12.77" commonly known as Giporoso place. Adaptive scheduling of the traffic lights to minimize the congestion problem was discussed. A numerical algorithm is developed and discussed to compute steady-state performance measures. The IoT-based platform that can be a powerful approach for decongesting road traffic at intersections has been discussed. The roles of information in traffic flow control and resource allocation were studied how queue length information can be conveyed to effectively control congestion effectively. The appropriate traffic signal timing must build on the factors of server utilization, average time spent by cars in the queue and the average number of vehicles in the row.

1.6 Thesis outline

The organizational perspective of this thesis entails focusing on decision-makers as the focus of existing speed-reducing measures. This thesis also pays attention to the ISA process and requirements by using an experimental methodology. This process evaluation provides an understanding of the number of issues pertinent to the implementation, and issues related to IoT, including technology architecture and standardization. A review of existing technology-based systems and applications to enhance road safety is presented, along with their associated requirements and benefits. A summary of the attempted research to develop mandatory ISA is provided, with the technical feasibility of ISA deployment. This thesis consists of five chapters.

Chapter 1 includes an introduction and discusses the research problem. Chapter 2 reviews the research on existing applications, technologies and systems for road safety and an effective transportation system including road traffic treatments and technological solutions. It concludes by introducing the possibility of an IoT based architecture for intelligent transportation. Chapter 3 details the process to manage and control the speed. An experimental and appropriate algorithm was proposed to implement the ISA system. Chapter 4 provides insight into the process of building an IoT-based traffic management center for effective management of the road intersection. Most of the accidents occur at intersections. The study used a situation where speed contributes to a high proportion of accidents that occurred in Kigali. Chapter 5 contains the conclusions and the final remarks.

CHAPTER 2: REVIEW OF ROAD TRANSPORTATION SYSTEMS, APPLICATIONS AND TECHNOLOGIES

This chapter provides an overview of current technologies, road safety enhancement and management systems. Advances in ICT have brought us the era of connectivity. Through connectivity, sensors, vehicles, roadside units, and other communication devices are capable of sharing traffic-related information. In addition, various cooperative intelligent systems have emerged as specialized applications that enable intelligent and coordinated traffic management decisions. The technologies reviewed open endless opportunities for improving efficiency, safety, and reliability with significant potential for enhancing competitiveness, minimizing environmental impact, and improving health outcomes.

Digital, energy and material technologies are expected to transform existing transportation systems individually and collectively by realizing novel solutions for transport, transport control and communication systems. This chapter presents a framework to help design their national strategies to develop transport systems and their expected outcomes, including road safety. Robust sensors, capabilities of the roadside infrastructure together with the potential of connectivity 5G/6G and beyond have provided enough technological base to deliver connected and automated mobility. The importance of a nexus between Government strategies and policies, medical, engineering and technology fields to address road safety challenges is needed.

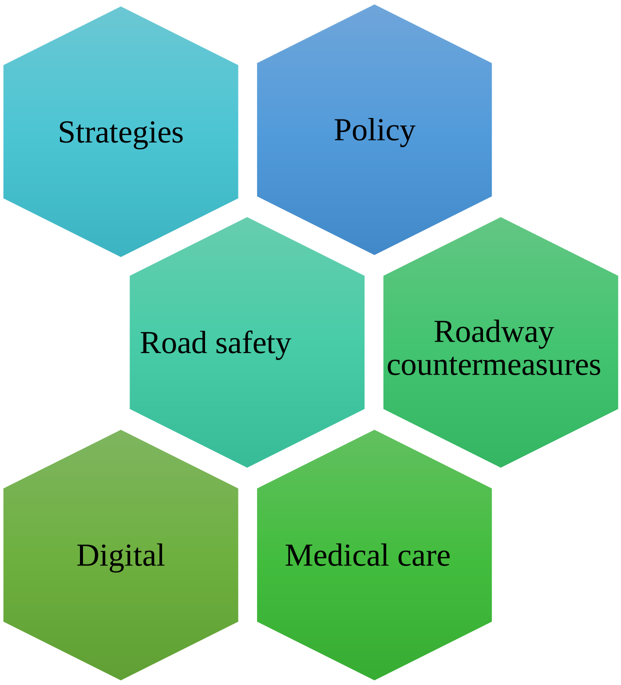


Figure 6 Nexus of fields to address road safety challenges.

The proposed framework could help LMI countries design their national strategies to develop transport systems and their expected outcomes. Opportunities, limitations, and challenges that need to be addressed to realize the benefits of the emerging technologies were investigated. Applying these technologies requires the right kind of governance in place that takes stock of the broader context [24].

2.1 Road transport in Rwanda

In Rwanda, transport is operated in three modes, namely: (i) land transport, (ii) air transport, and (iii) maritime transport. Land transport, which is currently practised through roads, is the main used mode in the country. The percentage of national roads (paved and unpaved) in good condition stands at 75.15%. The national paved road network is said to be in good condition and is estimated at 97%. Road transport is the predominant form of transport, catering to over 90% of freight traffic and passenger travel. The GoR is conscious of the importance of transport infrastructure development in delivering on its long-term development vision. The Ministry of Infrastructure (MININFRA) developed a Transport Sector Strategic Plan for the National Strategy for Transformation (NST1) to guide the transportation sector. However, the transportation sector keeps facing challenges, including, but not limited to (i) public transport characterized by delays, inaccessibility, and unpredictability, (ii) lack of streamlined bus schedules and delays at the terminals, (iii) lack of integrated public [25], [26].

Rwanda's transport safety is essential due to motorized and non-motorized traffic often sharing the same space. However, they are different in operational speed, knowledge of traffic regulations, and levels of protection. From the GoR’s perspective, future mobility in Rwanda will depend on three things: (i) an efficient road network, (ii) regular public transport availability and (iii) an effective institution's responsibility for urban transport planning and policymaking.

2.2 Policies and preferences

The GoR has separated functions by assigning policy, implementation, and regulatory responsibilities to a few agencies, some being highlighted to achieve effective road transport. Public transport policy and strategy explain the restructuring of public transport institutions based on their functional line. These lines are as follows:

- A political layer consists of MININFRA responsible for formulating integrated transport, public transport policies, and corresponding strategies. MININFRA together with its agencies has the mandate to plan, develop, manage, and maintain an efficient and integrated national transport infrastructure network. All these together are for facilitating economic development, environmental improvement, and regional integration.
- The authority layer consists of Rwanda Transportation and Development Agency (RTDA) which is in collaboration with the Rwanda Utilities Regulatory Authority (RURA). RTDA performs all tactical functions for public transport excluding regulation in collaboration with RURA. RURA is responsible for the regulation of the public transport system. This consists of monitoring transport operators’ practices, public transport fares setting and setting rules while also providing technical guidance.
- The infrastructure development layer consists of RTDA and the City of Kigali. RTDA is mainly responsible for developing, coordinating and monitoring transport development projects and conducting research in transport development.
- The enforcement layer consists of Rwanda National Police (RNP) responsible for safeguarding transport safety and security [27].

MININFRA's strategic plan identifies key transportation sector challenges as part of the multi-criteria analysis. Various issues were raised, such as inadequate provisions for integration into transportation infrastructure services, mitigation measures and emergency investigations. The implementation of an integrated transit system was recommended as a critical priority. Reorganization and improvement of existing modes were strategies for improving public transport services in Kigali city [25]. Plans to develop the urban public transport system suggest that Kigali city should develop an integrated transport system. Recommendations also included a land-use policy to take an integrated approach to traffic demand and supply management in various ways. The Rwanda ICT Strategic and Action Plan (NICI III–2015) shows how to leverage ICT in all sectors of the economy to increase private sector productivity. According to the Smart City Rwanda Master Plan, the demand for transport is expected to increase due to rapid urbanization.

However, public transport systems are characterized by overcrowding during peak periods and excessive waiting times during off-peak periods due to the growth of traffic volume which is not proportional to the available road traffic management infrastructure. The country experiences a high rate of injuries and fatalities from traffic crashes due to street designs, and delays in post-crash response. There is a lack of an appropriate system for data storage, management, and open access for the transport sector. Excessive reliance on personal motor vehicles also contributes to increased emissions in urban areas. Road transport is the second-highest source of carbon dioxide (CO_2) in Rwanda [28].

Therefore, identifying opportunities that enable a sustainable increase in the capacity of the current infrastructure is recommended. The Rwanda ICT market is characterized by high evolution and demand for services. 94.2% of geographic coverage and 96.6% of population coverage is 4G LTE technology [29]. Initiatives on applications together with platforms to improve service delivery in transport, including e-ticketing systems, and enforcement of vehicle speed governors will lead to safety. However, enhancing ICT integration in public transport, accidents, and real-time information is still needed. Preliminary analysis, such as social, regulatory, and infrastructural is needed. The correlation between various variables such as technologies with user-friendly applications attributed to individual acceptance of intelligent systems remains to be a challenge [30], [31].

2.3 Applications and emerging transport systems

By 2063, the necessary infrastructure will be in place to support Africa's accelerated integration and growth, technological transformation, and development. As far as transport is concerned, the African Union (AU) targets an improved transport sector by connecting all African capitals. Therefore, the EAC vision 2050 calls for enhanced ease of movement for people, goods, services, and capital. The road transportation system in EAC faces many challenges, some of them being the recurrence of road fatalities. Intelligent systems could be put in place to deal with traffic problems. As part of solutions to address road traffic challenges, digital technology could answer most of these challenges if they were carefully considered and implemented. Rwanda's vision 2050 is a comprehensive strategy focused on improving living standards, and transport is one of the main enablers of the vision. Given that ICT is an enabling tool for smart transport, it shall be at the core of the planning, implementing, and monitoring of all transport projects. However, these modern technologies face the challenge of providing sustainable smart mobility. Technologies discussed in this chapter are some emerging technological innovations proposed and used across the continent and the world. The technologies and systems used to support ITS can be grouped into cautious vehicles, safe roads, and post-crash care. Several technological tools can help drivers not to exceed the speed limit. Drivers can access information about the current speed limit in the area they are driving via in-vehicle devices such as smartphones and GPS. However, these systems do not always consider dynamic speed limits. Therefore, there is the possibility that the system's speed limits are not up to date.

Today, the speed limiter and the adaptive cruise control (ACC) which most new cars are equipped with can ensure that drivers do not drive faster than the permitted speed limit. ACC is promising to have the potential to enhance QoS and safety while potentially reducing the environmental impact of road traffic. ACC was designed mainly as a comfort system, to increase road capacity. Using radar, the ACC automatically detects ahead vehicles and adapts vehicle speed. ACC consists of three layers: the information perception layer, decision layer, and control layer. Hence, when no vehicles are in front of the ACC-equipped vehicle, ACC acts as a fixed speed cruise control and adjusts the vehicle's speed to a set speed limit set by the driver [32]. However, such systems can also be used to set a maximum speed above the maximum permitted speed. Driver behaviour factors including speeding were reported as the cause of road accidents [33].

Through artificial intelligence (AI), autonomous vehicles are promising to impact road safety [34]. From a transportation point of view, there is a requirement for roadside units (RSUs) capable of communicating, as intelligent vehicles are required to learn about various road situations from the roadside for safe decisions [35]. A considerable number of road accidents have been reported to have come from drivers, whether through reckless driving or health issues such as fatigue. Due to this, AI can positively impact road traffic safety since the vehicle would control itself and eliminate drivers' faults. Self-driven cars can also bring positive economic impacts, as some costs incurred by drivers would be eliminated. However, there is none in the EAC government with plans for their introduction. The availability of enabling infrastructures is lacking. For ease of mobility, vehicles communicate to everything (V2X), road-related conditions, and accident-related data sharing are made possible [36]. This is a broad set of technologies that ensure V2X such as other vehicles (V2V) and vehicle to infrastructure (V2I). This would enable data sharing related to road conditions, weather conditions, accidents, and several others.

Despite numerous road traffic challenges that might be answered, the proliferation of cars themselves serves as another challenge that needs attention. It has been observed that an increase in car density also increases the frequency of road accidents, therefore it is of great importance to increase V2V communication and V2I communication between cars and RSUs. RSUs could be a way of ensuring the exchange of information, knowledge, and costs in road transportation. Traffic lights make improving traffic flow efficiency on urban roads possible [37]. Intelligent in-vehicle and roadside traffic signals use adaptive traffic light control agents to produce appropriate signal control [38]. Among the ways of improving services to passengers, a way to predict bus arrival time is essential in reducing wait times at bus stops. However, it is tough to accurately predict arrival times due to diverse alternating factors (slippery roads due to weather, rain, sleet, or snow) and different road conditions. These challenges have triggered a solution based on long-range dependencies between multiple time steps for predicting bus arrival predictions through a recurrent neural network (RNN) [39]. The bottlenecks that occur in major cities are due to most vehicle road users do not predict a route that could be congested at a given time. An in-depth learning approach can improve the accuracy of traffic forecasts to mitigate traffic congestion [40].

Therefore, it is better to use automatic route crack detection methods [41]. Road damage is one of the factors that causes inconveniences on roads. Manual inspection of road conditions is a lengthy process. Digital cameras were proposed for inspection by producing a road surface map based on images, and laser scanners to produce a modelled surface map [42]. GPS monitoring and tracking speeding vehicles in real-time is an important asset. In Tanzania, buses require a micro-controller-based GPS/Global system for mobile (GSM). Facilitated by the microcontroller, the vehicle's speed data is interfaced with the GSM module and sent to the appropriate database. The GPS would help in identifying safe driving drivers [43]. Road traffic congestion control would be better when traffic lights operate based on the number of vehicles on the road. The IoT system can quickly be developed based on a Raspberry Pi, control cameras, infra-red (IR) sensors and radio-frequency identification (RFID) technologies [44], [45]. The cameras help manual control traffic lights after observing the situation on the roads. The IR sensors are used to quantify the number of vehicles on the road. The RFID tags are used to prioritize special emergency vehicles and personnel with executive duties [46]. The use of radar is to send a beam of electromagnetic radiation at a given distance to the target. The turn eco-signals carry information about the distance and the size of the opponent obstacle for driver awareness [47]. The discussed technologies were selected since they address road traffic challenges and are assumed to be the dependent variables for ITS.

Urban population growth in Africa is projected to reach 60 by 2050. The urban projection of Rwanda's working-age population is expected to increase from 1.6 million (2019) to 3.2 million in (2032) [48]. Hence, a survey was conducted to understand attitudes towards the applicability of some ITSs in Rwanda. Discussion of the finding highlights effective ways for the country to develop ICT implementation strategies for intelligent systems. From a transportation point of view, there is a requirement for RSUs capable of communicating with the vehicle. Autonomous vehicles (AV) are expected to reduce crashes, pollution, and congestion. The use of electric cars will reduce environmental pollution due to CO_2 emissions. However, in EAC countries none of them has put in place technical standards for e-vehicles, including environmental standards and regulations for the recycling of batteries and electronic waste, which will be one of the challenges. The GoR aims to reduce air pollution by up to 38% in 2050. The use of electric vehicles will account for 9% [49]. Based on the type of energy source, electric vehicles are categorized into battery electric vehicles (BEV) and hybrid electric vehicles (HEV) [50], [51], [52]. Based on the working principles of BEV, where only batteries feed the electric motor, and the vehicle solely relies on the energy stored in the battery packs, a speed mechanism was proposed [53]. Rwanda intends to replace internal combustion engine (ICE) motors with e-motors, an initiative to promote e-mobility and plan e-mobility transition. However, the GoR should lead the development of standards, and regulations and a policy framework for charging infrastructure, recycling of batteries, and data sharing. The transition from ICE vehicles to EVs should consider significant implications for existing automotive business operators. With the green transportation agenda, the GoR through the International Finance Corporation (IFC) has initiated a study on electric bus concept validation in Kigali. This started by developing a diagnostic framework to prioritize and evaluate the potential for the adoption of e-mobility solutions in Sub-Saharan African cities. It includes technological feasibility, operational structure, procurement, financing, and stakeholders' engagement. V2X communication ensures easy mobility [36]. Electric mobility is rapidly gaining attraction worldwide as an energy-efficient solution for the transport of goods and people while avoiding emissions.

The AU calls on African states to invest in infrastructure for innovation through technical improvements. Intelligent in-vehicle and roadside traffic signals use adaptive traffic light control agents to produce appropriate control signals [38]. In Rwanda, speed governors are being installed in public vehicles (public buses, school buses, etc.) and freight transport vehicles to enforce traffic rules to reduce traffic-related accidents. Road safety cameras are being installed on national and Kigali city roads. These cameras would also be used to collect traffic flow data, which can be used for transport planning and management. It is in this regard, that the procurement process for a feasibility study for the development of roadside stations in Rwanda was initiated through the support of the Central Corridor Transit Transport Facilitation Agency (CCTTFA) [54].

An in-depth learning approach can improve the accuracy of traffic forecasts to mitigate traffic congestion [40]. The internet of the road has profound benefits such as accident prevention and time-saving [55], and automatic route crack detection methods for roads [41]. The GPS to monitor and track speeding vehicles in real-time will help identify safe driving drivers [43]. The IoT system can quickly be developed based on a Raspberry Pi, control cameras, IR sensors, and RFID technologies [45]. The RFID tags are used to prioritize special emergency vehicles such as ambulances [46]. Road accidents constitute one of the priorities in transportation research. Road safety causes a substantial cost to economies, and significant trauma to societies. Sub-Saharan countries lack proper ways of reporting the intangible costs of road accidents, which leads them to the improper consideration of the road accident cost burden.

Hence, the countries need to put in place a favourable policy environment that encourages experimentation and supports the adoption of modern technologies and innovation. Africa may set its regulations and global standards in this field. This requires mobilizing regulators, standard-setting agencies and policymakers in technology development and application. Africa needs to make its own economic and social considerations for the emerging technologies to ensure no one is left behind. This is by determining the costs and benefits of different modes and models for deploying and building innovative transport systems in the immediate term. Social issues such as safety, privacy, and inclusivity need to be considered from the onset.

2.4 IoT enabled intelligent transport

Traffic management and travel information systems are already on the market. They have proved their effectiveness. Modern societies can rely on a traffic management system (TMS) to reduce the number of road traffic accidents and their negative consequences. TMSs are made up of applications and management tools that work together to improve traffic efficiency and safety. Transport modelling, and traffic forecasting are the backbones of road planning. Technology adoption in transportation is always challenging for technologists, managers, and executives. The ITS applications discussed are designed to improve road transport efficiency, safety, and sustainability. Smart infrastructure must be considered during road planning and design to enable the road's communication capabilities. Behind intelligent infrastructure, the ITS framework at the national level must be developed to assist road authorities in monitoring road traffic. The IoT-based ITS conceptual framework presented provides appropriate tools to understand the situation in Sub-Saharan cities. Figure 7 depicts a comprehensive map to understand the key factors to be considered in developing a transportation master plan.

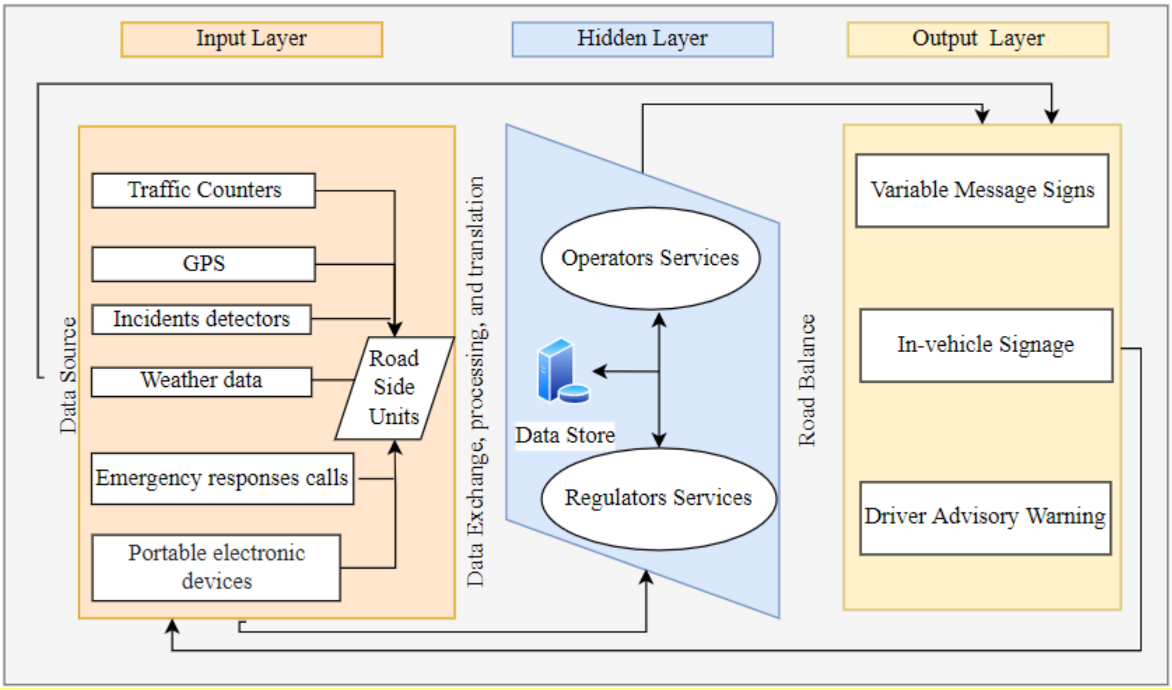


Figure 7 IoT based conceptual framework. Source: [24]

- The input layer is the data ingest layer. Integration of the IoT with road traffic information is collected using various technologies (inductive loop detectors, radar detectors, magnetometers, weight in motion systems, and speed detectors) to provide the status of road network issues. The whole traffic data source is gathered for data value harvesting and extraction. Public transit agencies and private sector tech firms can use the technology to simplify passengers' planning for their trips, but also the government can plan based on this data.

- Hidden layer, the traffic data is generated in various forms. The data is gathered for further translations at this processing layer. An IT system is built to distinguish pieces of information together with software that enables a particular purpose. Data transmission to disseminate processed data is performed at this layer. All road users, including passengers, car drivers, and cyclists, across all modes of road transport, would benefit from the effective use of generated data.

- Output layer, those acquired data after being processed are shared according to the user’s needs of the route or car. Access to information through devices is possible with Wi-Fi, LTE communication access for revenues, roadside variable messages, social media messages, and in-vehicle displays. Today, modern technologies paired with existing data sources give the world an unprecedented opportunity to address the increased demand for data.

The availability of high-quality, timely, open statistics and the ability to use data is critical for governments, the private sector, and the public to make informed decisions. Developing countries continue to face immense challenges in generating such data statistics. Today, new technologies paired with existing data sources give the world an unprecedented opportunity to address the increased demand for data. Apart from improving data monitoring, there is great potential to use technology to implement the sustainable development goals (SDGs).

2.5 Overview of the process improvement, methodology and tools

To conceptualize the ITS framework, an in-depth study was conducted through government documents, interviews, and a survey. The survey was conducted using a random sampling technique to obtain opinions, readiness for ITS, existing technologies, and transportation applications. Professionals from the government, private sector, academia, and public sector comprised the population of interest. Government agencies with primary responsibilities for transportation strategy, policy, implementation, and service delivery were chosen as they can influence traffic management practice. Analysis of the respondent's views concerning the literature reviewed was conducted. Respondents were selected based on the individual’s role in transportation practice, managerial decision-making, and their influence. Engineering students and professors were classified as public sector workers. The survey responses were analysed to find issues and challenges to be addressed for ITS implementation in Rwanda.

The respondent's perceptions were assumed to correspond to their critical perception of ITS as the majority were from the transportation sector. Out of 800 respondents, 225 responses were suitable for the analysis. Among responses, 28% of respondents were from the government, 28% from the industry/private sector, 23.11% from university and 20.89% from the public sector. Of the 220 respondents who preferred to share their education level, 1.4% were with primary level, 18.6% secondary level, and 80% university level. Out of the 225 responses, 26.22% of the respondents were familiar and 73.78% were not familiar with ITS. Similarly, when it comes to the smart road/highways concept, 35.56% have never heard of it while 64.44% did. A five (5) point Likert-type scale was used to examine the respondent's awareness of the technologies discussed above.

ICT infrastructures are needed to develop emerging technologies. The region's cities must enable V2X communication to achieve the ITS. An embedded device is required to facilitate vehicle communication. Out of 223 respondents, 90.13% were interested in seeing vehicles as nodes, whereas only 9.87% were hesitant. The V2X facility that allows vehicles to share traffic information is a way to improve transportation systems and associated road safety challenges.

However, there is little chance that a standard ITS will succeed in the region. ITS has a global dimension. EAC countries, Rwanda included, do not meet ITS standards for wireless communications, network architecture, and protocols. The creation of a commonly agreed standard for the data collection, control of vehicle networks, processing, and provision of information could harmonize ITS in the region. Infrastructures and their management have been a challenge for the least developed countries. Various goals and initiatives fail due to the complexity of government attempts to tackle each problem with one solution. Different technologies are expected to have a significant impact on road safety. New vehicles equipped with driver automation and connected transportation systems will improve road safety. The provision of infrastructure is the first step in the implementation of ITS. A typical context-awareness system is built based on perception (data collection), reasoning (processing), and the acting (information sharing) layer. Transport systems require dedicated agencies with skilled, professional planners and operators. As part of the exercise of skill development, developing a strategy and training, learning and development programs for public officials and practitioners are of great need. Table 2 presents the percentage of the respondent's familiarity with the technologies reviewed.

Table 2 Technology and systems awareness. Source: [24]

Sno.	Technology	Aware	Not Aware
1.	GPS tracking systems	51.1%	48.9%
2.	Smart traffic lights	49.3%	50.7%
3.	Self-driven vehicles	38.7%	61.3%
4.	Internet of roads	37.3%	62.7%
5.	IoT based traffic monitoring	35.6%	64.4%
6.	Traffic flows prediction	33.3%	66.7%
7.	Electric vehicles	32.4%	67.6%
8.	Intelligent road (RSU)	29.8%	70.2%
9.	Road damage detection	27.4%	71.6%
10.	Collision avoidance system	26.7%	73.3%

The achievement of ITS is beyond a strong political will. There is also a need to marry backgrounds and domains to develop and build technologies welcoming infrastructures. According to respondents' perception, there is a strong need to strengthen ICT/computer science and transportation. ITS implementation is a gradual process, starting with the provision of infrastructure. The communications infrastructures are critical for ITS functions' effective and efficient operation. For instance, the GoR is building roads, with lights, well-constructed footpaths, streets with open drains, speed bumps, large turning radius, traffic lights, cameras at intersections. The research presented in this chapter will assist municipal managers and program directors better understand the complex concept of intelligent transportation by breaking down the process into process objectives, components, and enablers. Multiple interpretations of ITS concepts are possible, which might blur the concept. Smart city indicators include smart mobility, smart people, smart governance, and a smart environment. In developing a smart city, smart mobility must be targeted to increase efficiency and service quality for citizens. Living standards will improve with the development of platforms compatible with innovative services. Research in the ITS field, and its deployment are focused on developed countries. Therefore, it is crucial to explore the concept in developing countries. In this work, an overview of the challenges of intelligent transport in the region with a specific focus on road safety was reviewed. Also, a survey was conducted by using a random sampling technique to obtain opinions on the readiness of ITS, existing technologies, and transportation applications. Vehicle infrastructure integration is the promise of revolutionary mobility improvements, and dramatic safety improvements. This research contributes to raising awareness of the possibility of ITS and provides a centralized platform for road data collection.

CHAPTER 3: REVIEW OF SPEED REDUCTION AND ADAPTATION MEASURES

Speeding is a major factor in traffic deaths and injuries. The role of speeding in crashes is described in terms of its effect on the driver, the vehicle, and the road. In 2019, speeding was a contributing factor in 26% of all traffic fatalities [56]. In high-income countries, speed contributes to about 30% of deaths on the road, while in some LMI countries, due to their data-hungry, speed is only estimated to be about half of all road crashes. Cruise control and speed limiter systems were introduced to influence drivers' speed management. They are available in a variety of new vehicle brands. Despite differences between models, speed management includes setting proper speed limits, improving the homogeneity of the traffic flow, and reducing speeding. Road safety measures can be subdivided into three categories: engineering (e.g., roadways configuration) [57], [58], enforcement (e.g., technological solutions) [59], [60], and education measures (e.g., public campaigns to educate the community safety benefits of complying with speed limits) [61], [62]. These speed measures have proven to be effective over time [63]. Speeding can be discouraged through roadway design, education, and enforcement. There are a few methods for reducing vehicle speeds. They can be classified as engineering-based interventions and behavioural-based interventions. Several resources are available that discuss the design, deployment strategies, and effectiveness of various speed-reducing measures.

3.1 Roadway configuration

This category of speed-reducing measures changes the roadway's design to enforce the desired speeds. Speed management aims to reduce the number of road traffic crashes, serious injuries and deaths that result from them. Numerous practices have been implemented in urban areas to reduce speeds. However, different design standards (French, British and American standards) are used by EAC member states. These are some engineering treatments for traffic-calming measures that are the most popular used to reduce speed or volume of traffic.

3.1.1 Speed humps and speed tables

The Ministry of Infrastructure and RTDA recommend the practice for the design and application of speed humps. Speed humps are intended for traffic speed reduction. They have gained acceptance by Rwanda and international jurisdictions. Mostly in Rwanda, humps are used to reduce the speed of vehicles around places where many pedestrians crossing are expected. They are also installed on the major arterial corridors and slopes. However, when considering the future increase in traffic demand, the current hump operation will need to be changed or improved. To meet the EAC standard, it is recommended to adopt its cross-section when rehabilitating the existing or new humps in the road network [64]. Each speed hump must be painted with a pattern that makes them visible to drivers. Humps should be placed near streetlights to increase night-time visibility and in a trapezoidal shape. The speed humps must be located with enough sight distance to allow drivers to see and then react so that those travelling at excessive speeds can maintain control of the vehicle when traversing the hump. The top length of the speed hump must range from 4m to 6m and height from 0.075m to 0.1m and the total length of road humps should vary from 4.0m to 9.5m. Speed tables are another version of speed humps. The significant difference is that the top of the speed table is flat instead of parabolic. Speed tables are typically used to slow drivers in the middle section of a city block or on approaches to multi lane roundabouts. Speed tables are most often used as an alternative to speed humps. Figure 8 shows the design of the speed hump crossed by the vehicles.

Figure 8 Vehicle passing on humps.

3.1.2 Speed zone and speed limits

Speed limits are an essential part of informing drivers of the appropriate speed on the road. Speed limits for rural and urban areas in EAC countries vary from no limits at all to limits. The inappropriate use of road signs, and the excess of roadside prohibitions may lead to unsafe driving. The speed limit should above all aid the driver's perception and facilitate the correct interpretation and evaluation of the layout and conditions of the route. Speed limits are in place to support mobility. The installation should be designed to achieve safety and efficiency within the confines of the available road space. Table 3 shows the urban and rural speed limit in EAC member states, though they are not specific for some countries.

Table 3 The maximum default speed limit in EAC countries.

Country	Rural speed limit	Urban speed limit
Rwanda	80 km/h	80 km/h
Uganda	100 km/h	50 km/h
Tanzania	-	50 km/h
Burundi	100 km/h	50 km/h
Kenya	100 km/h	50 km/h
South Sudan	-	50 km/h
DRC	90 km/h	60 km/h

In Rwanda, the speed limits on the freeways vary between 40 km/h in urban areas and 80 km/h in rural areas, although for most of the places in the city the maximum speed limit is 60 km/h. Road authorities monitor speed levels by using stationary and mobile speed cameras in high accident zones to reduce the number of fatalities. Since 2019, cameras have been put up in strategic areas of roads to ensure road users' safety and help to identify and fine violators.

3.1.3 Advisory speed warning signs

Efficient road signage is a critical component of the road network for enforcing traffic regulations and ensuring road safety. A road with poor signage or signage that is not well maintained is indeed unsatisfactory. In Rwanda, traffic signs are of three types with distinguishing shapes: signs that give orders, signs that warn and signs that give information. In most cases, circular signs give orders, triangular signs worn, and rectangular signs inform. Advisory speed signs are often used with a warning sign where the safe speed is lower than the applicable speed limit, such as in a curvature area (e.g., horizontal, and vertical curves). Figure 9 shows the advisory sign of 40 km/h as the maximum speed limit in the zone ahead that has a sharp road curvature.

Figure 9 An advisory road speed sign.

3.1.4 Roundabouts

A roundabout is a circular intersection design where traffic travels at low speed around a central island and entering traffic must yield to circulating traffic. Roundabouts improve safety, promote lower speeds, and reduce conflict points [65]. Roundabouts are of various types. The most available in Rwanda are single-lane and two-lane roundabouts. Single-lane roundabouts with good designs reduce 85^{th} percentile speeds to 27 km/h (17 mph). Multilane roundabouts often need to be combined with speed humps or speed tables. This reduces top speeds to anything below 40 km/h (25 mph) during low-volume times when drivers can straddle lanes, but even that is a lower speed than typical at many traffic signals. Two-lane roundabouts would typically have an inscribed circle diameter range of 55 m to 67 m. Roundabouts can be used even if there is very little cross-traffic. Motorists prefer them at busy locations as they reduce average travel times significantly compared to signalization [66]. A roundabout's safety performance is a result of its design. Vehicles travel in the same direction at roundabouts. They eliminate the right-angle and left-turn conflicts that are common at traditional intersections. It is difficult for drivers to speed through an appropriately designed roundabout [67]. Speed control is provided by geometric features and can be achieved at all times of the day. principle, lower vehicle speeds provide safety benefits, including helping drivers judge, adjust speed, and make crashes less severe. Figure 10 shows the design and various parts of the two lanes roundabout.

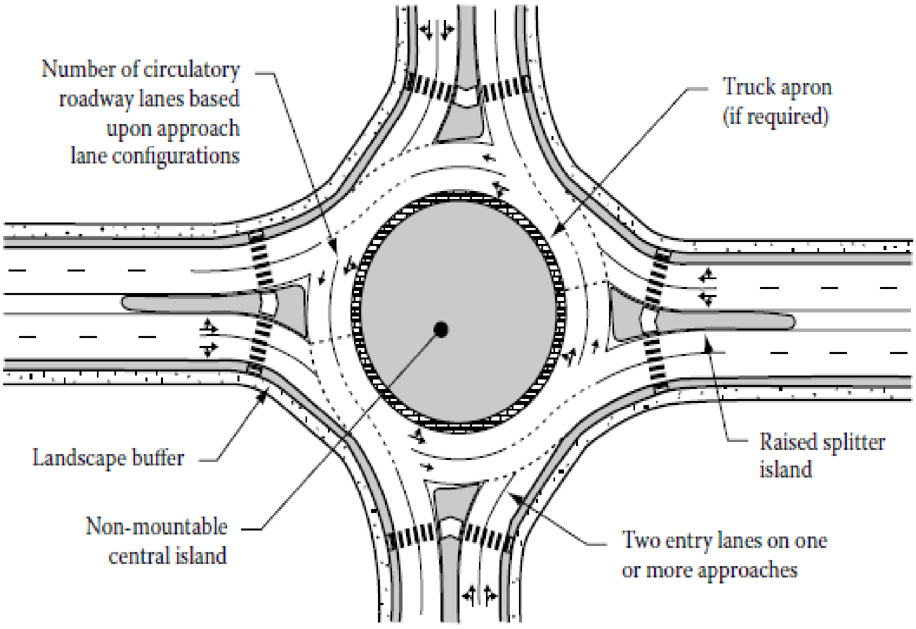


Figure 10 Features of a typical-lane roundabout. Source: [68].

3.2 Technological solution

Technological advances have created the opportunity to develop and test several innovative intelligent mobility solutions. Some systems build on roadside data. These can be in-vehicle itself and others which combine both RSU information and in-vehicle as sources. Enforcement countermeasures can detect speeding and penalize violators. However, there is a need to identify the functional requirements, equipment requirements, and personnel requirements of those technologies.

3.2.1 Speed governor and GPS tracker

As aforementioned, among the measures to reduce the number of traffic accidents, one has been the mandatory installation of speed governors on public buses, commercial vehicles, roadside speed cameras and arrive safely (Gerayo amahoro) program to curb the increasing rate of accidents and to promote a culture of safety consciousness. Apart from installing speed governors, road authorities can place a GPS tracker into vehicles to enable owners to monitor their vehicles. The data from the GPS tracker facilitate monitoring speeding, obtaining driver's information using the transport license system, and providing driver's position and contact information to RNP using short message service (SMS). GPS and in-vehicle computing capability, the prevailing speed limit can be determined. Hence, the speed governor should make it impossible to limit the driver to drive faster than the speed limit. If everybody always kept the speed limit, then the number of fatalities would be reduced by almost 30% to 50% [69].

3.2.2 Variable speed limit

An increase in average speed is relatively associated with an increase in a collision [70]. Nowadays, ITS-based solutions facilitate travel in a more organized way. One of the approaches has been the variable speed limit (VSL) to optimize traffic flow by adapting the speed limit to real-time conditions [71]. They enable speed limits to be changed dynamically in response to traffic conditions so that traffic incidents can be reduced significantly in free-way work zones. VSL has been used with other traffic flow control strategies to improve traffic throughput while reducing bottlenecks [72]. Variable message signs are installed on motorways to notify drivers about the current speed limits [73]. Their contributions are significant in terms of speed harmonization [74]. The presence of an active VSL in the region results in increased traffic density and inflow reduction. The VSL strongly influenced traffic flow dynamics, such as congestion management [75]. Today's real-time traffic data available for moving vehicles has enabled the development of ITS applications for traffic control services [76]. The GSM cellular network covers 96.4% of Rwanda. The fourth-generation long-term evolution (4G LTE) technology was deployed across 94.2% of its geographical coverage. Developing an application that is cellular communication-based is cost-effective. Road deaths in Europe make up 20% of young people (15-30 years). Hence, the European Transport Safety Council (ETSC) advocated the benefits of ISA systems that assist drivers at the speed limit. Some EU member states enforce fines for speeding and other traffic offenses as a solution. Moreover, member states are advised to act on speeding as part of a strategy for road safety for the next decade [77].

In recent years, automatic traffic sign recognition has been a subject of consideration due to its role in increasing traffic safety. The sign recognition process consists of the detecting and recognizing the symbolic meaning by a predefined meaning of the traffic symbols in the database. The automatic recognition system helps alert drivers to the presence of road signs [78], [79], [80]. With the global telecommunication scenario advancing towards multi-tier deployment, there will be network densification in the form of heterogeneous small cells of different coverage areas and traffic capacity. Deploying a V2I communication heterogeneous network environment and satisfying diverse application requirements could be burdensome [81]. Deployment of the 5G system model constituting a heterogeneous multi-tier, device-to-device communication will support V2I communication-based services [82]. While moving from one place to another, the vehicle will cross many small heterogeneous networks. This network connectivity will require faster and underlying network systems.

3.2.3 Traffic sign recognition

In recent years, evolution in ICT, and computation technologies and road environment have created a novel adaptive driving assistance system (ADAS) application that can identify situations and warn the driver accordingly. As a result, traffic sign detection (TSD) has become an important topic. The research on traffic sign recognition (TSR) systems has been centred on European traffic signs [83], [84]. Although, one of the challenging issues is that signs look very different across different parts of the world. A system that works well in Europe may not work in Africa or the United States of America (USA). The US signs are significantly different in appearance from those in Europe, depending on countries that have ratified the Vienna Convention on Road Signs. TSR after image acquisition, some pre-processing tasks are performed. The image is segmented using colour information, and then morphological closing is executed to find the segmented image. The TSR system is developed in different modules and algorithms for traffic signs detection. However, the system suffers from different challenges, like the inability to recognize signs accurately. Designed traffic sign detection and recognition to enhance driver safety through the fast acquisition and interpretation of traffic signs. However, major challenges include a low acquisition vision system, road conditions, a moving car, and an imperfect sign state such as physical degradation of signs. As an essential subsystem in intelligent transportation system technology, TSR systems based on computer vision have become an important research topic in ITS [85].

Nowadays, there is no significant study in areas of application of ADAS for African countries, where there are different driving styles and heterogeneity in road systems. New cars today have built-in autonomous features. Self-driving technology has the potential to reduce the increase in millions of lives lost by preventing road accidents. However, there is still a gap in terms of road infrastructure when it comes to LMI countries [86], [87], [88]. The majority of the ADAS studies are concentrated in Europe, where countries have similar road safety cultures and driving styles [89]. The field of Vehicular Ad hoc Networks (VANET) still needs attention due to its technological applications and technical challenges. From the communications in a VANET to be realized, vehicles and roads are equipped with wireless communication devices which include onboard units for vehicles and onboard nodes called RSUs deployed along the roads.

3.2.4 Intelligent speed adaptation (ISA)

ISA is an intelligent in-vehicle transport system, which warns the driver when exceeding the required speeding, by discouraging the driver from speeding or preventing the driver from exceeding the speed limit. The in-vehicle control system achieves acquisition and processing and realizes the control of mechanical actuators [90]. As a result, the market availability of cruise control and speed limiters has been increasing, and they are currently present in several brands of vehicles on the market.

3.2.5 Automated speed enforcement (ASE)

This consists of the use of automated speed cameras that record a vehicle's speed using radar and a camera that captures the vehicle when the threshold speed is exceeded. Fixed speed cameras are an effective mechanism for dealing with a specific location with known crash history. The cameras measure the average speed of vehicles over a substantial distance, and they are the most used in Rwanda to discourage drivers from over-speeding [61]. However, speed limits reflect a better balance between safety and mobility objectives. The most common ASE technologies rely on speed cameras, which are activated when a driver exceeds the specified limit. Violation evidence is processed and reviewed in an office environment and violation notices are delivered to the registered vehicle owner after the alleged violation [91], [92]. School zones, residential neighbourhoods and highway work zones are frequently selected as locations for ASE. Therefore, enforcement of speed limits by speed detection systems is effective in reducing crash and injury risks. Figure 11 shows the speed camera imposed on the road to capture the over speeding vehicles’ data for further police decisions.

Figure 11 Speed camera around Giporoso.

3.3 Dynamic speed adaptation architecture

3.3.1 Electric vehicles

An electric vehicle comprises batteries that store power, an electric motor that drives the wheels, and a controller that handles the flow of energy to the engine. The motor, controller, and power supply are the main components of an electric vehicle system. Electric motors are found in so many sizes and locations and have so many applications. Batteries come in two distinct flavours, including rechargeable and non rechargeable. The no rechargeable batteries are disposed of when they are out of power; while rechargeable batteries, you connect to a recharger or source of electric power to build them up to capacity.

Hence, regardless of the voltage source, the controllers which are built with reliable solid-state are designed to meet virtually any need of the electric car. The EV can run on electric propulsion or can have an ICE working alongside it. However, the EVs that use electric motors are more efficient than the power train of ICEs [93]. Depending on the power supplement and propulsion characteristics, the EVs are classified as battery electric vehicles (BEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV) [94], [95].

3.3.2 Speed control

Integrated hardware was configured along with the software to operate with different types of sensors and actuators. Those sensors consisted of infrared (IR) sensors, voltage sensors, GSM/GPRS module, a metal-oxide-semiconductor field-effect transistor (MOSFET), and a DC-DC converter. The in-vehicle device consists of the microcontroller which is the central part of acquiring the variable speed control design, an IR Sensor that measures infrared radiation in their environment [96]. This GSM/GPRS module allows data transmission to a remote web server and the GPS module. The EV was built with four (4) batteries connected in parallel. The electric motor only drives the vehicle. All batteries' positive and negative terminals were connected in parallel to maintain a constant voltage. With the mentioned sensors, the brain of the prototype was the microcontroller, which had the responsibility to regulate the inputs. The MOSFET's responsibility was to execute the speed control law. The designed control system has the desired behaviour. A voltage divider rule was used to convert a higher input voltage to a lower output voltage to control the speed of the motor. Input and out pulse width modulation (PWM) generated variable-width pulses to represent the amplitude of an analogue input signal. The current flow was controlled by regulating the amount of voltage across the motors. The microcontroller uses the PWM technique to control the speed of the motor is expressed as:

$$PWM = \frac{D}{256} \times 12V \quad (1)$$

where PWM is the pulse width modulation and D presents the duty cycle.

The duty cycle of the PWM signal (PWM wave) is on a score of 0-255 volts and was used to vary the speed of the motor. The MOSFET changes the amount of applied voltage to the motor which varies in 0-12 volts. The microcontroller was programmed to run the controller algorithm, sensor fusion, and serial port communication. A call to analogWrite (100) was applied for a speed limit of 40 km/h, analogWrite (150) for 60 km/h, analogWrite (200) for 80 km/h and analogWrite (255) for 100 km/h respectively, such that analogWrite (255) requested a 100% duty cycle equivalent to 12 V. Real-time vehicle data are transmitted through GSM/GPRS to the web-server database, assumed to reside in the traffic management center (TMC). Figure 12 shows the internal vehicle speed control system and the components.

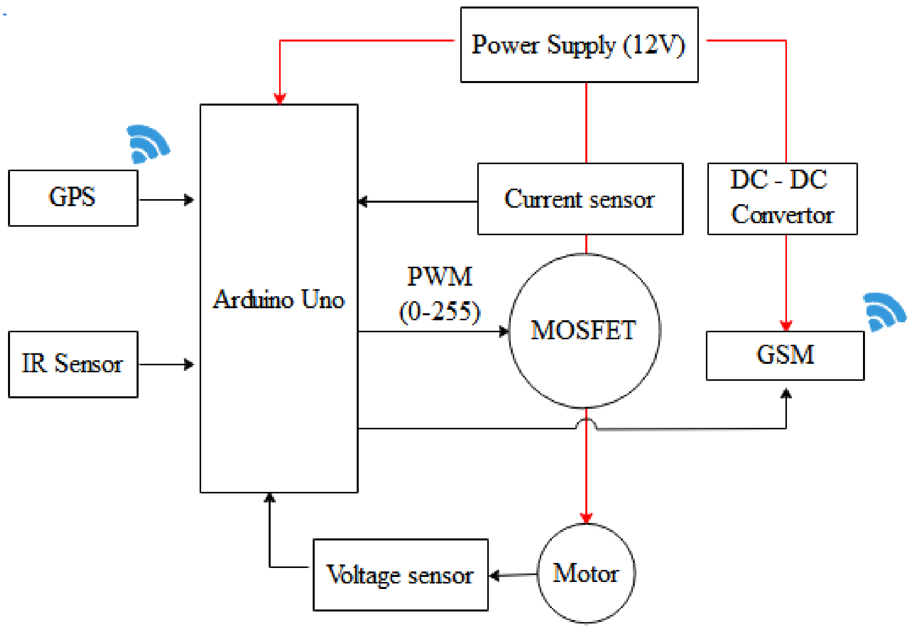


Figure 12 The architecture of the speed control system. Source: [90].

3.3.3 Voltage modelling system

Predictive models such as convolutional neural networks, hidden Markov and deep learning techniques have been developed to predict the speed based on previous speeding history. In this research, voltage prediction models were built to show the dependence between vehicle speed, the voltage supplied to the vehicle's motor, and road curvature information. In driving scenarios, speed is one of the major causes of accidents. Various variables such as road geometry, sight distance, and road surface type were found to contribute to speed. Hence, these factors that influence speed-related accidents were considered to develop DAS systems. Furthermore, location and geometric information about the road curvature [97], curve speed warning systems [98], and road curvature with speed limits can be used to adjust the vehicle's speed [99]. A predictive model can be embedded in the developed smart device installed in the vehicle to keep displaying the speed and inform the internal devices about the voltage to be supplied to the motors. The in-vehicle components collected the data used for modelling. Rwanda follows the policy on the Geometric Design of Highways and Streets [100].

Due to the shortage of data, standards require that curvature be used to set up speed limits [101]. The voltage, which is the electrical energy from the car's batteries supplied to the motors to cause the rotation of the car's wheels, was predicted. A comparison between the two models, MLR and RF, was performed to find the best model to predict the required voltage to be supplied to the motors. The correlation between voltage with imposed speed limits and road curvature information was transformed to linearize the speeding function. The driver's operating speed depends on the supplied voltage from the batteries, which in turn depends on the maximum lawful speed posted on the regulatory sign and road curvature information. If the voltage increases, the speed increases. In contrast, the decrease in voltage is equal to the magnitude of the operating speed.

3.3.3.1 Multiple Linear Regression (MLR)

The MLR technique can be used to model the voltage data for the speed control of the EV in terms of other parameters of the imposed speed limit and the curvature information. For the MLR model, the dependent variable voltage is assumed to be a function of k independent variables $x_1, x_2 \ldots x_n$, here referred to as the speed limit and road curvature data. MLR considers the inclusion of various explanatory variables, speed limit and road curvature, to study the voltage phenomenon. Multiple regression is an extension of simple linear regression. It is then expressed as:

$$y_i = b_0 + b_1 x_1 + b_2 x_2 + \cdots b_k x_i + e_i \quad (2)$$

Where y is an independent variable $b_{0,}, b_1, b_2 \cdots b_k$ are fitting constants, $x_i (i = 1, 2 \cdots k)$ are predictor variables, and e_i is a random error.

3.3.3.2 Random Forest (RF)

The RF model is a machine learning model that combines the classification algorithm to make output predictions from a sequence of regression decision trees. The model is based on the concept of ensemble learning, independently constructed based on a random vector sampled from the input data prediction built on the classifier in the assembly. The number of trees in the forest and the number of variables utilized to develop each tree are the primary characteristics influencing the RF model's capacity to estimate.

$$MSE_{OOB} = \frac{1}{n} \sum_{i=1}^{n} (O_I - P_{iOOB})^2 \quad (3)$$

where n is the observation number and P_{iOOB} is the average of the OOB's predictions across all the trees.

For the MLR and RF models presented, the informational character of the models may be considered sufficient based on the number of parameters selected to assess each model. To evaluate the performance of both the models, the results were evaluated by the mean absolute error (MAE), mean squared error (MSE), root-mean-square error (RMSE), and R squared (R^2). The voltage modelling scenario used was considered a regression problem, a set of statistical processes for estimating the relationships between the response variable and predictor variables, hereby referred to as the posted maximum speed and the road curvature information. The MAE is a risk metric corresponding to the expected value of the absolute error. The MSE is the average of a set of errors. The RMSE is the standard deviation of the residuals (prediction errors). The R^2 is a statistical metric used to measure how much of the outcome is to be expected (voltage to be supplied). The R^2 values range from zero to one [0, 1]. Hence, zero (0) illustrates that the voltage to be supplied to the motor cannot be predicted by the speed and curvature values, while one (1) implies the perfect prediction of both predictors without the error.

3.3.4 IoT system design for vehicle monitoring

With the help of the microcontroller, the in-vehicle device packs the data and then uploads the vehicle's data to the Cloud web platform through the GSM/GPRS module. The vehicle's speed, the voltage supplied to the motor, and the current and geolocation data are collected. Road authorities and drivers could use various intelligent terminals to access the cloud platform as well as obtain data in real-time. The layers of the architecture are the sensing layer (moving car equipped with sensors), network connectivity layer (GSM communication), and service layer (the users). The data collected at the sensing layer are obtained in a variety of formats, including comma-separated values (CSV). Data-based models fully become actionable at this level. Hence, the data might be analysed to become valuable information to road traffic authorities or health personnel's specific requirements and patterns. Based on the functional requirements, data-driven models that learn data might be developed to make use of the vehicle's data.

Developing an IoT-based solution that allows road users and road authorities to track vehicles' data in real-time would contribute to road safety measurements. For example, setting speed restrictions is one of the strategies for reducing the increase in speed-related accidents. Therefore, it is vital to build responsive and effective decision support mechanisms to handle speeding-related issues. The remote database was used to keep the collected vehicle data for data analysis services and user-oriented application services [105]. Different groups of users access all tracking information from a web-based application in real-time. These users may include an admin facility to contact the driver, and the user to track their driving history. This application/service layer is where industry-specific applications such as predictive models can be developed based on a custom application.

The sensors were connected to a microcontroller board with the GSM/GPRS module enabled to send data to the configured database server in the experimental setup configuration. The EV was built with four (4) 12V batteries linked in parallel. The electric motor only drives the vehicle. The positive and negative terminals of all batteries were connected in the same manner to maintain a constant voltage (12V). Together with the mentioned sensors, the brain of the prototype was the microcontroller that had the responsibility of regulating the inputs. In this research, the training dataset consisted of 70%, whereas the remaining 30% of the records were used for a test. This produced better error results, compared to the 80% testing and 20% training method. The voltage modelling scenario used in this work was considered a regression problem, a set of statistical processes for estimating the relationships between the response variable and predictor variables, hereby referred to as the posted maximum speed and the road curvature information. Figure 13 shows the architectural diagram of a cloud based IoT platform developed with the primary goal of tracking and storing the data of moving vehicles.

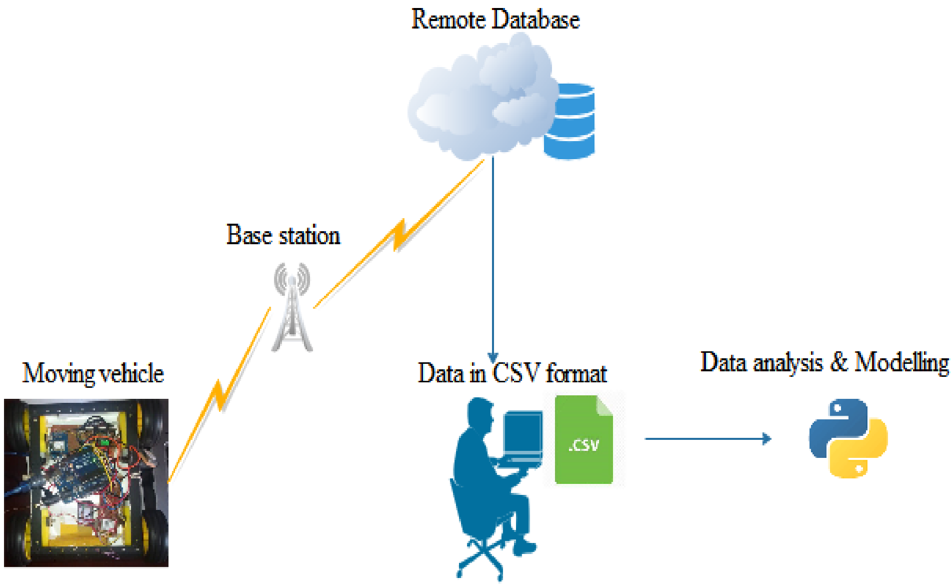
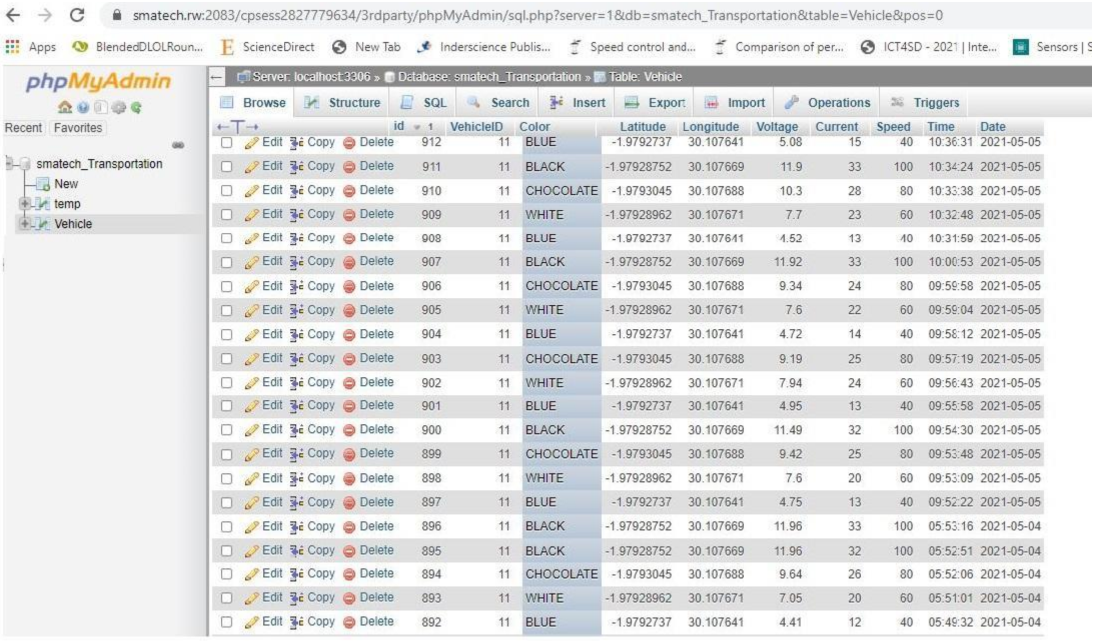


Figure 13 The fundamental layout of IoT-based vehicle monitoring. Source: [90].

Figure 14 presents the layout of the data transmitted by the database. Both prediction models were tested using the acquired sensor data captured by the developed IoT system and the curvature data. Figure 15 shows that the speed increases proportionally for every positive increase in voltage. The function box plot in the seaborn library produces the plots that are used to determine whether the imposed speed limit and road curvature have more voltage outliers.



id	VehicleID	Color	Latitude	Longitude	Voltage	Current	Speed	Time	Date
912	11	BLUE	-1.9792737	30.107641	5.08	15	40	10:36:31	2021-05-05
911	11	BLACK	-1.97928752	30.107669	11.9	33	100	10:34:24	2021-05-05
910	11	CHOCOLATE	-1.9793045	30.107688	10.3	28	80	10:33:38	2021-05-05
909	11	WHITE	-1.97928962	30.107671	7.7	23	60	10:32:48	2021-05-05
908	11	BLUE	-1.9792737	30.107641	4.52	13	40	10:31:59	2021-05-05
907	11	BLACK	-1.97928752	30.107669	11.92	33	100	10:00:53	2021-05-05
906	11	CHOCOLATE	-1.9793045	30.107688	9.34	24	80	09:59:58	2021-05-05
905	11	WHITE	-1.97928962	30.107671	7.6	22	60	09:59:04	2021-05-05
904	11	BLUE	-1.9792737	30.107641	4.72	14	40	09:58:12	2021-05-05
903	11	CHOCOLATE	-1.9793045	30.107688	9.19	25	80	09:57:19	2021-05-05
902	11	WHITE	-1.97928962	30.107671	7.94	24	60	09:56:43	2021-05-05
901	11	BLUE	-1.9792737	30.107641	4.95	13	40	09:55:58	2021-05-05
900	11	BLACK	-1.97928752	30.107669	11.49	32	100	09:54:30	2021-05-05
899	11	CHOCOLATE	-1.9793045	30.107688	9.42	25	80	09:53:48	2021-05-05
898	11	WHITE	-1.97928962	30.107671	7.6	20	60	09:53:09	2021-05-05
897	11	BLUE	-1.9792737	30.107641	4.75	13	40	09:52:22	2021-05-05
896	11	BLACK	-1.97928752	30.107669	11.96	33	100	05:53:16	2021-05-04
895	11	BLACK	-1.97928752	30.107669	11.96	32	100	05:52:51	2021-05-04
894	11	CHOCOLATE	-1.9793045	30.107688	9.64	26	80	05:52:06	2021-05-04
893	11	WHITE	-1.97928962	30.107671	7.05	20	60	05:51:01	2021-05-04
892	11	BLUE	-1.9792737	30.107641	4.41	12	40	05:49:32	2021-05-04

Figure 14 Data presentation in the database. Source: [90].

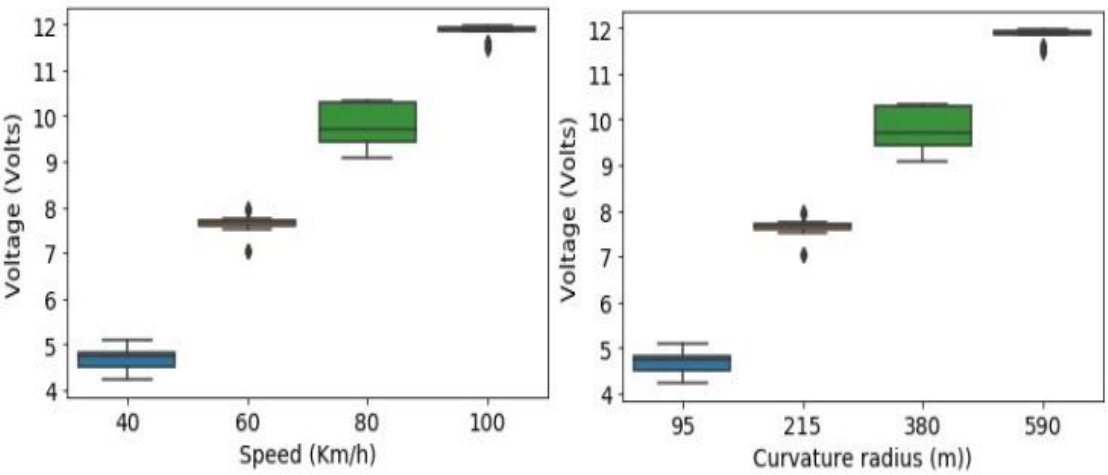


Figure 15 Relationship between variables. Source: [90].

The results of the preferred model were compared for the two machine learning algorithms to evaluate the efficiency of the proposed models. To verify the prediction capability of the proposed models, the accuracy of the RF model had a significant improvement over the MLR model. With the highest R^2 = 0.988 and lowest MAE = 0.194, MSE = 0.066, RMSE = 0.258, respectively, compared to the MLR model which has a lower R^2 = 0.986 and higher MAE = 0.223, MSE = 0.074, RMSE = 0.273. Hence, the RF-based prediction model showed the highest prediction accuracy in terms of performance concerning R^2, with an R^2 of 98.82% compared to MLR, which has an R^2 of 98.68%.

CHAPTER 4: SENSOR NETWORKS TECHNOLOGY FOR TRAFFIC MANAGEMENT

This chapter provides an overview of traffic flow management at intersections while enhancing traffic safety. One of the essential components delivering safe roads is the speed limit and effective traffic coordination, particularly at junctions. A lack of hierarchical highway and road intersection management in the least developed countries is a common phenomenon. The increased number of vehicles causes congestion at road intersections, leading to traveller delays, fuel waste, and an increase in air pollution. We highlight the need for an IoT based TMS to enhance the sustainability of urban mobility systems in this chapter. A centralized traffic management center (TMC) could help in signal optimization while increasing safety. The queue information of each pattern movement is processed based on the arrival rate of cars on each road segment of the intersection. Hence, this could help reduce the delay and the number of no serious injury accidents that occur at the junctions. An IoT-based traffic management center was proposed to describe data acquisition, processing, and traffic light actuation. To reduce the delay, the central processing entity analyses flow pattern rates for prioritization.

4.1 Introduction

The road intersections are designed to facilitate vehicles turning in their directions. Signalized intersections are places where two or more roads intersect. Activities including turning left, crossing over, and turning right have the potential to cause conflicts, which can lead to crashes. Vehicle queues at road intersections are a part of the transportation system. Waiting lines are still the most common issue at traffic signal intersections. In 2008, about 40% of all crashes that occurred in the USA were intersection-related crashes [102]. Congestion causes traffic delays, wastes fuel and reduces the QoS for both people and goods moving between different points. One of the ITS applications is traffic control, which aims to reduce travel time [103], [104]. Different intersection control methods have been utilized to coordinate traffic smoothly [105]. However, despite the efforts devoted to developing sophisticated systems, few decision support systems exist to help traffic controllers [106]. The wireless network is a part of ITS that connects devices to transmit data [107]. One of the well-known applications of wireless networks for traffic control is V2I [108]. V2I changes a car into a wireless mobile node by enabling vehicles to connect to infrastructures and create a network [109]. Over the years, several applications along with controlling algorithms have been introduced for intelligent traffic light controlling [110]. A platform to provide travel information in real-time [111]. Adaptive traffic signal control was made possible in VANETs through V2V and V2I to allow the intersection control unit to schedule traffic [112]. In V2I, travelling cars detect the closest traffic signal. This provides a report of the traffic characteristics of the respective travel flow.

Traffic lights play a key role in improving traffic efficiency. The V2I communications report the real-time data of the traffic flow at the road intersection where the RSU is installed. Each RSU uses the phase-based strategy algorithm to optimize the traffic flow by reducing the delay time of travelling cars in front of each located traffic light [109]. However, traffic flow management systems at the intersection keep relying on individual control with pre-timed fixed cycles without being adapted to real-time traffic. Traffic light optimization is a state-of-the-art issue for improving traffic congestion at road intersections. However, sensor data coverage for LMI countries like EAC's could be limited due to implementation, management, and maintenance costs. In ITS applications, short-term traffic estimation has been widely used to reduce traffic data collection costs while improving traffic flow, traffic management, and safety. In this work, we focused on road intersection management, mainly in environments with reservations about further road extensions' financial capabilities. By intelligently re-assigning green lights from the highest flow patterns to less congested ones, traffic congestion can be managed quickly. Moreover, re-assigning reduces the loads without being attended to by human intervention. Path flow estimator (PFE) [114], and artificial neural network (ANN) [115] models have been used to estimate turning movement counts at intersections. However, most of these studies focused on predicting traffic volume at signalized intersections, or on freeways. On the other hand, the non-parametric classification method includes k-nearest neighbors (KNN) techniques to estimate short-term traffic volume at the signalized intersection [116], and the XGBoost model to estimate turn movements in real-time at signalized intersections [117].

Numerous studies for intersection performance monitoring have shown how traffic data can be captured and transmitted to the intersection control node using various technologies. Various studies are using vehicle loop detectors and closed-circuit television (CCTV) to calculate, estimate, and lengthen the intersection's queue [118]. Wireless magnetometer sensors were majorly used to capture the change in magnetism caused by a passing car and transmit all data to the RSU. The TMC directly communicates with RSUs to assign traffic signals to a particular road segment. Hence, operation automation intelligently manages, maintains, and proactively executes computations via end-to-end communication systems [119], [120]. Therefore, developing solutions for traffic signal optimization through the TMC is crucial to meeting the growing demand for road traffic management [120]. A model for real-time traffic light scheduling was proposed based on queuing theory. It is assumed that wireless magnetometer sensors capture the traffic arrival rate. The sensors are embedded in the road surface of each lane to detect the car's presence in the individual lane at a given time of the period. A queuing model-based approach is presented to solve the problem of traffic light scheduling mathematically.

4.2 Design methodology

This research employs multiple queuing theories to understand traffic flow behaviour and how it relates to effective scheduling to optimize traffic flow, consequently reducing accidents at the junction. The study primarily used time-series data collected on different days during three consecutive months at the area. A mid-block survey (field observation) was conducted in the area in Figure 16. The data was collected using traffic counting forms by five data collectors. The form contained information about flow per lane, waiting time at the queues, and the time it takes for a particular queue length to cross the junction at the area presented. Classified traffic volume surveys were conducted at selected mid-block line points for 7 hours (06:00 am to 10:00 am) and (4:00 pm to 7:00 pm) on a typical working day as per study area location. Classified traffic volume counts were made throughout the 7-hour duration of the survey. As part of the same study, the data collection was conducted to collect traffic flow information and data for use during simulation.

Figure 16 Study area location. Source: [120].

4.3 Traffic flow and queuing model

The proposed system relies on IoT technology to estimate the green light period based on the arrival rate of vehicles as per the observed pattern. Several traffic sensors have been manufactured, such as inductance loops, radar sensors, infrared detectors, and road embedded sensors, to provide a reliable count of road traffic data. The distribution rate (the number of vehicles crossing the intersection from the source side to the destination), defines the quality of the intersection operation. It is assumed that the traffic flow rate captured by ground sensors that are embedded after the decision region is transmitted to the RSU that sends all data to the TMC. The lane flows are given to the system (RSU) lane by lane while the patterns are compared and ordered. The threshold based on experimental values determines the green time estimation per pattern. The density of the four-direction count extracted from the previous flow rate is now used to predict the timer value for the next timing predictions.

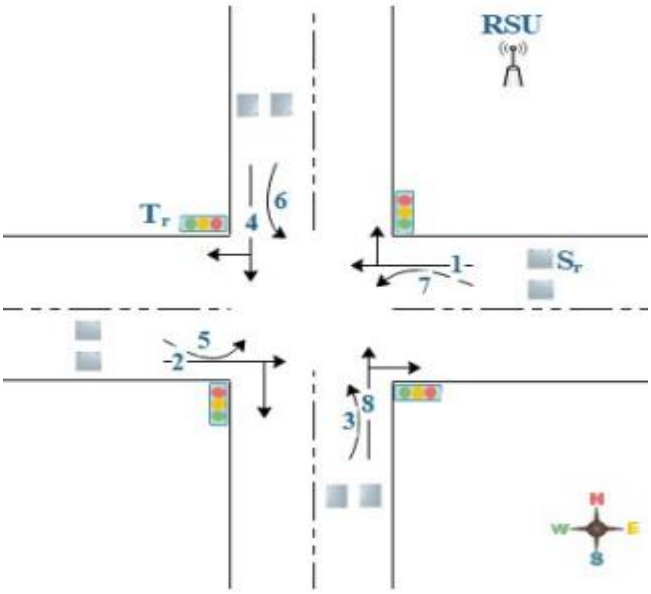


Figure 17 The layout of the intersection (ID 301). Source: [120].

Queuing is characterized by an arrival rate, a control flow policy, and a servicing facility responding to the traffic demand. From Figure 17, let λ_1 and μ_1 be the arrival rate and service rate of the N4&S8

direction. Also, λ_2 and μ_2 are the arrival rate and service rate of E1&W2 movement respectively. These flow rates are then compared with arrival rates of the N4&S8, N6&S3, and E7&W5 directions. The arrivals are fed to the queue in a regulated fashion by a flow controller, which is the RSU.

The term "system" is used to denote the intersection control system composed of sensors, cameras, traffic lights, and RSU. The service rate of the system is the number of vehicles that the system can serve per unit time (throughput). The calling population is an infinite population model with unlimited system capacity. The control flow policy resides in the TMC to match the best possible exponential time for any rate for the RSU to command the traffic light. Figure 18 depicts the real-time traffic flow at the junction.

Figure 18 Traffic flow at the Intersection ID 301.

The adaptive signal serves one pattern after comparing both patterns. After that, the arrivals are analysed. They are then classified, where higher priority queues are weighted and then prioritized from higher to lower. Suppose the weights of queues are 6, 4, 10 and 1. The green signal time length is calculated for each queue which has weight based on a probabilistic analysis of these queues. Therefore, they are processed from the queue which has weights equal to 10, 6, 4 and 1 respectively. Let δ_1 serve the N4&S8 and E1&W2 flows and δ_2 serve the N4&S8, and N6&S3 flows respectively.

The developed queuing model applies an adaptive control strategy that is based on the rolling horizon scheme. Here, the adaptive signal serves two queues until the queue is cleared, then the second queue and then the signal goes back to serving the first movement. Defining the arrival rate of a pattern and its distribution rate, the traffic signal switches as the queue vanishes during the whole green phase. The communication performances between sensors, RSU and TMC vice versa are assumed to be perfect, resulting in no data loss during packet transmission. After the data aggregation, the intersection control system model is M/M/es/∞/∞ where M is exponential type, es the number of parallel traffic lights. The queue challenges at the intersection will be solved by considering the Little's Law:

$$L = \omega\lambda \tag{4}$$

where L is the average number of cars in the system, ω is the average waiting time of the cars in the queue, λ is the cars' arrival rate.

The TCM is a central system for traffic signal timing, cycle time, split phase, split time, and several parameters for traffic control policies. In the proposed multiple queuing models, it is assumed that the existence of a traffic flow counters, effective communication system facilitating data transfer and information sharing. The decentralized traffic control in this model assumes that each intersection's traffic flows status is shared and managed in the TMC depicted in Figure 19.

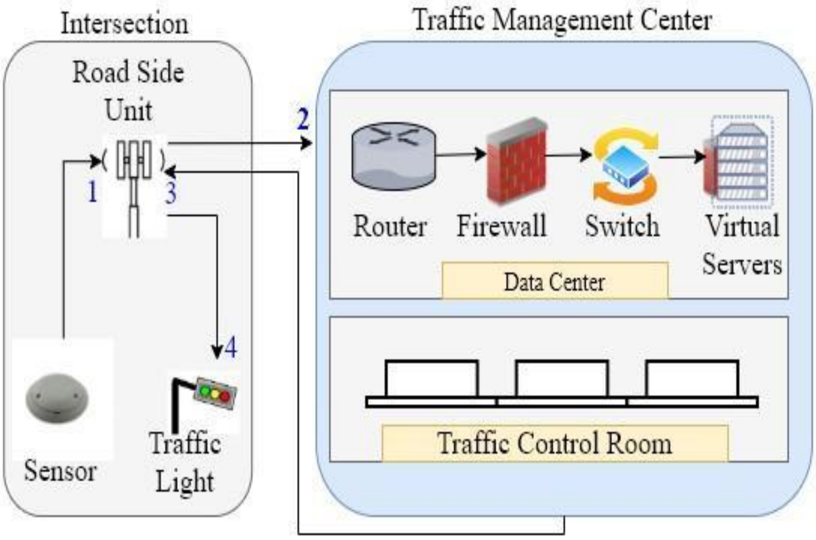


Figure 19 Traffic management center architecture diagram. Source: [120].

The facility controls its data separately in the edge server for a typical location. Traffic data are only shared among adjacent intersections. Intelligently reassigning green light from a congested pattern to less congestion, overcrowding of vehicles is managed in a timely way. Vehicles flow at the crossroads are not usually continuous and stable instead, traffic flows are complex and may change suddenly. The traffic optimizations and vehicle flow control reside at the TMC that commands the RSUs after distinguishing isolated intersections from the adjacent intersection by which roadside data are shared for traffic light synchronization. The TMC knows the intersection's layout, map and determines the headings that correspond to an approach on each of its lanes. It is assumed that the traffic flows are shared in adjacent intersections, compared to synchronizing light signals in the neighbourhood. The Green and Red phases must be articulated according to the flow sharing. The server utilization is the proportion of time that the traffic intersection is busy. It is observed by ρ and is defined over the closed time interval of [0,1]. The intersection management performance varies widely for a given traffic light's utilization value. Considering a system, the utilization depends on the traffic light numbers, the arrival rate, service rate and traffic signal utilization related by the below equation:

$$\frac{\lambda}{c\mu} < 1 \tag{5}$$

where λ is the cars' arrival rate, μ is the service rate and c is the number of servers (traffic lights). Further define ρ as the system utilization, $\frac{1}{\mu}$ as the service time, P_0 as the probability of having no car in the queue. Hence, for an optimized process the probability P_0 was calculated.

$$P_0 = \left\{ \left[\sum_{n=0}^{C-1} \frac{\left(\lambda/\mu\right)^n}{n!} \right] + \left[\left(\frac{\lambda}{\mu}\right)^c \left(\frac{1}{c!}\right) \left(\frac{c\mu}{c\mu-\lambda}\right) \right] \right\}^{-1} \quad (6)$$

where, the probability that servers are busy is:

$$P\left(L_{(\infty)} \geq c\right) = \frac{\left(\frac{\lambda}{\mu}\right)^c P_0}{c!\left(1-\frac{\lambda}{c\mu}\right)} = \frac{(c\rho)^c P_0}{c!(1-\rho)} \quad (7)$$

$$L = c\rho + \frac{(c\rho)^{c+1} P_0}{c(c!)(1-\rho)^2} = c\rho + \rho \frac{P(L(\infty) \geq c)}{1-\rho} \quad (8)$$

$$\omega = \frac{L}{\lambda} \quad (9)$$

$$\omega_q = \omega - \frac{1}{\mu} \quad (10)$$

$$L_q = \lambda \omega_q = \frac{(c\rho)^{c+1} P_0}{c(c!)(1-\rho)^2} = c\rho + \rho \frac{P(L(\infty) \geq c)}{1-\rho} \quad (11)$$

$$L - L_q = \frac{\lambda}{\mu} = c\rho \quad (12)$$

Since the focus is on the intelligently controlled intersection, the following assumptions are considered:

- Wireless magnetometer sensors are embedded on the road surface to send the queue length of the i^{th} lane at the time t_r to the RSU

- Intelligent RSU has communication capabilities to transmit traffic data to the TMC

- Vehicles to different destinations are on the corresponding lanes such that there is no lane-changing behaviour

- Dual ring signal control is based on higher queue length.

4.4 Simulation, results, and discussion

Overcrowding of vehicles can be managed promptly by intelligently reassigning the green light from a congested pattern to a less congested way. Vehicle flows at intersections are rarely continuous and stable; instead, traffic flows are complex and can change unexpectedly. The TMC oversees traffic optimizations and vehicle flow control. It commands the RSUs after distinguishing isolated intersections from adjacent intersections and sharing roadside data for traffic light synchronization. The TMC is familiar with the intersection area and the map. Therefore, it determines the headings that correspond to an approach on each of its lanes. In case of adjacent intersections, traffic flows are assumed to be shared and then compared to synchronize light signals in the neighbourhood. In this regard the survey was conducted in a manner to understand the traffic pattern within the entire study area and adjacent intersections. The traffic counts in terms of the numbers of cars arriving at junctions ID 300, ID 301 and ID 302. Figure 20 shows the outflow of the intersection ID 300 that on the contrary causes the congestion at intersection ID 301 as input flow.

Figure 20 Outflow traffic from intersection 300.

The peak hour traffic at the mid-block locations is presented for the five days of the week. According to Figure 21, it was observed that on average the traffic at junction ID 301 varies from 1127 to 1445 on Monday, 1113 to 1705 Tuesday, 1161 to 1590 Wednesday, 990 to 1862 Thursday and 1041 to 1764 on Friday. It is seen that intersection ID 301 experienced high traffic volumes and variation relative to the other two intersections. Therefore, the peak hour traffic at the mid-block locations is presented for the five days of the week and the hours 7:00 am to 9:00 am and 6:00 pm to 7:00 pm experience peak traffic. The applicability of the queuing model was then demonstrated by using average traffic flow data of a single pattern. The two-day data of W2&E1 flows containing 90% of the West and East cardinal directions data are used for experiments. The traffic flows W&E are asymmetrical. The number of traffic lights to serve the traffic demands are two traffic signals. The average number of cars waiting to be served was observed to be high at peak time, which is 7:00 am to 8:00 am and 5:00 pm to 6:00 pm on both days.

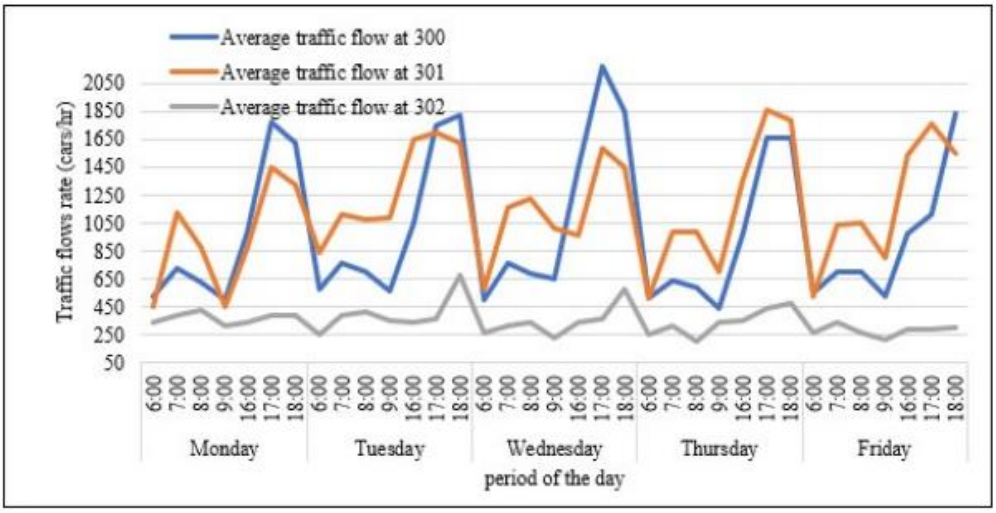


Figure 21 Hourly traffic flow by day to the area of the study Source: [120].

The method of queue analysis in this work was the multi-server queuing modelling system with λ that varies over the day and the μ which is fixed to 30 cars per minute on average per single server. Figure 22, Figure 23 and Figure 24 depict the variation of hourly traffic flow at each of the three intersections on different days of the week, from Monday to Friday.

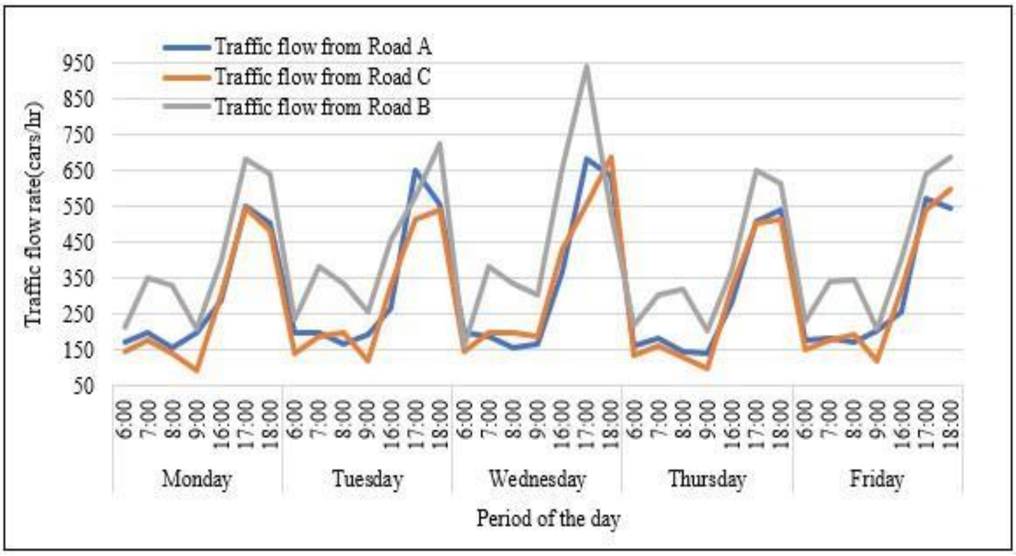


Figure 22 Traffic flow at intersection ID 300. Source: [120].

The analytical and mathematical analysis of the intelligent traffic signal-based queue length control is evaluated. First, the traffic volume at the intersection is calculated. Then, the lane flows are given to the RSU lane by lane, while the patterns are compared to be ordered. The threshold based on experimental values determines the green time estimation per pattern. The density of the four directions counts extracted from the previous flow rate is now used to predict the timer value for the next timing predictions. Later, the queuing theory-based traffic light scheduling model was presented to evaluate how to increase the road intersection throughput while minimizing the waiting delay.

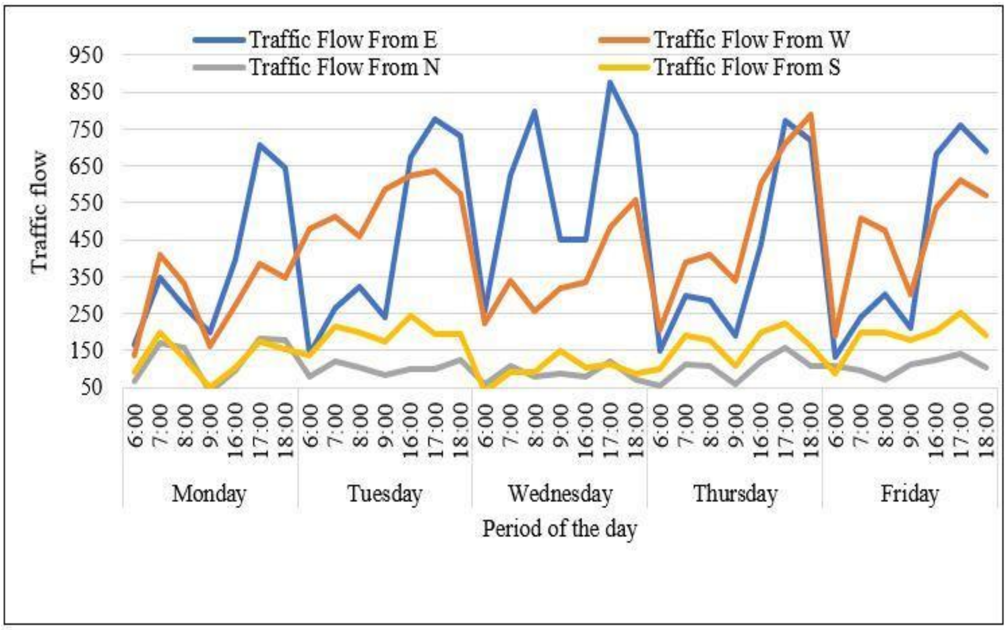


Figure 23 Traffic flow at intersection ID 301. Source: [120].

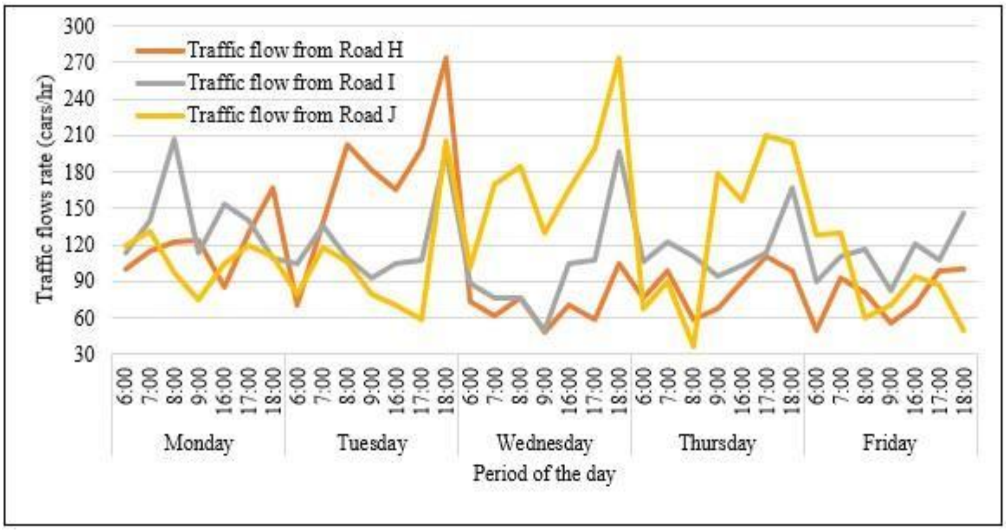


Figure 24 Traffic flow at intersection ID 302. Source: [120].

It is observed that server utilization decreases as the arrival rate decreases. Let's take Monday where the arrival is 4.5 cars/min from 6:00 am - 7:00 am. The traffic light utilization is 0.075 compared to when the arrival is high at 11.3 cars/min the traffic intensity is at 0.188. It has been shown that traffic signal lengths must depend on the arrival rate. The service rate as the number of cars that cross the intersection in each period depends on the arrival rate. This depicts that the service rate increases as the arrival rate increases. As the number of service facilities cannot be increased in this scenario. The green time of the signal can be changed based on the period, the arrival and waiting time that a car must wait in the system to be serviced. Hence, the cost is associated in terms of delay and pollution. Figure 25 shows how the server utilization factor decreases as the number of servers increases. During the waiting time of cars at peak hours, the green period must last long enough to increase the throughput that was built in the queue during the red interval. In reverse, the increase in the delay measured in terms of average waiting time to be served is further analysed. It was observed that for the arrival rate of 21.15 cars/min, the average waiting time is at 0.059 minutes compared to when the arrival rate is 4.5 cars/min we have a waiting time of 0.217 minutes.

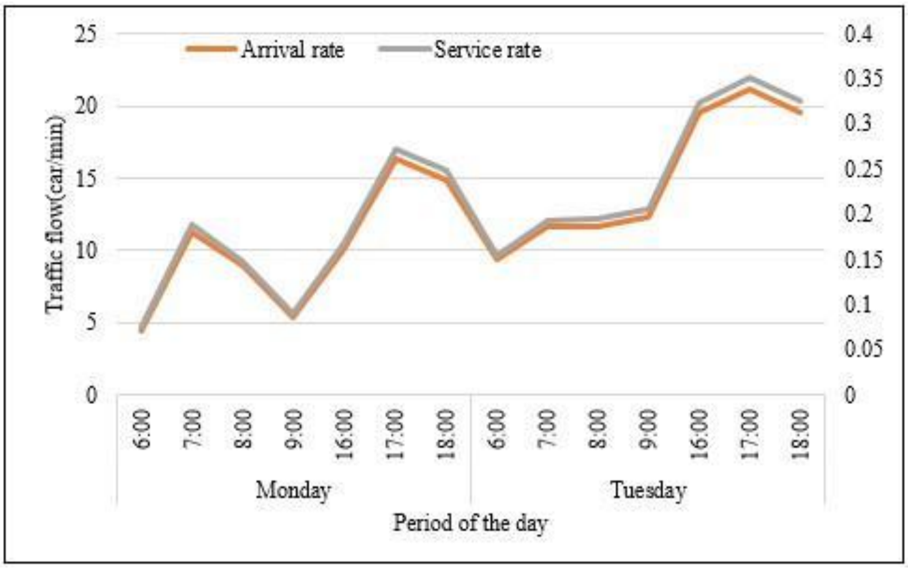


Figure 25 Arrival rate vs server utilization.

The traffic light cycle planning enhances the efficiency of traffic flow at the intersection.. On the contrary, congestion manifests with a longer waiting time at the junctions, resulting in increased queue lengths as depicted in Figure 26. The demand for traffic light cycle analysis is required for the decongestion of the intersection.

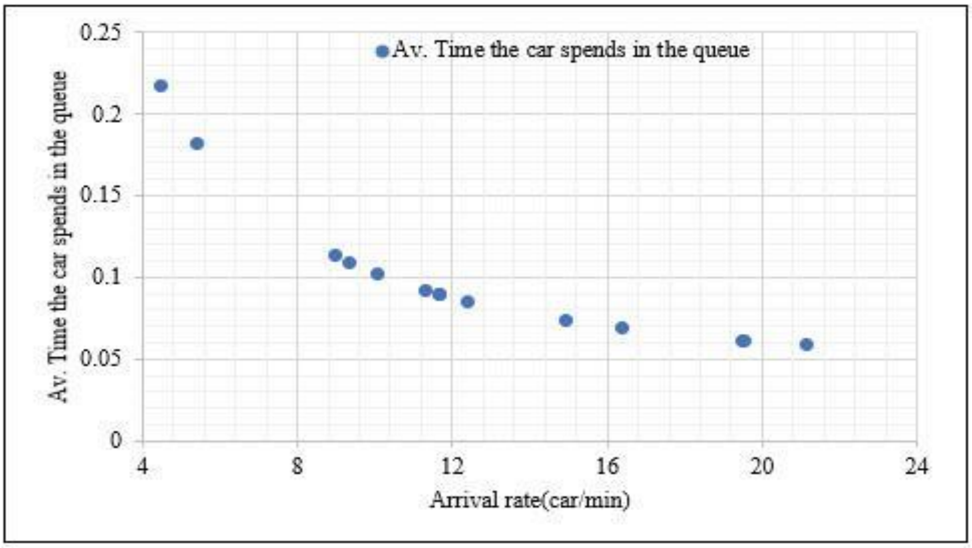


Figure 26 Server utilization vs average time a car can spend in the queue. Source: [120].

The main challenge at the intersection is to reduce congestion. Adaptive scheduling of the traffic light to minimize the congestion problem is crucial to strengthening the sustainability of urban mobility systems. Timely traffic congestion is managed intelligently by re-assigning the green light for the highest flow pattern to the less congested ones. The increase in the number of vehicles leads to congestion at road intersections and collision occurrences. Therefore, reducing congestion in particular segments is the main concern to be solved. A novel multi-server queuing model for traffic signal optimization to strengthen the sustainability of mobility at the Giporoso intersection, one of the busiest intersections in Kigali city, was proposed. It was found to be one of the solutions to reduce accidents and congestion in the area.

Given the arrival rate of cars on each intersection road, the queue information for every pattern movement is processed. The data is collected on the IoT platform through wireless magnetometer sensors. It is further sent to TMC for further analysis. The queuing theory concepts were applied to the collected data. Further analysis and processing lead to the actuation of traffic lights to disperse and redirect traffic. The central processing entity analyses flow patterns for prioritization to reduce the delay and accidents which may occur due to inappropriate speeding to cross the intersection, as traffic volumes affect accident frequency. The suggested performance metrics such as arrival rate, waiting time, the average number of cars in the queue and intersection utilization are analyzed and evaluated using ground truth data.

CHAPTER 5: CONCLUSION

This chapter looks back on the research work and the findings by attempting to answer the research question. It then provides a summary of the thesis followed by a brief discussion of the research contributions. Finally, the chapter concludes with a look back at how some concepts might evolve in the long term, including extensions and avenues for future research. This thesis examined various technologies that are expected to impact on road safety significantly. In this thesis, we investigated the process of implementing intelligent transportation initiatives, the opportunities and challenges of implementing ITS in developing countries like Rwanda.

Smart transportation is promising to improve road safety and transport management. For developing ITS, a traffic management center is required. In addition, road data transmitted by either roadway-based sensors or probe-based sensors need further analysis for a road user to gain meaning from them. In this research, the data was collected to evaluate practitioners' and policymakers' points of view on ITS. After the analysis, an IoT-based ITS platform was proposed for improved transportation. This research can help road transport managers understand the complex concept of intelligent transportation. It can also help to know the requirement, breaking the process down into goals, components, and process enablers. An IoT-based platform powered by advances in ICT, mobile technologies, internet access, and other technological advancements will improve transportation.

This thesis presented a novel feature engineering approach that builds on IoT features to control and monitor vehicle speed not to exceed the maximum imposed speed limit of a particular zone. A data acquisition along with a communication system based on GSM/GPRS was introduced. The design and the execution for all the voltage measures were analysed to maintain speed. Synchronization between software applications and hardware features has been successfully programmed. The transmission synchronization tests demonstrated that the GSM/GPRS-based real-time monitoring was successful.

Further, the research proposed a TMC that builds on the sensor network data to control and schedule traffic flow at the intersections. ITS applications and systems for safety are broadly classified into mobility, safety, and environment. Mathematical modelling and technology integration approaches were proposed as a solution to some road traffic safety causal factors. A queuing theory model demonstrated itself as a tool to analyze and understand queue-related parameters at road junctions, as serious accidents are much more likely to occur at high speeds and in complex situations. The results demonstrate that queuing theory is a simple but powerful tool road managers can build to plan traffic flow scheduling. Traffic management includes road traffic safety management such as traffic optimization, traffic state estimation and prediction. When considering the great potential of ITS and the power of IoT, there is a gap between research and practice concerning developing intelligent systems to reduce traffic accidents. However, the researcher also ran into some limits. The principal was to obtain access to the datasets. Unfortunately, it was difficult to find filtered accidents data and their details. Given the time constraints and the original objectives of the study, the researcher did not deploy the models. The implementation of the research findings will be done in the future.

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Appendices

Appendix 1. General survey questions (Paper I)

1. Sector the interviewee belongs (Institution):
   Government ☐
   Industry/Private Sector ☐
   Public sector ☐
   University ☐

2. Level of Education:
   Primary ☐
   Secondary ☐
   Tertiary and above ☐

3. Email address (if any): ____

4. Do you have a driver's license?
   Yes ☐
   No ☐

5. Are you familiar with the Intelligent Transport System (ITS)? *
   Yes ☐
   No ☐

6. Have you ever heard about smart roads/highways?
   Yes ☐
   No ☐

7. If yes, what do you expect from a smart road/highway? *Please tick from the list as many as you can*:
   Drone enhancement for data capture, search and rescue ☐
   Vehicle to infrastructure communication capabilities ☐
   Vehicle condition diagnostics ☐
   Traffic congestion alert ☐
   Speed limit alert ☐
   Others: (*specify*) ____

8. From your experience or knowledge, what causes mostly road accidents?
   Driver's behaviour ☐
   Driver's health issues ☐
   Pedestrians/animals/objects on the road ☐
   Vehicle condition ☐
   Road condition ☐
   Environmental and climatic factors ☐
   Others: (*specify*) ____

9. From your experience, which portion of the road registers many accidents? Check all that apply.
   Roundabout ☐
   Crossroads/intersections ☐
   Flat road ☐
   Slope/road incline ☐
   Others: (specify) ____

10. Under each cause in (8), rate on the scale of 1-5, where 1 represents strongly agree and 5 represents strongly disagree.
    Scale: 1. Strongly agree
    2. Agree
    3. Neutral
    4. Disagree
    5. Strongly disagree

    Driver's behaviour ☐
    Driver's health issues ☐
    Pedestrians/animals/objects on the road ☐
    Vehicle condition ☐
    Road condition ☐
    Environmental and climatic factors ☐

11. Which intervention(s) do you think is/are effective in reducing road accidents?
    Health education/road accidents surveillance system ☐
    Driver's driving history ☐
    Road safety policy/National Strategy ☐
    Safety equipment ☐
    Traffic data collection ☐
    Others: (*specify*) ____

12. What do you think should be available to address road safety issues?
    - Health education/Trauma management ☐
    - Training/learning and development ☐
    - Research and academic capacity ☐
    - National strategy ☐
    - Financial aid ☐
    - Policy ☐

13. Would you wish your car/vehicle to have an in-vehicle device that connects it to the internet?
    Yes ☐ No ☐

14. What technology competencies are required to sustainably manage transport systems?
    - Electrical/Mechanical/Automobile/Computer Engineering ☐
    - Transport/Geomatics/Highway Engineering ☐
    - ICT/Computer Science ☐
    - Physics/Electronics ☐
    - Environmental Science ☐
    - Others: (*specif*y) ____

15. How best can a country harness the emerging digital technologies in the transport system?
    - Develop an academic program ☐
    - Establish a think-tank ☐
    - Establish regulations ☐
    - Develop a strategy ☐
    - Develop a policy ☐

16. What type of digital cameras should be installed on the roads?
    - Live streaming cameras for real-time location views ☐
    - Automatic Number Plate Recognition (ANPR) camera ☐
    - Traffic violation cameras ☐
    - Average speed camera ☐
    - Speed camera ☐

17. Which information in your mind should the cameras capture on the road/street?
    - Vehicular data ☐
    - Passenger data ☐
    - Road/street user data (faces only) ☐
    - Road/street data (whole body) ☐
    - No image or video data capture ☐
    - Others: (*specif*y) ____

18. Who should own camera data?
    - Rwanda Ministry of Infrastructure (MININFRA) ☐
    - Rwanda Utilities Regulatory Authority (RURA) ☐
    - Rwanda Transport Development Agency (RTDA) ☐
    - Rwanda Information Society Authority (RISA) ☐
    - Rwanda National Police (RNP) ☐
    - Others: (*specify*) ______________________________

19. Which database should be used to monitor and track the car's movement?
    - Rwanda Ministry of Infrastructure (MININFRA) ☐
    - Rwanda Utilities Regulatory Authority (RURA) ☐
    - Rwanda Transport Development Agency (RTDA) ☐
    - Rwanda Information Society Authority (RISA) ☐
    - Rwanda National Police (RNP) ☐
    - Others: (*specify*) ______________________________

20. In Table 1 below are the 10 selected digital technologies. Indicate your level of familiarity with each of them using the following scale. *
    1. Very familiar
    2. Familiar
    3. Neutral
    4. Not familiar
    5. Ignorant

Sno	Technology	Level
1.	Self-driven vehicles (AI)	
2.	Electric vehicles	
3.	Internet of roads (RSUs) communication	
4.	Internet of roads (smart roads\V2X)	
5.	Smart Traffic Light	
6.	Traffic flow prediction	
7.	Road damage detection	
8.	IoT based traffic monitoring	
9.	Collision avoidance	
10.	GPS tracking systems	

21. From 10 technologies which should be the main of focus for the case of Rwanda. Indicate them using appropriate numbers (you can choose as many as possible considering cost-effectiveness).

Sno.	Technology	Selection
1.	Self-driven vehicles (AI)	
2.	Electric vehicles	
3.	Internet of roads (RSUs) communication	
4.	Internet of roads (smart roads\V2X)	
5.	Smart Traffic Light	
6.	Traffic flow prediction	
7.	Road damage detection	
8.	IoT based traffic monitoring	
9.	Collision avoidance	
10.	GPS tracking systems	

22. Which energy technology would be good to digitize the transport system?

Dynamo/electromagnetic/rotor effect from the wheels in motion ☐

Radio frequency/vibrations/wind/lightning energy ☐

Geothermal ☐

Solar ☐

Grid power ☐

Others: (*specify*) ____________________

Appendix 2: Interview and discussion questions (Paper I)

Name of respondent:
Respondent's position:
Respondent's institution:

1. What are your main responsibilities in the institution?
2. For how long have you been in the institution?
3. What are the activities related to road safety undertaken within your institution?
4. To what extent are those activities, goals achieved?
5. What are the indicators of their achievement?
6. Who are involved in those activities?
7. What are the parties involved?
8. What are the existing road safety strategies?
9. How do you see ICT integration in road transport in Rwanda?
10. What should be done to reduce road traffic accidents in Rwanda?

List of Publications

This thesis is based on the following papers which were referred to in the text by their roman numbers.

I. G. Antoine, C. Mikeka, G. Bajpai, and V. Andras, “Towards a Framework for Context-Aware Intelligent Transportation System: Case of Kigali”, in *ICT Systems and Sustainability.*, pp. 591-599. Springer, Singapore, Jan. 2022. doi.org/10.1007/978-981-16-5987-4_60

II. G. Antoine, C. Mikeka, G. Bajpai and K. Jayavel, "Speed management strategy: Designing an IoT-based electric vehicle speed control monitoring system", *Sensors.*, vol. 21 no. 9, pp. 6670, Oct. 2021. doi.org/10.3390/s21196670

III. G. Antoine, C. Mikeka, G. Bajpai, and V. Andras, “Real-time traffic flow-based traffic signal scheduling: a queuing theory approach”, *World Review of Intermodal Transportation Research.*, vol. 10, No. 4, pp.325-343, Dec. 2021. doi.org/10.1504/WRITR.2021.10043273