Decarbonisation Using Fuel Switching in Freight Transport: A Case of Kenya

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Declaration and Approval

Declaration

I declare that this work has not been previously submitted and approved for the award of a degree by this or any other University. To the best of my knowledge and belief, the dissertation contains no material previously published or written by another person except where due reference is made in the dissertation itself.

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Abstract

Traditionally, the transportation sector has relied on fossil fuels such as coal, petroleum and natural gas. However, the urgent need to reduce greenhouse gas (GHG) emissions has prompted a global shift towards renewable energy sources. In Kenya, the transportation of freight cargo is predominantly done by trucks that rely on diesel as their main energy source. The nation has made several efforts to mitigate these increase in emissions such as the promotion of electric vehicles, the development of the National Climate Change Action Plan (NCCAP), provision of non-motorised transport (NMT) infrastructure and international commitments like the COP 26 declaration that aims to accelerate the transition to 100% zero carbon vehicles. Furthermore, research on mitigating transport emissions has been carried, however some researchers focused on modal shift, other scholars focused on shifting only passenger cars while others focused on one fuel switch option only. This study's objective was to analyse the current road sector emissions associated with freight transport, primarily HGVs.

In this study, fuel switching options for HGVs were modelled. The model was based on the Avoid-Shift-Improve (ASI) theory which had three (3) scenarios, the Business as Usual (BAU) , centralise scenario and the improve scenarios. The study concluded that the BAU scenario should not be allowed to continue and policy changes were necessary to mitigate its emissions. In the centralise scenario, the emissions were similar to that of the BAU reporting just a 2.3% reduction in emissions by 2050. The improve scenario was seen as the most promising scenario in CO_2 abatement recording 16.4% reduction in CO_2 emissions by 2050.

Keywords: Freight transport, fuel switch, decarbonisation, Kenya, CO_2 reduction, well to wheel emissions, Avoid-Shift-Improve.

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List of Abbreviations

ADO – Automotive diesel oil

AGO – Automotive Gas Oil

ASI – Avoid, Shift and Improve

BAU – Business as usual

BEV – Battery Electric Vehicles

CNG – Compressed Natural Gas

DV – Diesel Engine Vehicle

ESME – Energy System Modelling Environment

FAEE - Fatty Acid Ethyl Esters

FAME - Fatty Acid Methyl Esters

FCV – Fuel Cell Vehicles

GTAP – Global Trade Analysis Program

GVWR – Gross Vehicle Weight Rating

HDEV – Heavy Duty Electric Vehicle

HFCV – Hydrogen Fuel Cell Vehicle

HGV – Heavy Goods Vehicle

ICE – Internal Combustion Engine

JRC-EU-TIMES – TIMES model for the Joint Research Centre – European Commission

KWh – Kilo-watt Hour

LCV – Light Commercial Vehicle

LCFS – Low Carbon Fuel Standard

LEAP – Long Range Energy Alternatives Planning

LHV – Lower Heating Value

LPG – Liquefied Petroleum Gas

MAED – Model for Analysis of Energy Demand

MGR – Meter Gauge Railway

$MtCO_2e$ – Million Tonnes of Carbon dioxide equivalent

NDC – Nationally Determined Contribution

OSeMOSYS – Open Source Modelling System

PA – Paris Agreement

PJ – Petajoule

RES – Reference Energy System

R&D – Research and Development

SER - Steam Ethanol Reforming

SMR - Steam Methane Reforming

TIMES – The Integrated MARKAL_EFOM System

UNFCCC - United Nations Framework Convention on Climate Change

WTW – Well to wheel efficiency

ZEV – Zero Emission Vehicles

Definition of terms

Avoid, Shift Improve – is a framework used to guide sustainable decision-making by focusing on avoiding negative environmental impacts, shifting towards sustainable alternatives, and improving the efficiency and effectiveness of existing practices (Maduekwe et. al, 2020).

Business as usual scenario – is a scenario where nothing significant has changed from the existing state of affairs. In this state, there are no major disruptions, crises, or changes in the economic, political, or social environment that would significantly alter the operations or strategies of businesses (Shafiei et.al, 2015).

Calorific value/ energy value - is the energy released when a substance undergoes complete combustion (Chang, 2015).

Fuel switching – is the process of transitioning from one type of fuel to another for various purposes, such as energy generation, heating, transportation, or industrial processes (Ritchie & Roser, 2021).

Gravimetric energy density - is the amount of energy stored per unit mass of a substance (Singh et. al, 2015).

Gross Vehicle Weight Rating – is the maximum allowable weight limit that has been determined by the vehicle manufacturer. It represents the maximum total weight of a vehicle, including its curb weight (the weight of the vehicle itself), passengers, cargo, fluids, and any additional accessories or modifications (Cunanan et.al, 2021).

Low-carbon fuel standard – is an emissions trading rule intended to lower, relative to traditional petroleum fuels like petrol and diesel, the average carbon intensity of transportation fuels in a given jurisdiction (Lepitzki & Axsen, 2018).

Tank to wheel (TTW) emissions – This measures the energy consumption and emissions from the point where the fuel is in the vehicle's tank or battery to when it is used for propulsion. It focuses only on the efficiency of the vehicle itself (Samaras & Meisterling, 2008).

Transesterification reaction – This is a chemical reaction in which ester molecules are transformed into different ester molecules through the exchange of alkoxy groups between an ester and an alcohol (Chang et.al, 2017).

Well to tank emissions (WTT) – This covers the energy and emissions from extracting, refining, and delivering fuel before it reaches the vehicle. It excludes the actual use of the fuel in the vehicle (Samaras & Meisterling, 2008).

Well to wheel (WTW) efficiency – represents a vehicle's or fuel system's total energy efficiency, accounting for all energy generation, distribution, and consumption processes, from raw material extraction to the vehicle's ultimate use (Samaras & Meisterling, 2008).

Wheel to well (WTW) emissions – This refers to the total energy use and emissions from the full lifecycle of a fuel, from production (extraction, refining, and transportation) to its use in a vehicle. It is a sum of well to tank emissions and tank to wheel emissions (Samaras & Meisterling, 2008).

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I am also grateful to my classmates and colleagues, whose encouragement and reminders, served as motivation complete this degree on time. Their support was outstanding and kept me focused and committed to my research.

Dedication

To my late mother, who encouraged me to pursue a Master's degree and build my qualifications portfolio, I thank you for your support and encouragement. I thank my teachers and classmates for the many spirited debates and brainstorming sessions we had as we pursued this degree. To my colleagues who allowed me time off to write this dissertation.

Chapter 1: Introduction

1.1 Background

Traditionally, the transportation sector has relied on fossil fuels such as coal, petroleum and natural gas. However, the urgent need to reduce greenhouse gas (GHG) emissions has prompted a global shift towards renewable energy sources. According to International Energy Agency (2014), almost 80% of the fuels currently used in transport sector comes from petroleum, with the transportation industry using about 20% of the energy produced worldwide. These fuels include aviation fuel, marine fuel, liquefied petroleum gas (LPG) and gasoline/petrol, which are used across all modes of transport. Given their high emission factors, exploring alternative pathways to sustainable transportation is essential.

Hydrogen, biofuels, and electricity represent distinct yet interrelated solutions in the pursuit of sustainable transportation. Each pathway offers unique advantages and faces specific challenges that necessitate a comprehensive examination. Electricity is deemed a promising candidate, in Kenya, as it can be generated from renewable sources. An International Trade Administration report from 2022 states that more than 80% of electricity in Kenya comes from clean energy sources (International Trade Administration, 2022). Therefore, electricity can be utilized directly in electric cars (EVs) or electrolyzed hydrogen to produce green hydrogen.

Hydrogen's potential as a green energy source in sustainable transportation is derived from its adaptability. Jelti et.al. (2023) states that hydrogen has two uses as an automotive fuel: it can be used in fuel cells or in internal combustion engines (ICEs). Fuel cell vehicles (FCVs) mitigate hazardous air pollutants and reduce GHG emissions by using hydrogen to create power and its only by-product is water in contrast to ICEs. It offers a viable alternative for long-range and heavy-duty transport applications. Hydrogen produced from biomass feedstock is classified as a biofuel.

Through the production of an agricultural fuel substitute for ICEs, biofuels have become a clean energy pathway for sustainable transportation. This is because they provide a low-carbon and renewable alternative for powering automobiles as they are made from organic materials. Shaifei et al. (2015) states that biofuels lower GHG emissions from cradle to grave thereby aiding in the fight against climate change. Biofuels come in several varieties, like bio-ethanol and bio-diesel. While bioethanol is manufactured from crops biodiesel is made from animal fats combined with conventional fuel.

Hydrogen, biofuels and electricity provide alternative pathways for clean sources of fuel for green mobility. These pathways have characteristics that are advantageous in comparison to fossil fuels. Jelti (2023) contends that clean energy pathways may reduce reliance on foreign oil and may help stabilise fossil fuel prices. In addition to reducing GHG emissions and contributing to a low-carbon future, these pathways can serve as extra source of energy for the primary sectors. Biofuels could potentially boost the income for agricultural producers, while the adoption of electric vehicles will increase the need for electricity, leading to more efficient use of electricity produced.

Kenya has relied on fossil fuels in the form of diesel and petrol as the primary energy sources for all vehicle types. A report by Government of Kenya (2019), states that the transport industry accounted for 11.25 $MtCO_2e$ in 2015 and the road subsector was responsible for 6.9 $MtCO_2e$ - which was about 61% of all transport emissions. Moreover, HGVs contributed 2.89 $MtCO_2e$, - which was about 40% of all road emissions. It is therefore key that other pathways for HGVs be considered if Kenya is to meet its sectoral mitigation target of 3.46 $MtCO_2e$ by 2030.

Heavy Goods Vehicles (HGVs) in fall under class 7 and 8 vehicles as presented in Figure 1.1.

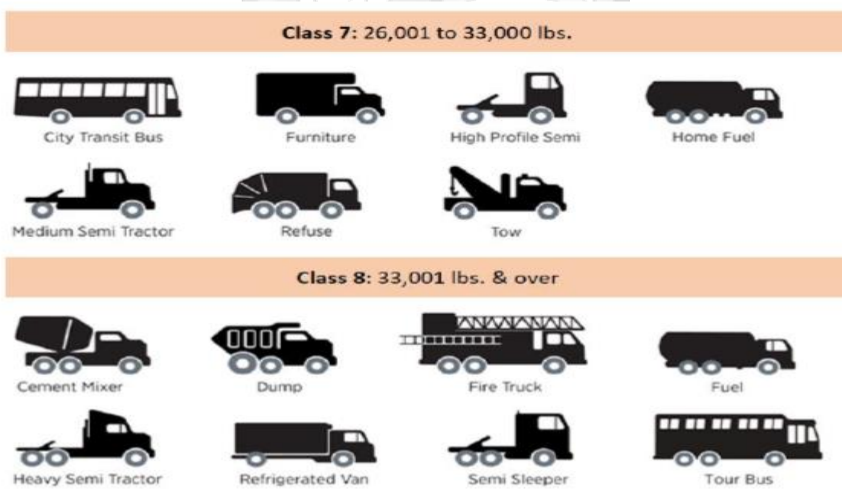

Figure 1.1: Classes and applications of heavy-duty vehicles (Cunanan, et.al, 2021)

Figure 1.1 classifies HGVs based on their gross vehicle weight rating (GVWR). Class 7 vehicles represent medium-duty trucks used for regional hauling and local delivery of cargo. Their GVWR ranges from 11,793 to 14,969 kg. Class 8 vehicles represent HGVs used for long-haul transportation with a GVWR greater than 14,969 kg. These HGVs include tractor-trailers, tanker trucks, and other heavy-duty configurations. This research looked at these vehicle categories, analysed their fuel consumption and quantified their emissions.

1.2 Problem Statement

In Kenya, freight cargo is primarily transported by trucks, classified as Heavy Goods Vehicles (HGVs). These trucks mainly run on diesel and gasoline, making them heavily dependent on fossil fuels. As a result, HGVs significantly contribute to carbon emissions released into the atmosphere. Carbon emissions raise the atmospheric concentration of greenhouse gases, which causes an increase in earth's temperature as well as changes to weather patterns like acid rain, droughts, and floods, they are a contributing factor to global warming. Moreover, high levels of carbon emissions degrade air quality which in turn poses health problems such as respiratory and cardiovascular diseases. According to Kenya Pipeline Corporation (2010), imported oil not only serves the Kenyan economy but also its neighbours which include the Democratic Republic of Congo (DRC), Uganda and Rwanda.

A report by the Government of Kenya (2019) shows that emissions from Heavy Goods Vehicles (HGVs) accounted for nearly 40% of all road sub-sector emissions. Furthermore, a report by World Bank Group (2023) shows that transport sector emissions increased to 12.09 $MtCO_2e$ in 2019, from 11.25 $MtCO_2e$ in 2015. Kenya has made several efforts to mitigate these increase in emissions such as the promotion of electric vehicles, the development of the National Climate Change Action Plan (NCCAP), provision of non-motorised transport (NMT) infrastructure and international commitments like the COP 26 declaration that aims to accelerate the transition to 100% zero carbon vehicles. Despite these efforts, the amount of transport emissions continue to increase. Research on mitigating transport emissions has been carried, however some researchers focused on modal shift, other scholars focused on shifting only passenger cars while others focused on one fuel switch option only. This study’s objective was to analyse the current road sector emissions associated with freight transport, primarily HGVs. Fuel switch alternatives such as electricity and bio-fuels were analysed in this study as alternatives to petroleum and their impact in mitigating road sub-sector emissions.

1.3 Objectives of the Study

1.3.1 General Objective

To develop a decarbonisation model using fuel switching in freight transport sector for reduced carbon emissions.

1.3.2 Specific Objectives

i. To evaluate carbon dioxide (CO_2) emissions related to transportation of cargo in Kenya
ii. To quantify the energy demand and subsequent CO_2 emissions associated for transportation of freight goods in Kenya.
iii. To model fuel switching options for heavy goods vehicles (HGVs).
iv. To develop a framework for transition to cleaner transport methods.

1.4 Research Questions

This research shall answer the following questions:

i. What are the emissions related to freight transportation?
ii. What is the total energy demand for freight transportation in Kenya?
iii. What other energy source alternatives are available in cargo transport? And what quantity of emissions is abated?
iv. What assumptions can be made and policies implemented to create a framework for model implementation?

1.5 Justification of the Study

Sustainable Development Goal 7 (SDG 7) aims to ensure access to affordable, reliable, sustainable, and modern energy for all. In the context of the transport industry, pursuing alternative fuel pathways aligns directly with this goal by reducing reliance on fossil fuels, which are finite resources with negative impacts on the environment. By transitioning to green energy sources such as electricity, hydrogen, or biofuels, the transport sector can mitigate greenhouse gas emissions, improve air quality, and contribute to a more sustainable energy future. A United Nations Special Edition Report (2023) contends that renewable energy use is growing in the electricity sector, however, it is limited in the transport sector. Alternative fuel pathways in the transport industry can foster innovation, spur economic growth, and enhance energy security. Moreover, diversifying fuel sources reduces dependence on imported oil and enhances energy resilience, mitigating risks associated with price volatility and geopolitical tensions. Policymakers can use the results of this study to inform decisions such as taxes levied on HGVs that rely on fossil fuels as opposed to renewable energy, which as a direct implication in the achievement of SDG 7.

Kenya, as a Party to the United Nations Framework Convention on Climate Change (UNFCCC), submitted its Nationally Determined Contribution (NDC) in July 2015. In December 2020, the country revised its NDC target, increasing its commitment to reducing greenhouse gas (GHG) emissions from 30% to 32% by 2030. The commitment to reduce GHG emissions was based on a report by Ministry of Environment and Forestry in 2020. The GHG emissions included in the NDC were of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) gases. In order to achieve its NDC, Kenya must undertake environmentally sustainable measures in the energy, industrial processes, product use, transport, agriculture, land use, forestry, and waste management sectors. This study was focused on mitigating CO_2 emissions in the transport sector. Policymakers can use the results of this study to assess the impact alternative energy sources have in reducing CO_2 emissions in the transport sector.

1.6 Scope of the Study

In this study, only vehicles that are over 7.5 tonnes were considered as HGVs. The age of the vehicle and whether or not the vehicle is subjected to routine service is not factored into the model. The study also focuses only of carbon dioxide CO_2 emissions, and does not consider other emissions such as methane (CH_4) and Nitrogen oxide (N_2O) emissions. Furthermore, the study only concentrated on the quantity of emissions and subsequent secondary reactions from the emissions are not considered.

1.7 Limitations of the Study

The study faced the following limitations;

i. In this study, assumptions on when electric trucks will be adopted and the current transition from the current diesel trucks to electric HGVs were made.

ii. This study projected transport road sector emissions up to 2050, however, possible future changes in policy and regulations which are crucial in the feasibility and adoption of decarbonisation strategies were not considered.

Chapter 2: Literature Review

2.1 Introduction

This chapter presents a theoretical and empirical review for energy modelling in the transportation sector. Theoretical concepts for clean alternative energy sources such as carbon emissions, hydrogen, electricity from renewable sources and biofuels have been presented in the first section of the chapter. The section also delves into the concepts related to energy models. A critical review of empirical studies in energy modelling in the transportation sector is also presented in this chapter. The last section of this chapter discusses the study gaps that this research aims to fill.

2.2 Theoretical Review

2.2.1 Carbon Emissions

Carbon emissions refer to the release of carbon dioxide (CO_2) and other carbon compounds into the atmosphere, primarily as a result of human activities such as burning fossil fuels, industrial processes, transportation and deforestation. They contribute to the greenhouse gas effect, which is the trapping of heat by the emitted gases that leads to an increase in the surface temperature of the earth which leads to global warming (Fan et. al, 2018). Examples of the emitted gases include carbon dioxide (CO_2), sulphur oxides (SO_x) fluorinated gases, such as sulphur hexafluoride (SF_6), carbon monoxide (CO) methane (CH_4), nitrous oxides (NO_x), and water vapour. Of these gases CO_2 is the most prevalent. It is primarily emitted from man-made activities such as the combustion of carbon-based fuels. CH_4 is present in smaller quantities and is emitted through natural sources such as permafrost thawing and human activities such as agriculture. Nitrous oxides are emitted from agricultural and industrial activities and fluorinated gases such as sulphur hexafluoride (SF_6) and hydrofluorocarbons (HFCs) are used in various industrial applications and refrigeration.

According to Xing et al. (2020), there is public concern about the release of these gases into the atmosphere. It is therefore critical to reduce these emissions in order to slow the progression of climate change which in turn will reduce the earth's temperature and associated health risks. Fan et.al (2018), contend that in the transport industry, optimisation studies must evaluate air pollutants.

2.2.2 Fuel Switching in the Transport Sector

Fuel switching is the process of transitioning from one type of fuel to another for various purposes, such as energy generation, heating, transportation, or industrial processes. In the transport sector, fuel switching refers to a transition from carbon-based fuels such as coal, diesel and gasoline to cleaner alternatives such as green electricity, hydrogen and biofuels. The transportation industry may mitigate greenhouse gas emissions, improve air quality, and help create a more sustainable energy future by pursing these choices. According to Shioshansi and Webb (2019), there are more than 1.2 billion automobiles on the road, increasing daily petroleum use and, in turn, per capita emissions. Fuel switching offers the transportation sector a chance to become less carbon-intensive when it comes to the delivery of cargo using heavy goods vehicles (HGVs).

HGVs are important for the transportation of freight around the world, and the emissions they produce have a major effect on emissions and air pollution. The Environmental Protection Agency (2021) estimates that 23% of the greenhouse gas emissions in the United States of America are caused by heavy-duty and medium-duty automobiles. Therefore, there is need to consider alternative fuels in order to mitigate these emissions. However, this transition entails intricate considerations, including technological readiness, infrastructure development, regulatory frameworks, and economic feasibility. By exploring and implementing fuel switching strategies in HGV transportation, stakeholders can achieve substantial environmental benefits while advancing toward a more resilient and low-carbon future.

Figure 2.1 presents the energy consumption and CO_2 emissions in the transportation sector. Ritchie and Roser (2021) estimate that in 2020, there were about 34.8 billion tons of CO_2 emissions overall, with the transport sector accounting for 23% of emissions and 28% of consumption, according to the Intergovernmental Panel on Climate Change Report. 34% of the carbon dioxide emissions in the transportation sector are attributed to trucks and heavy vehicles. To reduce these emissions, it is critical that the transportation sector adopt fuel-switching alternatives. Fuel switching has substantial financial and economic ramifications even though it is a lucrative and promising option

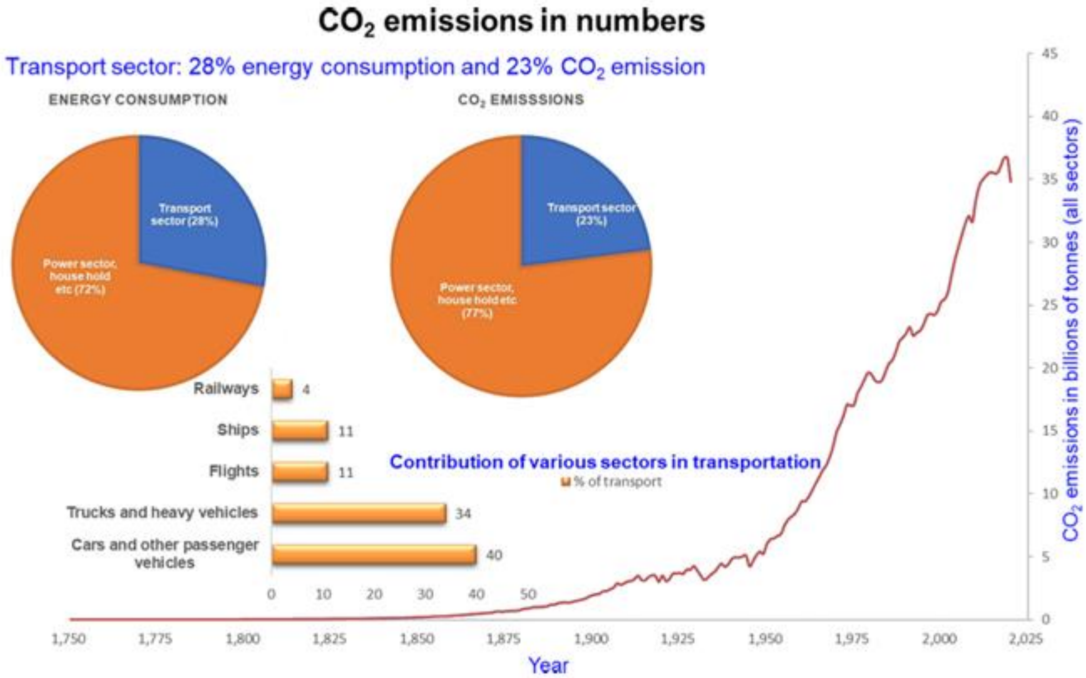

Figure 2.1: CO_2 emissions in numbers by 2020 *(Ritchie & Roser, 2021)*

Switching to alternative fuels has many long-term advantages such as environmental decarbonisation which leads to good air quality, reduction in global ground temperatures and reduced reliance on fossil fuels which are exhaustible. It, however, involves trade-offs between cost implications both short-term and long-term, technological advancements and energy security. For instance, the adoption of electric vehicles (EVs) requires significant upfront investment in new vehicles, batteries and charging infrastructure. According to Cunanan et.al. (2021), there is a major concern in the weight of a battery in heavy duty electric vehicles (HDEVs). This is because these vehicles are heavy and carry a lot of weight and may require a very large battery that increases the overall weight of the freight vehicle. As stated by Tran et al. (2021), a typical battery goods truck has a range of approximately 100–200 km on a single charge. This means that charging stations would have to be setup at least 100km from each other, hence huge initial capital investment.

Fuel switching in the transport sector can have significant economic implications. For example, reducing dependence on imported oil through the adoption of domestically produced alternative fuels or EVs can reduce vulnerability to oil price shocks and improve energy security, benefiting the overall economy. Additionally, spending money on infrastructure and new technology for fuel switching can boost the economy in allied industries and generate new job possibilities. However, traditional fuel providers, such as gasoline stations, may face reduced demand during the transition to electric or alternative fuel vehicles. This may lead to shifts in business models in the fuel retail sector and potential job losses. Cunanan (2021) states that battery-electric HDVs are the have the highest vehicle cost compared to diesel ICEs and hydrogen fuel cells. Furthermore, Sandaka and Kumar (2023) contend that due to the low uptake of alternative fuels, the cost of vehicle components for EVs and hydrogen fuel cell vehicles (HFCVs) is high and may discourage investors from alternative fuels. Overall, the economic implications of fuel switching in the transport sector are multifaceted, involving trade-offs between costs, technological innovation, energy security, and broader macroeconomic factors.

2.2.3 Alternative Sources of Fuel

2.2.3.1 Biofuels

Renewable fuels made from organic materials like plants, algae, or animal faeces are called biofuels. These biofuels are utilized more frequently to lessen greenhouse gas emissions and lessen dependency on non-renewable energy sources. They are regarded as a substitute to traditional fossil fuels. The many categories of biofuels are categorized according to their generation level, feedstock, and production methods.

First-generation biofuels are made from food crops such as sugarcane, vegetable oils and corn. One example is biodiesel, which is produced from animal and vegetable lipids and used in diesel-powered vehicles (DVs). Another illustration is bioethanol, which is made from biomass materials like cellular yeast and sugarcane or beetroot, which are based on starch, and sucrose. First generation biofuels, according to Alalwan et al. (2019), cannot take the place of fossil fuels since food demands must be met first.

Woody biomass, algae, agricultural leftovers, and non-food crops are the sources of second-generation biofuels. Biogas, which is generated from organic waste, cellulosic ethanol, and renewable diesel are a few examples. Chang et al. (2017) state that lignocellulose, which comprises of lignin, hemicellulose and cellulose, produces second-generation bioethanol and makes up around half of all biomass worldwide. Furthermore, bioethanol has been acknowledged as a possible substitute for fuels derived from petroleum due to its low cetane number, high octane number and high heat of vaporization. Wood chips and switch grass are examples of the agricultural and forest leftovers that are used to make lignocellulose, which is then used to produce ethanol.

Fuel crops like algae contain microorganisms that produce third generation biofuels. When compared to conventional crops, algae-based biofuels have the potential to produce more energy per unit of land. Aron et.al (2020) contend that third generation biofuels show the lowest net greenhouse gases emissions. The only drawback being that they require more energy to process and are therefore less environmentally friendly when used for electricity generation. These biofuels are derived from monoalkyl esters from plant oils and animal fats.

Finally, the bio-hydrogen component is usually present in fourth generation biofuels. Hydrogen created from the reforming of bioethanol is known as bio-hydrogen. They are also known as advanced or next-generation biofuels, represent a newer category of biofuels that aim to overcome some of the limitations associated with previous generations of biofuels. Biogas and syngas, two byproducts of biomass conversion that are commonly used in gas turbines or traditional internal combustion engines to produce heat or power, are hydrogen-rich gases. Chang (2017) argues that although the biofuel pathway is promising, fuel cells are a more efficient, silent, and clean approach to transform hydrogen energy into electricity.

To decrease the dependence on petroleum and mitigate greenhouse gas emissions in the transportation industry, biofuels have been seen as a viable and sustainable solution. This is largely because they share similar technologies with the internal combustion engines (ICE) and could use the same technology almost seamlessly. As per the IEA (2008) report, biodiesel is presently mixed with conventional diesel in numerous nations. The percentages vary; for example, 5% (BD5) in France, 20% (BD20) in the USA, and 100% biodiesel in some German Lorries. According to a Ministry of Energy (2020) report, blends in Kenya can contain anywhere from 1% and 99% diesel (B1) to 25% and 75% diesel (B25).

2.2.3.1.1 Biofuel Pathways

Biofuels are regarded as a promising and sustainable option to lessen petroleum dependence and GHG emissions in the transportation sector. They are a clean energy pathway for sustainable transportation by producing an agricultural fuel alternative for petroleum dependent engines. Three common pathways for biofuels are bioethanol, biodiesel and bio-hydrogen.

An alcohol called bioethanol is made from biomass feedstock, which includes cellulosic biomass, sugarcane, and starch crops. Its main application is as a fuel for transportation, either in combination with petrol or on its own. It is made when yeasts ferment glucose by a process called anaerobic respiration, which turns glucose into carbon dioxide and ethanol as illustrated in equation 2.1.

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \qquad (2.1)$$

Ambaye et al. (2021) state that the production of biofuels using thermo-bio-chemical processes from crop plant residues, micro- and macro algae, and other biomass wastes, such as bioethanol, is an environmentally acceptable method of obtaining energy. Remaining waste is also being utilized as a feedstock to produce ethanol. First-generation bioethanol is obtained from either starch or sucrose biomass, whereas second-generation bioethanol originates from lignocelluloic biomass.

Biodiesel is a renewable fuel that is obtained from organic materials, typically vegetable oils, animal fats, or recycled cooking oils. Transesterification, the primary production step, is reacting the feedstock with an alcohol, such as butanol, methanol, ethanol, or isopropanol. Higher molecular weight alcohols improve the cold flow characteristics of the resultant ester and result in a less efficient transesterification reaction (Chang et al., 2017). Equation 2.2 illustrates how the reaction proceeds in the presence of a catalyst, such as potassium or sodium hydroxide, to create fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE), with glycerine as a byproduct.

$$Vegetable\ Oil + Alcohol \rightarrow Esters + Glycerine \qquad (2.2)$$

The term "biohydrogen" describes hydrogen gas (H_2) that is generated from biological sources by a variety of biological processes, most commonly by microorganisms like bacteria, algae, or cyanobacteria. In this case, it refers to hydrogen obtained by steam ethanol reforming (SER) of bioethanol and hence a fourth generation biofuel. Rathi et.al (2024) argue that the generation of biohydrogen from lignocellulosic materials is an eco-friendly path in the production of biofuels. Additionally, significant developments in the biohydrogen manufacturing process have resulted in increased power generation, which is crucial for the long-term use of energy. The conversion of ethanol into hydrogen, in most cases, involves the use water in the steam reforming process, a process similar to reforming natural gas as shown in equation 2.3.

$$C_2H_5OH + H_2O \rightarrow 2CO + 4H_2 \qquad (2.3)$$

2.2.3.1.2 Social Concerns for Using Biofuels

Food crops including corn, sugarcane, and beetroot are used as feedstock for first-generation biofuels by both plants and animals. The struggle between humans and energy sources for feedstock may intensify as a result of the generation of biofuels from food crops. According to a report by World Bank (2010), in 2006-2008 there was a commodity price boom in the United States. This was because of an unlucky scenario that saw high oil prices and low harvests lead to a deadly combination. Furthermore, financial investors focusing more on the production of biofuels than food crops. This scenario should be viewed as an eye opener and the production of biofuels should originate from second to fourth generation biofuels to prevent a recurrence of such a scenario.

2.2.3.2 Hydrogen as an Automotive Fuel

Hydrogen's clean burning characteristics and ability to reduce greenhouse gas emissions from transportation have attracted a lot of interest in it as a possible vehicle fuel. Given that it is widely available on Earth in mixed form and has a high gravimetric energy density, makes it a suitable energy source. Hydrogen presents itself as a good man-made energy source for the transportation industry due to its availability. Singh et al. (2015), however, argue that there is still a problem with its economically viable sustainable generation from renewable resources. Thus, there is need for thus hydrogen to be stored in the vehicles in order to provide a decent driving distance. Its application in long-lasting energy conversion devices and the creation of infrastructure for its supply are still difficult tasks.

Hydrogen production presents a big challenge, despite the fact the many ways there are to produce it. Hydrogen production from steam methane reforming (SMR), gasification of coal or other hydrocarbons and from biomass can be done on large-scale and are relatively less expensive. However, releasing carbon emissions presents a challenge. According to Tashie-Lewis and Nnabuife (2021), in order to generate 1 kilogramme of hydrogen at maximum conversion efficiency, water electrolysis needs a minimum of 39.4 kWh of energy. Though most electrolysers won't run at maximum efficiency, they still need to use around 50 kWh to produce one kilogramme of hydrogen, and attempts are being made to improve the electrolysis process' efficiency. Acar and Dincer (2013) state that the electrolysis of water presents the cleanest option for hydrogen production but on a small scale. Nevertheless, they contend that it is a zero-emission process that produces pure hydrogen and pure oxygen.

Given that hydrogen emits water vapour emissions, using it as fuel for automobiles is an environmentally friendly method of transportation. It has the potential to improve energy supply security and is capable of being produced from a broad range of energy sources. According to Moriarty & Honnery's (2019) analysis of hydrogen's potential as a fuel for transportation, freight transportation will be the primary use for hydrogen, not small cars. There are two methods to use hydrogen as fuel for automobiles. First, to power the internal combustion engine with fuel. Secondly, to power fuel cells. Since fuels don't use up energy when stopped, like at a red light or in traffic, the second option is thought to be better than ICEs.

2.2.3.2.1 Advantages of Hydrogen as a Fuel

Several features of hydrogen make it superior to both biofuels and fossil fuels as it can be used in ICEs and fuel cells and is highly abundant, clean, colorless, odorless, non-toxic, and non-corrosive. It is the lightest element in the universe, as evidenced by its position at the top of the periodic chart. Out of all conventional fuels, hydrogen has the highest specific energy content in the world. When hydrogen is used in ICEs, it can use the existing vehicle infrastructure, moreover, it can be used as fuel cells.

Hydrogen used in fuel cells is silent and simple, as fuel cells have no mechanical components and operate at lower temperatures and pressures compared to internal combustion engines (ICEs). Fuel cells have high performance and they convert hydrogen fuel to energy for movement through an electrochemical reaction that has a higher efficiency than combustion.

It is important to note that some hydrogen from water hydrolysis is far more energy efficient than when it has been re-electrified. Moriarty & Honnery (2019) state that using the H_2 from water hydrolysis directly as a fuel operates at 50-60% efficiency full cycle, while re-electrified H_2 gives about 27 - 38% efficiency at full-cycle. Moreover, fuel cells possess the ability to cogenerate, meaning that the leftover heat produced by the electrochemical process can be incorporated into the vehicle's heating system. Fuel cells provide users a sense of fuel security because if there is fuel to generate electricity, the fuel cell never runs down.

Hydrogen can also fuel in the traditional ICEs therefore making sure that manufacturers can utilise the current vehicles without having to design new vehicular infrastructure. According to Akal et al. (2020), the effects of adding hydrogen to the fuel system in internal combustion engines (ICEs) vary. In most petrol engines, the power and torque figures increased, however in LPG and diesel engines, they declined. While some diesel engines produce more nitrogen oxide, petrol and LPG engines emit fewer harmful exhaust fumes. Chang (2015) states that hydrogen's energy yield of 120MJ/kg, is about 2.75 times higher than carbon-based fuels currently in use. Because of this characteristic, hydrogen has a higher calorific value than petrol because it can store about 2.6 times as much energy per unit mass.

2.2.3.2.2 Limitations of Automotive Hydrogen

Hydrogen may be an exciting emerging technology in the automotive energy sector; however, it does bare some limitations to its counterparts. Hydrogen is referred to as a "secondary" fuel because it does not exist on its own naturally as oil does and requires energy to be produced. Singh (2015) contends that its low volumetric density is a huge challenge as it would require four times as much volume than gasoline to produce the same energy. This volume is great and in turn means the use of heavy canisters which make the transport and storage of hydrogen complex. According to Akal et.al (2020), using hydrogen in vehicles reduces the amount of torque and engine power in diesel and LPG engines. This reduces the efficiency of the vehicle and is thus counterproductive as the vehicle is less efficient.

The production of some components of the fuel cells requires a higher cost as hydrogen fuel cells have not been widely adopted and lack economies of scale, making their cost of production high. According to Sobrino et.al. (2010), the cost of a fuel cell vehicle is 30% more than that of a similar vehicle that uses gasoline or diesel. The subsequent low demand for fuel cells means it hydrogen cannot yet compete with conventional technologies. Lastly, catalytic poisons can affect fuel cells. This is the process by which electrodes accelerate electrochemical reactions using catalysts. The fuel cell irreversibly deactivates when it comes into contact with catalytic poisons, which include heavy metals, carbon monoxide (CO), and different sulphur compounds.

2.2.3.3 Use of Electricity in the Automotive Industry

Electric cars (EVs) are becoming more and more common for several reasons, including their lower cost and growing public awareness of environmental and climate change issues. To reduce carbon emissions, the transportation industry is advocating for the adoption of electric vehicles. According to a report by the European Commission (2011), the transport sector contributes over 28% of the total emissions of carbon dioxide (CO_2), with road transport accounting for more than 70% of these emissions. To prevent the build-up of CO_2 and other greenhouse emissions, authorities in the majority of rich countries and some emerging nations are promoting the use of electric vehicles. This is being done through various incentive programs and tax breaks on importation and manufacturing of EVs.

2.2.3.3.1 Advantages and Disadvantages of Electric Vehicles

EVs have zero emissions because they do not emit tailpipe pollutants, carbon dioxide (CO_2) or nitrogen dioxide (NO_2). However, electronic vehicles are not entirely zero carbon if they utilise electricity from generated from carbon-based fuels such as coal, petroleum or natural gas. Furthermore, battery manufacturing processes have adverse effects on the carbon footprint.

Second, EVs are more energy-efficient than conventional cars. It is crucial to remember that power plant efficiency affects the overall well-to-wheel (WTW) efficiency. The range of overall WTW efficiency for gasoline-powered vehicles is 11% to 27%, whereas the range for diesel-powered vehicles is 25% to 37%, according to Albatyaneh et al. (2020). By contrast, EVs fed by natural gas power plants have a WTW efficiency ranging from 13% to 31%, whereas EVs fueled by renewable energy sources have an overall efficiency of up to 70%.

Thirdly, the smaller engine components of EVs translate into lower maintenance costs. Their engine types are more straightforward because they don't need a cooling circuit to mitigate combustion, a gearbox, a clutch, or components to muffle engine noise. According to Sanguesa et.al (2021), the lack of engine noise makes travelling in EVs more comfortable. Furthermore, since these vehicles have few and simple mechanical parts, they suffer less wear and tear from engine vibrations and fuel corrosion and are less prone to breakdowns.

EVs face battery related challenges; majorly, the driving range of an EV is limited in comparison to vehicles that use gasoline or diesel. According to Nissan Leaf (2021), the maximum driving range of the Nissan Leaf is 364 km. Additionally, Tesla (2021) claims that the range of the Tesla model S is greater than 500 kilometers. Second, it can require four to eight hours to fully charge a full battery pack. According to Tesla (2021), using a fast-charging station, charging to 50% capacity takes 20 minutes, while charging to 80% capacity takes roughly 30 minutes. The battery packs are expensive, heavy, and need a large amount of room in vehicles. According to Berjoza and Jurgena (2017), the weight of these cars' batteries ranges from about 200 kg to 300 kg, depending on the battery capacity.

2.2.4 Energy Models

Energy modelling is a computational method used to analyse, predict, simulate and optimise energy systems, processes and behaviours in the commercial, transport, industrial, agricultural and residential sectors. It involves creating mathematical representations of various aspects of energy consumption, production, distribution, and other related factors to better understand energy flows through a system and to predict future energy patterns or outcomes. The primary objectives of energy models, according to Gerboni et al. (2017), are to estimate supply and demand for energy, assess how policies and actions affect an energy system, and calculate the implications of various targets, such greenhouse gas emissions. Moreover, they argue that energy models serve as a useful tool for decision-makers by comparing the financial implications of various configurations. Energy modelers employ energy modelling methods to characterize energy systems across various locations and illustrate the fuel sources and technologies that are needed to meet energy demand. Energy modelling tools come in a variety of forms and can be classified into two primary methods: top-down and bottom-up approaches.

The bottom-up technique is characterized by a high degree of technological detail and is often used to estimate and forecast probable future scenarios of an energy system. It accounts for both supply and demand for energy commodities. Two further categories can be made out of them: simulation models and optimization models. Simulation models are used to compare two or more scenarios. The IAEA (2006) suggests using the Model for Analysis of Energy Demand (MAED) as an example of bottom-up energy demand modelling tool that can project future energy demand based on socioeconomic, demographic, and technological factors. Optimization models try to find the most economical/most efficient fuel mix and technology combination to minimize or maximize a given objective function by applying a set of constraints. Howells et al. (2011) cite the Open Source Energy Modelling System (OSeMOSYS) as an optimization model as bottom-up model that provides the least cost optimal solution for agricultural, electrical, commercial and transport sectors. Bottom-up models, which take into consideration scale effects, learning curves, and improvements in research and development (R&D) can forecast a dynamic progression of the technological improvements of the gadgets. They are defined by a combination of economic criteria, such fixed and variable costs, with a set of defining parameters, like efficiency, technological life, and emission factors.

The top-down approach in energy modelling is a method where the overall system is analysed first before delving into specific details. This approach involves starting with an overview of the entire energy system and then gradually refining the analysis to include more detailed information as required. Gerboni et.al (2017) states that these models are mainly related to the econometric models. Examples of these models include the General Equilibrium Model for Economy-Energy-Environment (GEM-E3) and the Global Trade Analysis Program (GTAP) model.

2.2.5 Energy Modelling in the Transportation Sector

Energy modelling in the transport sector involves the use of computational methods to simulate, analyse and predict energy consumption, carbon emissions and travel demand. It involves the creation of mathematical representations of various aspects of transportation systems such as, vehicles, infrastructure, travel patterns, and energy sources, to understand and quantify energy flows, emissions and associated costs. Gerboni et.al (2017) assert that many optimizations bottom-up models are available with several applications in the transportation sector. Consider the examination of how the transportation industry affects the energy system as a whole or how particular environmental regulations affect the advancement of technology in the transportation industry.

TIMES (The Integrated MARKAL_EFOM System) models are energy models used for long-term energy and environmental policy analysis. They are based on the bottom-up approach meaning they represent the energy system in detail taking into consideration various technologies, resources and sectors. These models also incorporate economic and environmental factors thereby providing comprehensive insights into the energy system's behaviour under different scenarios. Thiel et al. (2016) assessed the impact of EU automobile CO_2 regulations through 2050 using the JRC-EU-TIMES (TIMES model for the Joint Research Centre – European Commission) model. Pye and Daly (2015) employed ESME (Energy System Modelling Environment) to investigate the UK's carbon reduction pathways with an emphasis on the role of transport demand side policies, or the modal shift, to the de-carbonization in mid- and long-term scenarios. Governments, academic institutions, and international organizations frequently employ TIMES models for long-term planning and analysis of energy policies.

2.3 Empirical Review

There has been interest by scholars in developing energy models in the transport industry as the world moves towards a low carbon future. A number of researchers have critically reviewed fuel switching options and CO_2 abatement as the countries of the world aim to honour the Paris Agreement (PA). Scholars have investigated how the low carbon fuel standard (LCFS) can help achieve long-term goals for reducing greenhouse gas emissions. Lepitzki & Axsen (2018) examined how LCFS, when combined with other climate policies, can lower carbon emissions in British Columbia, Canada. This analysis takes into account climate policies such as carbon pricing, zero emission vehicle mandates, and fuel economy restrictions. The authors created an optimization model for fuel supply and a dynamic vehicle adoption model that they applied to the personal and goods vehicle industries. They discovered that in order to meet the 2050 GHG targets, a combination of the strictest policies is needed. Furthermore, LCFS was found to have a lower impact in the personal vehicle sector and have larger impacts in the freight sector where a switch to zero emission vehicles does not necessarily cut GHGs. Lepitzki & Axsen concluded that LCFS could be vital in decarbonizing the transportation sector with careful policy design.

While the research conducted by Lepitzki & Axsen (2018) concisely shows the value of LCFS in the decarbonisation of British Columbia, Canada, it leans more towards policy formulation as opposed to carbon dioxide (CO_2) abatement. The study comprehensively explains that combination of most strict policies used across Europe is required to achieve the 2050 GHG targets. However, the policy models computed do not give a numerical value for the amount of CO_2 reduced when ambitious polices are implemented and the cost per CO_2 abatement.

Scholars have focused on policy modelling by analysing the impact of electric vehicle adoption and subsequent CO_2 emissions. A study of transportation emissions scenarios in New York City under various electrical carbon intensities and rates of adoption of electric vehicles was carried out by Isik et al. in 2021. Using a scenario framework, an advanced technology-driven bottom-up energy system optimization model was employed to analyze the impact of air emissions and costs on the transportation industry. The study discovered that deeper reductions in air pollutants need the electrification of light-duty cars at earlier times. Moreover, EVs' increased energy efficiency makes a significant contribution to the decrease of CO_2. The researchers concluded that the cost-effectiveness of CO_2 reduction paths for the transportation sector is largely unaffected by uncertainties related to the de-carbonization of the electric grid. The study carried out by Isik et.al

(2021) gives a comprehensive analysis of adoption of electric vehicles in New York City. The research concisely models the effect of adopting electric vehicles and the potential CO_2 abatement. While this analysis is comprehensive, it is limited to light-duty vehicles. Furthermore, the research only accounts for one pathway to the reduction of CO_2 emissions, the adoption of EVs. My research shall model other alternative energy pathways for sustainability such as hydrogen and biofuels, in addition to electronic vehicles.

The role of hydrogen in the transition from a fossil-fuel economy to a low-carbon society has also been explored by various researchers. Espegren et al.'s (2021) research examined hydrogen's function in Norway's energy transition, in line with EU efforts to find ways to collaborate with surrounding nations to create a global market for hydrogen. The researchers employed three models in their study. These models are an energy model that looks at the role of hydrogen from the standpoint of the energy and power markets without taking exports of hydrogen into account, an economic model to investigate how value is created in the export of hydrogen, and a socio-technical case study on the factors promoting and impeding Norway's generation of hydrogen. They concluded that Norway's transport and industrial sectors must have access to hydrogen and renewable energy in order to decarbonize, and that maintaining a high level of economic activity requires hydrogen. Espegren et.al (2021) presents a detailed account of the role of hydrogen in the decarbonisation of the Norwegian transport industry. It concisely discusses how the focusing on hydrogen in the transport industry will lead to structural changes in the economy. Furthermore, the study delves into the impacts of new technologies, the key enablers and barriers in this transition. While the study does discuss the three fuel alternatives to fossil fuels, hydrogen, biofuels and electricity, its primary focus is on the introduction, production and export of hydrogen fuel. Furthermore, computations for reduction of CO_2 emissions and the subsequent economic benefit are not discussed.

The effect of the Avoid, Shift, and Improve (ASI) policy strategies on changing transport networks has been studied too. In Lagos, Nigeria, Maduekwe et al. (2020) carried out research on vehicle emissions and energy usage in road travel. To ascertain the best ASI choice for the city, they projected future energy demand and greenhouse gas emissions using the Long Range Energy Alternative Planning (LEAP) model. The existence of extremely old cars, which is sensitive to the percentage of vehicles of a given age restriction that are still being driven, proved to be the primary barrier to the study's emission target. They concluded that in order for Lagos to meet its goal of a

50% reduction in emissions by 2032, the age limit for cars should be lowered from 40 to 22 years old, and the annual growth rate of automobiles should be lowered from 5% to 2% between 2020 and 2032. The study conducted by Maduekwe et.al (2020) thoroughly analyses the road transport system in Lagos, the most populous city in Nigeria, and its emissions. The study succinctly analyses the BAU scenario in Lagos and uses the LEAP model to predict a future that aims to achieve a 50% emissions reduction by 2032. Although the study is extensive, it focuses on vehicle age as the main reason for increased CO_2 emissions. Furthermore, the study proposes the reduction of GHG emissions by limiting the vehicle age while my study will approach the reduction of emissions using alternative sources of energy.

Research on cutting CO_2 emissions for China's urban passenger transport sector was carried out in 2019 by Li & Yu (2019). Creating a National Energy Technology-Transport (NET-Transport) model was the goal of the study in order to evaluate the effects of switching to alternative clean fuels. In addition, the model sought to reduce future energy demand and CO_2 emissions by promoting public transit and increasing vehicle efficiency. The researchers discovered that if clean fuel usage is encouraged and vehicle efficiency is raised, China's urban passenger transport sector's CO_2 emissions might peak at 225 $MtCO_2$ in 2030. This is because of increased population and increased vehicle demand. While the research conducted by Li & Yu (2019) is exhaustive, clear and concise, it focuses on the public transportation sector only. The vehicle types considered in this research are taxis, buses and cars. The study does delve into the use of alternative fuels such as electricity, compressed natural gas (CNG) and liquefied petroleum gas (LPG), not all the sources considered are clean energy sources. Furthermore, the study does not touch on heavy duty vehicles (HDVs) and CO_2 emissions from them are not within the scope of this study.

Decarbonisation of the transport industry has been researched using different approaches. Salvucci et.al (2019) conducted a study on decarbonising the Scandinavian transport sector by modal shift. The study uses the TIMES-Nordic model to depict the national energy systems of Denmark, Norway and Sweden. The researchers used substitution elasticities to model modal shift for both passengers and goods. According to the analysis, rail and non-motorized modes replace cars for passenger vehicles, while trucks and ships are replaced by rail for freight, with the outcomes being contrasted under a higher carbon tax. A cost-effective mitigating measure, the modal shift, is expected to reduce cumulative transportation-related CO_2 emissions by 2.2% and petroleum consumption by 26PJ by 2050. Additionally, the study carried out a sensitivity analysis on the investment costs of electric vehicles, which showed that in a future where electric vehicles are more competitive and the power sector has nearly decarbonized, CO_2 taxes would not be successful in encouraging car substitution. Salvucci et.al (2019) study comprehensively shows that modal shift is more effective than the CO_2 emission tax in decarbonising the Scandinavian transport sector. While the study is detailed and succinct, it does not explore fuel switching methods in road transport but rather, it focuses on changing the modes of transport as a means to decarbonisation. The study highlights rail as the preferred option for both passenger and freight transport. Furthermore, the research considers alternative fuels and hydrogen, LPG, natural gas blending, electricity and biofuels, but the model focuses on replacing modes of transport and not alternative fuels. My study proposes to incorporate alternative fuels in freight transport.

Scholars have analysed the impact of a combination of energy efficiency approaches have reducing CO_2 emissions. Valderrama et.al (2019) conducted a study on CO_2 equivalent emission scenarios for the Columbian transport sector. A carbon emission accounting model that links vehicle stock, fuel consumption, and emissions to travel demand was developed by the researchers. The study considered modal shift, new engine technology, fuel switching, and energy efficiency. According to the report, under the BAU scenario, the examined strategies might cut cumulative emissions by 8% and 18% through 2030 and 2050, respectively. The yearly mitigation coast, according to the researchers, is substantial and ranges from 0.5% to 4% of the GDP of the country. Lastly, the report suggested non-technological measures to achieve low-carbon transport systems in Columbia, including increased use of public transport and freight sector reorganization. The research conducted by Valderrama et.al (2019) details the entire transport sector of Columbia, from rural, inter-urban and urban areas. While the study considers fuel switching as a means to reducing carbon emissions, it does not consider fuel switch to renewable alternatives in freight transport. The scholars focused on fuel switch to liquefied natural gas and modal shift to rail for freight. My study proposes to focus on fuel switching in freight transportation and the reduction in CO_2 emissions.

Energy modelling for the road transport of petroleum products between Nairobi and Mombasa was carried out by Ngure (2015), where the authors developed an energy demand model for road cargo transport. By identifying new issues, locating potential energy-saving opportunities, and offering alternate policy solutions, the study aims to influence policy. Three models—the fuel consumption model, the trip production model, and the energy demand model—were created for this study.

According to the study's findings, in order to save as much energy as possible when transporting petroleum products by goods, HGVs must keep an average speed of between 70 and 75 km/h. The research carried out by Ngure (2015) mainly focuses on energy savings that can be attained using the HGVs that rely on automotive diesel oil (ADO). The study focuses on optimizing trips and speeds in order to use less fuel. Although the study gives a concise approach to energy efficiency, it does not analyse the fuel switching options available. My study will focus on fuel switching in freight transport and the reduction in CO_2 emissions.

A study assessing Kenya's low carbon future was carried out by Gachanja et.al (2023). In their baseline analysis, the study analysed various sectors including electricity generation, transport, buildings, manufacturing, power generation and land use. The researchers identified the transport sector as the largest contributor of carbon emissions in Kenya. They developed KCERT 2050, which is a modelling tool designed to assist in the identification and evaluation of the synergies and trade-offs within sectoral decarbonisation pathways in Kenya. This is done with the aim of achieving a net-zero emissions pathway by 2050. The scholars concluded that the transport sector was one of the most difficult to decarbonise due to its reliance on fossil fuels. Furthermore, the recommended the uptake of initiatives such as developing a Mass Rapid Transit System in major cities, electrification of the standard gauge railway and adoption of electric vehicles. The study carried out by Gachanja et.al (2023) focuses on decarbonisation in various sectors such as electricity generation, transport, buildings, manufacturing, power generation and land use. Furthermore, in the transport sector, all forms of transport such as air, water and land are considered with the goal of achieving net-zero emissions. My study will provide a more specific approach to decarbonisation in the transport sector. It will focus on quantifying carbon emissions in freight transport by road. Fuel switching is the only pathway my study will consider for decarbonisation.

A study on how emerging economies can meet development and climate change in a transport energy system was also carried out in Kenya by Dixon et.al (2024). The authors modelled co-developed scenarios from a socio-technical point of view as they developed a transport energy system model specifically for Kenya. The developed model is useful for decision making, informing policy at national, regional and international levels, with the main objective of the study was for Kenya's transport-energy system to meet its developmental and climate goals. The scholars found that this would require strong policy support for efficient public transport and targeted support for road vehicle electrification. Furthermore, the study concluded that, from a macro-fiscal point of view, an increase in uptake of has negative impact on taxation, however, it has a positive impact on the balance of payments by reducing the fuel imports bill. The research done by Dixon et.al (2024) comprehensively analyses Kenya's transport system, both public and private means of transport. The researchers found that for Kenya to meet its climatic goals, strict policies that increase the uptake of e-mobility will have to be employed. Although the study is comprehensive, it only considers one pathway for fuel switching, which is e-mobility. Furthermore, the study focuses on modal shift as the optimal pathway for decarbonisation.

This research aims to quantify the amount of carbon emissions reduced when fuel switching options such as hydrogen and biofuels are used as opposed to fossil fuels.

2.4 Summary of Gaps

In the analysed studies, it has been illustrated that the mitigation of carbon emissions in the transport sector is of importance as the countries of the world aim to honour the countries the Paris Agreement (PA). All the studies have attempted to reduce CO_2 emissions using various methods such as modal shift, optimizing the BAU scenario and fuel switching. The studies, however, have not analysed the potential benefits that can be realised by considering fuel switching in freight transportation. The following are the study gaps:

i. While Espegren et.al (2021) explored the fuel switching options in a bid to reduce carbon emissions in freight transportation but considered electricity as the only fuel switch option.

ii. Isik et.al (2021) have explored the fuel switching options in a bid to reduce carbon emissions in freight transportation but considered hydrogen as the only fuel switch option.

iii. Maduekwe et.al (2020) analysed decarbonisation of the freight transport sector in Lagos Nigeria, with his main focus being vehicle age.

iv. Salvucci et.al (2019) have analysed the decarbonisation of the freight transport sector in the Scandinavian region focusing primarily on modal shift.

v. Li & Yu (2019) discussed all three fuel switching technologies in the decarbonisation of transport in their regions, but their main focus was on introduction, production and export of a specific fuel. Furthermore, computations for reduction of CO_2 emissions and the subsequent economic benefit are not discussed.

vi. Ngure (2015) analysed freight transportation of petroleum products, but focused only on optimising the use of fossil fuels and not fuel switching in decarbonisation.

vii. Gachanja et.al (2023) analysed decarbonisation in Kenya, their study focused on various energy sectors such as electricity generation, transport, buildings, manufacturing, power generation and land use. Furthermore, in the transport sector, all forms of transport such as air, water and land are considered with the goal of achieving net-zero emissions. My study focus will be solely on road transport with an emphasis on freight in HGVs.

viii. While Dixon et.al (2024) analysed Kenya's transport system, they considered only one pathway for fuel switching, e-mobility. Moreover, the researchers concluded that modal shift was the optimal pathway for decarbonisation.

The present study therefore capitalizes on some of the gaps of presented here and provides an alternative approach in the mitigation of carbon emissions in large cargo transport.

2.5 Conceptual Framework

A conceptual framework is a logically developed, described and elaborated network of interrelationships among the dependent and independent variables. The independent variables are those that can be manipulated depending on the focus of the study. The dependent variables are those in which the effects of the changes in the dependent variable can be observed.

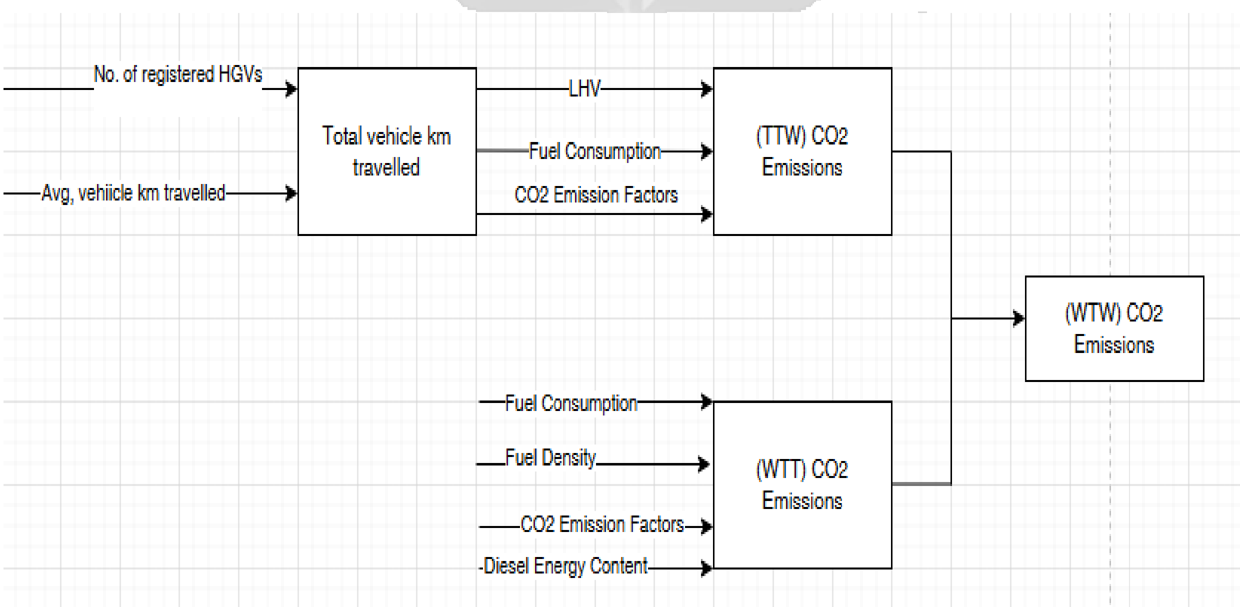

Figure 2.2: Conceptual Framework for de-carbonization model used in this study

Figure 2.2 presents the conceptual framework for the proposed de-carbonization model. The study focuses on the effects of fuel switching on carbon dioxide (CO_2) abatement. This study considered the full life cycle analysis (LCA) i.e. well to wheel (WTW) emissions. For HGVs, the WTW emissions is the sum of the well to tank (WTT) emissions and the tank to wheel (TTW) emissions. When computing the WTT emissions the model considered fuel consumption, fuel density, emission factors and the diesel energy content as the independent variables. For the TTW emissions, this study considered diesel exhaust emissions, the fuel lower heating value, and tail pipe emissions as the independent variables. The alternative energy sources such as hydrogen, electricity and biofuels was computed using the framework presented in Figure 2.2.

Chapter 3: Methodology

3.1 Introduction

In this chapter, the steps and methods required to meet the study objectives have been presented. The first section will describe the area of study. The second section discusses how the model is formulated and the formulas used in emission analysis. The final section details the data collection methods and presents the scenario analysis.

3.2 Study Area

The study focused on freight transport in Kenya where Heavy Goods Vehicles (HGVs) mainly use class A roads for long distance cargo haulage. According to the Kenya Roads Board (KRB) digital portal, class A roads account for 4,551.45 km of paved and unpaved driving surfaces. These roads link cities to places of international importance which include cities/towns from neighbouring countries such as Malaba, Namanga, Moyale, Nadapal and Mandera. HGVs also use class B roads when hauling cargo such as petroleum to smaller cities/towns within Kenya. These roads account for 14,962.07 km of paved and unpaved roads. Figure 3.1 presents a class A and B road network under consideration in this study.

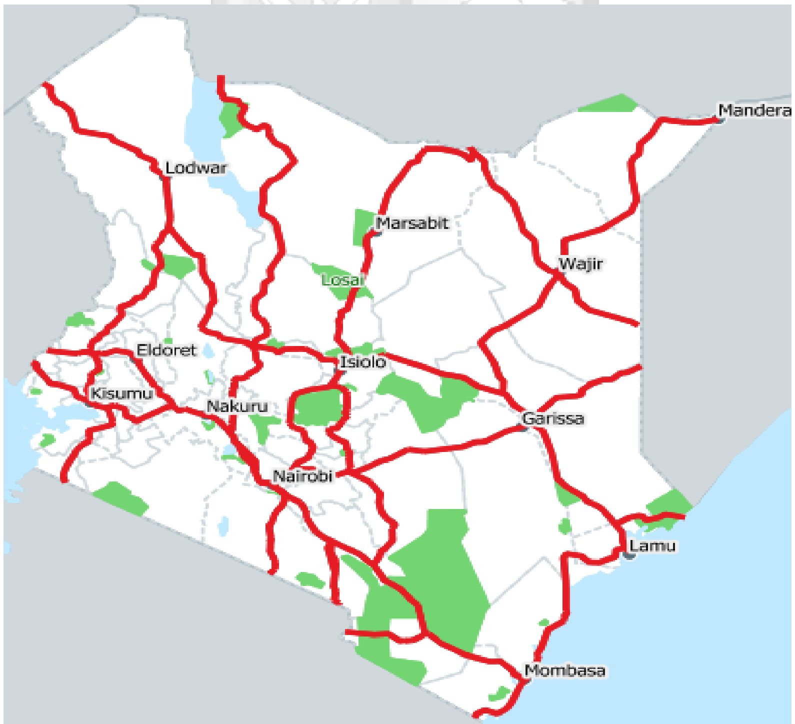

Figure 3.1: Class A Roads in Kenya (KRB Map Portal)

Table 3.1: Road Classification in Kenya (KRB Digital Logistics Capacity Assessment - Road Network)

Class	Roads	Paved (km)	Unpaved (km)	Total (km)
S	S1, S2, S3, S4-A, S4-B	123.11	-	123.11
A	A1 – A14	4,551.45	1919.92	6,471.37
B	B1 –B153	7,002.87	7,959.20	14,962.07
C	C107, C111, C115	2,693	5,164	7,857
D	Secondary roads	1,238	9,483	10,271
E	Minor roads	577	26,071	26,649

Table 3.1 presents the classification of roads in Kenya. Class S – roads connect two or more cities or provide a bypass thorough a city that safely carries a large volume of traffic at the highest speed of operation. Class A roads are international trunk roads that are used to link areas of international imprtance. Class B roads are national trunk roads that are used to link roads of national importance while class C are primary roads link provincially important centres. Class D roads link centres of local importance while class E roads link any minor centres.

3.3 Previous Methods used in Decarbonisation in Freight Transport

There are various methods that have been analysed and reviewed in the past with the aim of reducing carbon emissions in the transport sector. These methods include, fuel switching, modal shift, improving vehicle efficiency and freight and logistics optimization.

Fuel switching is defined as the process of transitioning from one type of fuel to another for various purposes such as energy generation, heating, transportation or industrial processes. In the transport sector, fuel switching refers to a switch from fossil fuels to renewable energies. Valderrama et.al (2019) analysed the impact of fuel switching from diesel to liquefied natural gas (LNG). Furthermore, Espegren et.al (2021) focused on fuel switching to hydrogen only in a high income economy.

Modal shift refers to changing the way people or goods are transported from high emission modes such as private cars to lower emission alternatives public transport, walking, rail and cycling. Many researchers have analysed it critically as a strategy to decarbonise the transport sector. Salvucci et.al (2019) analysed decarbonisation in the Nordic transport climate using modal split. Valderrama et.al (2019) analysed the Colombian transport sector that focused on modal shift to rail.

Other methods such as improving vehicle efficiency and improving freight transport and logistics have been studied extensively. In this study, fuel switching was analysed considering an energy mix of biofuels and electricity to replace low sulphur diesel in freight transport. In Kenya, there has been an uptake in the use of electric vehicles since 2018 and the subsequent vehicle charging infrastructure has grown significantly (EPRA, 2024).

3.4 Model Description

In this study, the vehicle stock for the years 2015-17 was based on Ogot et.al (2018), which used the Handbook Emission Factors for Road Transport (HBEFA) fleet model. HBEFA projected vehicle fleet based on the number of new registrations and survival probabilities per vehicle segment i.e. passenger car (PC), buses, HGVs etc. The survival rate for HGVs in this study was calculated using the modified Weibull distribution in equation 3.1.

$$S_{v,age}^{w} = \exp\left[-\left(\frac{Age+ a_v}{T_v}\right) b_v\right] \tag{3.1}$$

Where,

$S_{v,age}^{w}$	The survival rate for HGVs as a proportion of the number of vehicles registered in 2023 and still being in service at a specified base year
Age	Median age of the HGVs
a_v	Shape parameter, rate of vehicle registration of HGVs
b_v	Scale parameter, characteristic life of the HGVs
T_v	The characteristic service life of the vehicle category

The number of in-service HGVs, N_s, was estimated by multiplying the survival rate with the annual new vehicle registration information from each year, r_k. The summation of the individual products based on equation 3.2 yields the estimated HGV vehicle population for the period under review.

$$N_s = \sum_{k=0}^{T} r_k \, x \, S_{v,k}^{w} \tag{3.2}$$

With the estimated number of vehicles for each age group, N_k, estimated using equation 3.3

$$N_k = r_k \, x \, S_{v,k}^{w} \qquad (3.3)$$

$S_{v,k}^{w}$	The survival rate for HGVs as a proportion of the number of vehicles registered in a specific year.
r_k	Annual vehicle registration for a specific year

3.5 Calculation of CO_2 Emissions

In this research, calculation of the CO_2 emissions from Heavy Goods Vehicles (HGVs) for diesel, bio-diesel (BD20) and electricity as fuel switching options was carried out. A full life cycle analysis (LCA) was considered in the study as the emissions considered where Well to Wheel (WTW) or Cradle to Grave (C2G). As such, well to tank (WTT) tank emission factors and tank to wheel (TTW) emission factors were considered in this study.

The tank to wheel (TTW) emissions for diesel for diesel is 2.68 kg CO_2 per litre and biodiesel is 1.92 kg CO_2 per litre as per the report conducted by the joint Research Consortium in 2008 (JRC, 2008). In the case of EHGVs (Electric Heavy Duty Vehicles), TTW emissions was taken as zero (0). The total emissions were computed simply using equation 3.4.

$$CO_2 \; Emissions \; = Total \; fuel \; consumption \; \times Emission \; Factors \qquad (3.4)$$

The calculation of Tank to Wheel (TTW) CO_2 emissions, or tail-pipe emissions, was calculated using the framework presented in Figure 2.

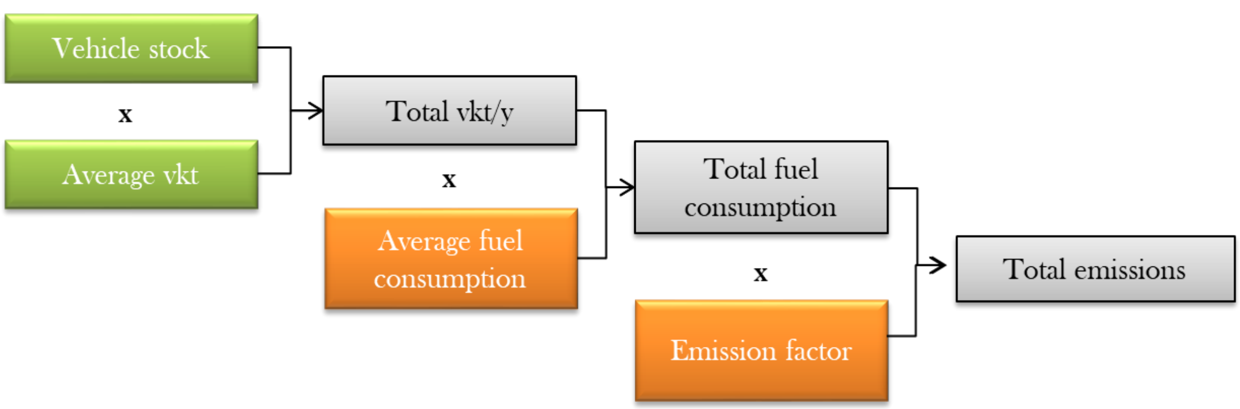

Figure 3.2: Calculation methodology

Figure 3.2 presents how the total emissions are computed, where the total vehicle kilometres (VKM) travelled by HGVs is found by multiplying the number of HGVs currently in stock with the Average vehicle kilometres travelled. To compute the total fuel consumption, the total VKM is multiplied by the average fuel consumption. Finally, the emissions are computed by multiplying the Total fuel consumption with the emission factor for diesel.

3.5.1 CO_2 Emissions for HGVs using Diesel

The diesel in Kenya is classified as low-sulphur distillate diesel also referred to as automotive gas oil (AGO) extracted from crude oil refining. According to JEC (2023), the diesel energy content is approximately 45.6MJ/kg with the emission factor of 18g CO_2e/MJ for low sulphur diesel. The fuel density of diesel is given as 0.84 kg/l and its Lower Heating Value (LHV) is 43 TJ/1000 tonnes. The Transport Inventory Greenhouse Gas Emission Reporting tool (2021) classified the vehicle economy for diesel per weight class. For example, a HGV that weighs less than 7.5t consumes 13.15 litres per 100km.

Thus, in this research, the total well to tank (WTT) CO_2 emissions for diesel was given by equation 3.5.

$$E_{diesel} = FC \times Density_D \times EF_D \times EC_D \tag{3.5}$$

Where,

E_{diesel}	Diesel Emissions (in kg/tonnes)
FC	Fuel Consumption (litres/km)
$Density_D$	Fuel Density for diesel in (kg/l)
EF_D	CO_2 Emission Factor for diesel
EC_D	Diesel energy content

The tail-pipe or tank to wheel (TTW) emissions for diesel HGVs was given by equation 3.6

$$E_{diesel} = LHV_D \times FC \times EF_D \tag{3.6}$$

Where,

E_{diesel}	Diesel Emissions (in kg/tonnes)
EF_D	CO_2 Emission Factor for diesel (in kg/TJ)
FC	Fuel consumption (in tonnes)
LHV_D	Lower heating value for Diesel

The summation of equation 3.5 and 3.6 gives the Well to Wheel (WTW) Emissions for diesel.

3.5.2 CO_2 Emissions for HGVs using Bio-diesel (BD20)

In this study Bio-diesel 20 (BD 20) was the fuel switching option considered. BD 20 is a blend of diesel and bio-fuels in an 80/20 split. It contains 80% diesel and 20% biofuels. With this combination, BD 20 can be used in existing diesel engines without having to do engine modifications. This research considered a blend of the existing low sulphur diesel with bio-fuels primarily from soy waste. According to JEC (2023), a soy based biofuel has an energy content of 37.8MJ/kg the emission factor is 8gCO_2e/MJ. The fuel density of diesel is given as 0.86 kg/l and its lower heating value is 42.00TJ/1000 tonnes.

Therefore, in this research, the total well to tank (WTT) CO_2 emissions for bio-diesel 20 was calculated as weighted average between diesel and biofuels as presented in equation 3.7.

$$E_{BD20} = 0.8 \times (Equation\ 3.5) + 0.2 \times (FC\ x\ Density_B) \times EF_B \times EC_B \qquad (3.7)$$

Where,

E_{BD20}	BD 20 Emissions (in kg/tonnes)
FC	Fuel Consumption (litres/km)
$Density_B$	Fuel Density for BD20 in (kg/l)
EF_B	CO_2 Emission Factor for BD20
EC_B	BD20 energy content

The tail-pipe or tank to wheel (TTW) emissions for HGVs using BD (20) was given by equation 3.8

$$E_{diesel} = LHV_D \times FC \times EF_D \qquad (3.8)$$

Where,

E_{diesel}	BD (20) Emissions (in kg/tonnes)
EF_D	CO_2 Emission Factor for BD 20 (in kg/TJ)
FC	Fuel consumption (in tonnes)
LHV_D	Lower heating value for BD 20

3.5.3 CO_2 Emissions for Electric HGVs

For electric HGVs (EHGVs), the emission considered in this research was well to pump (WTP) emissions only. Tail pipe emissions were assumed to be zero because electricity is a clean energy source. The WTP emissions are essentially grid emissions which are calculated using equation 3.9.

$$E_{Electricity} = E_{demand} \times EF_{grid} \times (1 + LF_{TD}) \tag{3.9}$$

And the total energy consumed is given by equation 3.10.

$$E_{demand} = E_{consumed} \times D_{fleet} \tag{3.10}$$

Where,

$E_{Electricty}$	Total emissions from electricity (in kg/tonnes)
E_{demand}	Total Energy required from the grid (Kwh/Gwh)
EF_{grid}	Grid Emission factors (gCO_2e/MJ)
LF_{TD}	System losses due to transmission and distribution
D_{fleet}	Total distance covered by fleet (in km/year)
$E_{consumed}$	Energy consumption per HGV (kwh/km)

3.6 Data Collection

The data used in this study is provided by the Transport Inventory and Greenhouse gas Emission reporting Tool for Kenya (Kwoba, 2020). Another key data set is from a government publication on the characteristics of the in-service fleet in Kenya conducted by Ogot et.al (2018). In this study, data to generate the model was collected through government periodicals and publications. The specific data to be collected is presented in Table 3.2.

Table 3.2: Secondary Data

Organization	**Data Type**	**Publication/ Report**
National Transport and Safety Authority (NTSA)	Age, in-service vehicle population characteristics	KNBS Economic Surveys 2023
Kenya Power and Lighting Corporation (KPLC)	TTW emission factors for Grid Emissions	Least cost Development Plan (LCPDP) 2019 - 2030

Kenya Roads Board (KRB)	Road network distances for HGVs	KRB Digital Repository
Energy Petroleum Regulation Authority (EPRA)	Fuel Price Data Emission Penalties	EPRA Bi-Annual Report 2023-2024.

3.7 Scenario Development

Scenario development considers alternative futures by constructing logical and feasible narratives. DeCarolis (2017), defines a scenario as a specified future where assumptions are translated into parameters and input into an energy system model. The narratives and assumptions presented in this dissertation are grounded in the Avoid-Shift- Improve (ASI) theory as presented in Figure 3.3.

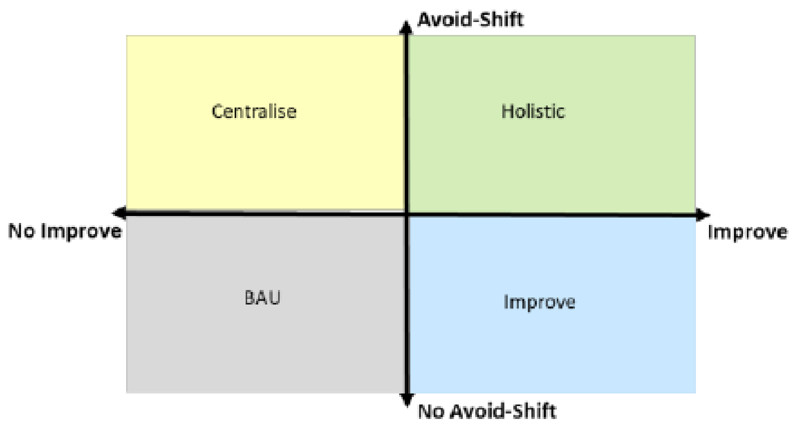

Figure 3.3: Scenario Matrix

Figure 3.3 presents scenarios designed on a matrix based on ASI which provides four (4) base scenarios. The y axis explores two futures, one where policy focuses on centralising public transport and the other where technology continues to dominate. The x- axis also presents two (2) futures one where policy is introduced to incentivise fuel switching and the Business as Usual Scenario where everything remains the same.

3.7.1 Business as Usual (BAU) Scenario

In the BAU scenario, the study assumed that no policy for fuel switching occurred. The number of trucks registered was assumed to follow the same pattern as the last 5 – 10 years. Furthermore, all HGVs were considered to use low sulphur diesel, the average vehicle kilometres travelled and the HGV vehicle distribution per category by one HGV remained unchanged.

3.7.2 Centralise

The centralise solution presented a realistic scenario where decarbonisation was achieved using biofuels which reduced the amount of carbon dioxide emitted while using the existing internal combustion engine. (ICE) In this scenario, the model replaced the traditional low sulphur diesel with BD 20 while all other factors such as number of trucks, total distance travelled and vehicle fleet remain unchanged.

3.7.3 Improve

In this study, the improve scenario reflected a future where electrification was used to meet carbon emission targets. In this scenario, electric HGVs were assumed to be available in the market in 2030. The adoption of electric HGVs was similar to the adoption of electric vehicles, As per the study conducted by Iyer et.al (2023), the median age of all electric HGVs was assumed to be 10 years. The grid emission factors in this study were adopted from Least Cost Power Development Plan (2010-2030) (Notter et. al 2018). Finally, the study assumed that no policy was implemented that targets modal shifts

3.8 Ethical Consideration

This research will endeavour to meet all the ethical requirements as stipulated in the Strathmore guidelines. The work shall be conducted in accordance with the ethical research provisions of the University. This will include protecting the respondents, by observing anonymity and by giving them the option to opt out of the research whenever they feel like. Consent shall also be sought from the respondents. Full disclosure on the uses of the data will be useful in enhancing ethicality of the process. The respondents will be informed that the data is useful for the research work and will be exposed to examiners and classmates, during seminars. Any requested documents will be submitted to the Strathmore University Institutional Scientific and Ethics Review Committee (SU-IERC). The work shall adhere to the guidelines set by the National Commission for Science, Technology, and Innovation (NACOSTI) to ensure that the rights, safety, and dignity of individuals and communities participating in the research are protected.

Chapter 4: Results and Discussion

4.1 Introduction

The first section of this chapter presents the data that was collected during the study. A description of how the transport decarbonisation model was created has also been presented. The second section discusses the results obtained from the model. The last section provides a framework of how the model can be adopted and how it can inform policy.

4.2 Data Collection and Analysis

This study relied on secondary data. The relevant data was collected from government publications, research papers and government reports. Relevant was collected such as vehicle stock, vehicle weight range, average vehicle kilometres travelled, grid emission factors and the number of registered HGVs. Data on the number of registered HGVs in Kenya is presented in Table 4.1.

Table 4.1: Registered HGVs in Kenya per year. KNBS (2024)

Year	HGVs registered/year	Cumulative (from 1968)
2010	4,924	95,628
2011	5,247	100,875
2012	7,821	108,696
2013	9,570	118,266
2014	10,681	128,947
2015	13,785	142,732
2016	9,632	152,364
2017	7,460	159,824
2018	6,514	166,338
2019	6,518	172,856
2020	6,476	179,332
2021	7,071	186,403
2022	10,075	196,478
2023	13,635	210,113

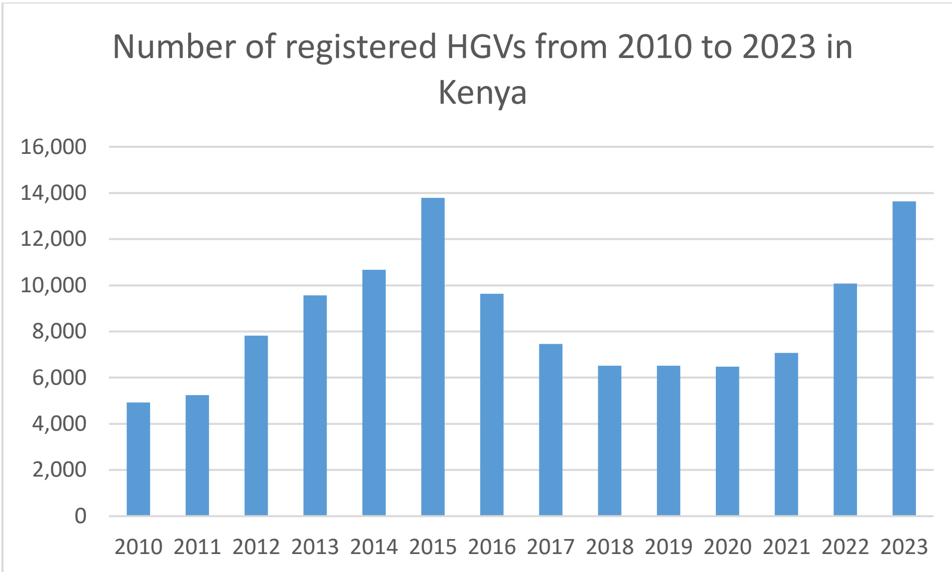

Figure 4.1: Number of registered HGVs in Kenya from 2010 to 2023 *((KNBS), 2024)*

The data presented in Table 4.1 has been represented graphically in in Figure 4.1. The data was collected the Kenya National Bureau of Statistics Surveys (KNBS). This data is collected and updated annually by KNBS with the latest report being in 2024. The registration of HGVs in Kenya started in 1968 as shown in the appendix.

Data on vehicle weight category, average vehicle kilometres travelled (VKT), fuel density, Lower Heating Value (LHV) of diesel, CO_2 emission factors and average fuel consumption was obtained from (Kwoba, 2020). A summary of the data is presented in Table 4.2 and the entirety of the data is in the appendix.

Table 4.2: Data on Diesel Trucks (Kwoba, 2020)

Category (Rigid Truck)	**CO_2 Emission Factor (kg/TJ)**	**Average VKT km/year**	**Fuel Density (kg/l)**	**LHV (TJ/tonnes)**	**Avg, Fuel Consumption (litres/100km)**
<7.5t	74,100	48,383	0.84	43.00	13.15
7.5-12t	74,100	35,823	0.84	43.00	19.89
12-14t	74,100	35,823	0.84	43.00	21.69
14-20t	74,100	25,588	0.84	43.00	26.34
20-26t	74,100	19,831	0.84	43.00	33.45
20-28t	74,100	63,205	0.84	43.00	33.30
28-34t	74,100	63,205	0.84	43.00	35.33
34-40t	74,100	64,620	0.84	43.00	41.04

The data in Table 4.2 shows the different fuel consumption rates and vehicle kilometres travelled annually in relation to the gross weight of the truck. From the data, heavier trucks consume more fuel when all other parameters are kept constant.

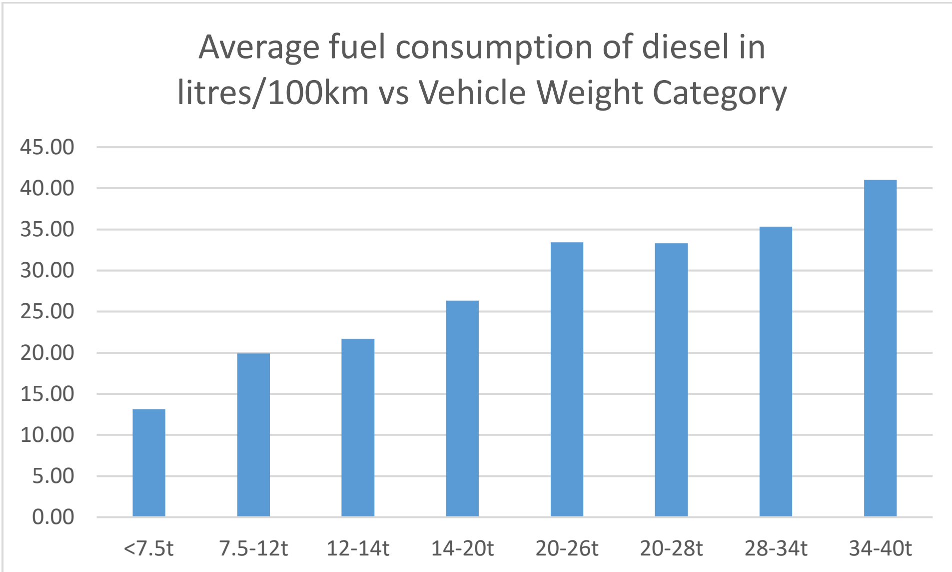

Figure 4.2: Average fuel consumption in litres/100Km vs Vehicle Weight Category

Figure 4.2 presents data on how heavier HGVs consume more fuel than the lighter HGVs. It provides a visual representation of the data in Table 4.2. From the graph, HGVs that weigh less than 7.5 tonnes consume 13.15 litres of diesel per 100 km on average, while HGV trucks that weigh 34 to 40 tonnes consume 41.04 litres of diesel per 100 km. It is important to note that, the CO2 emission factor remains constant regardless of the weight of the vehicle.

In this study, data grid emission factors are used to estimate the Well to Plug (WTP) emissions for electric heavy goods vehicles. Data on grid emission factors and their projections are presented in Figure 4.3.

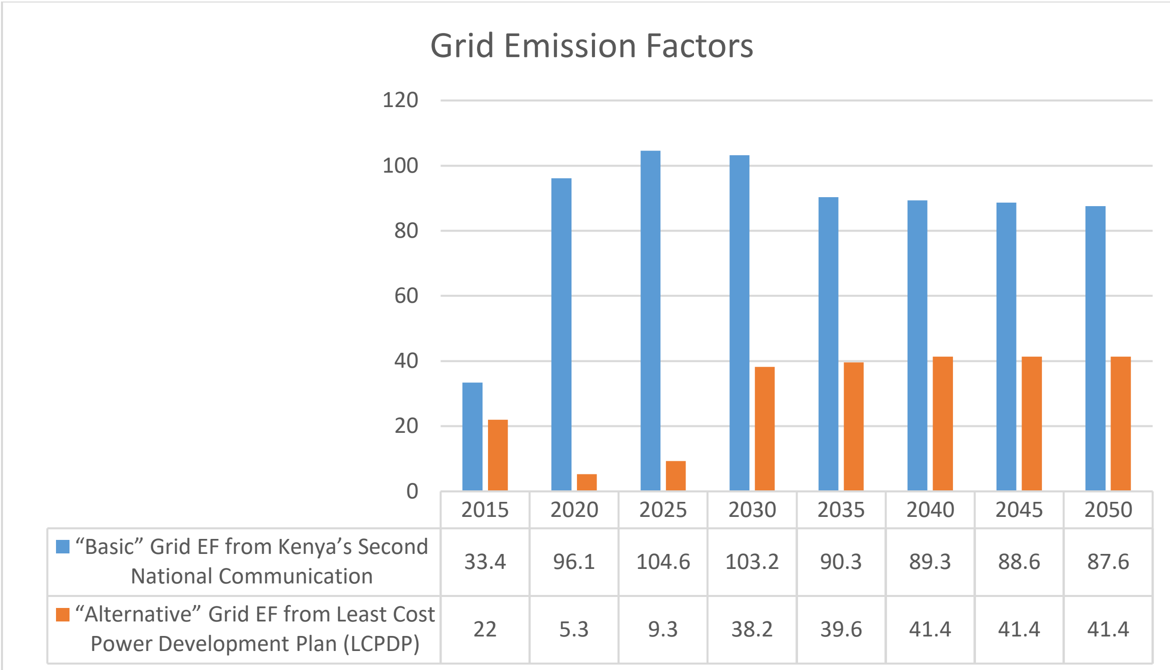

Figure 4.3: Data on Grid Emission Factors. Government of Kenya (2015) and ERC (2018)

Figure 4.3 presents the current grid emission factors and their projected values up to the year 2050. Data from the "basic" scenario was collected from Government of Kenya (2015) while data from the "alternative" scenario was collected from the Least Cost Power Development Plan (LCPDP) vision scenario (ERC, 2018). This study used the grid emission factors projected by the ERC (2018). According to Notter et.al (2018) the LCPDP scenario assumes that geothermal energy will account for the largest share of production by 2037. Furthermore, the use of oil to generate electricity, is assumed to be phased out by 2020 and the electricity gap would be covered by imports.

4.3 Model Formulation

This study aims to reduce carbon emissions into the atmosphere using cleaner energy sources electricity and biofuels in freight road transport. To this end, a model was developed to approximate the quantity of CO_2 emissions that can be abated if the fuel switching options considered in this study are adopted. In this section, the projection of HGVs up to 2050, the biofuel considerations adopted in the model, and the adoption of electric HGVs are discussed and analysed.

4.3.1 HGV projection

This study forecasts the quantity CO_2 up to the year 2050. In the business as usual (BAU) scenario, the growth of HGVs was approximated using trend-line analysis as shown in equation 4.1. The rate of growth was determined by average growth rate equation as shown in equation 4.2.

$$y = mx + c \tag{4.1}$$

Where,

y	Projected HGVs per year.
m	The rate as shown in equation 4.2
x	Rate of change
c	y-intercept

The rate of growth for HGVs was estimated using equation. 4.2.

$$GR = \left(\frac{Final\ Value}{Initial\ Value}\right)^{\frac{1}{T}} - 1 \tag{4.2}$$

Where,

GR	Growth rate
Final Value	Registered HGVs in 2023
Initial Value	Registered HGVs in 1968
T	Time period

4.3.2 Bio-Fuel Specifications

In this study, BD20 was preferred because it can be substituted seamlessly with diesel without having to change the vehicle infrastructure. This means that the internal combustion engine would be retained and no major overhaul of the vehicle combustion engine will be required. BD 20 is a blend of diesel and biofuels where 80% is diesel and 20% is bio-fuel. To this end, the BD 20 fuel specifications shown in Table 4.3 where adopted.

Table 4.3: Specifications for Bio-diesel 20. (Virginia State University, 2021)

Category (Rigid Truck)	CO_2 Emission Factor (kg/TJ)	Fuel Density (kg/l)	LHV (TJ/tonnes)	Avg, Fuel Consumption (litres/100km)
<7.5t	73.400	0.86	42.00	13.28
7.5-12t	73.400	0.86	42.00	20.09
12-14t	73.400	0.86	42.00	21.91
14-20t	73.400	0.86	42.00	26.60
20-26t	73.400	0.86	42.00	33.78
20-28t	73.400	0.86	42.00	33.63
28-34t	73.400	0.86	42.00	35.68
34-40t	73.400	0.86	42.00	41.45

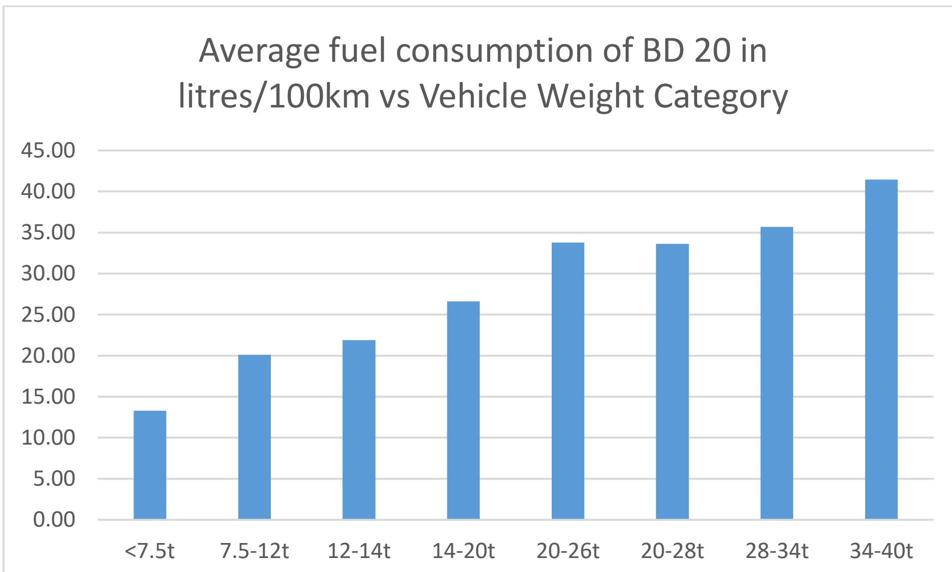

Figure 4.4: Average fuel consumption of BD 20 in liters/100km vs Vehicle Weight Category

Figure 4.4 presents data on how fuel consumption increases with the weight of the HGV. It provides a visual representation of the data in Table 4.3. From the graph, HGVs that weigh less than 7.5 tonnes consume 13.28 litres of diesel per 100 km on average, while HGV trucks that weigh 34 to 40 tonnes consume 41.45 litres of diesel per 100 km. It is important to note that, the CO_2 emission factor remains constant regardless of the weight of the vehicle. BD 20 has a lower density, lower LHV and a lower carbon emission factor than conventional diesel. However, according to, Virginia State University (2021), the internal combustion engine (ICE) of a HGV consumes up to 1 % more than if it were using regular diesel.

4.3.3 Electric Scenario

In this study, the electric scenario was developed and analysed by combining the existing BAU scenario and adoption of electric HGVs. The rate of decline of diesel HGVs was estimated using the negative compound interest formula as presented in equation 4.3.

$$Final\ value = Principal\ \times (1 - rate)^T \tag{4.3}$$

Where,

Final value	Number of HGVs in the projected year
Principal	Number of HGVs in the previous year
Rate	Computed by Equation 4.4.
T	Time period

The rate of decline of diesel HGVs in the electric scenario was estimated based on the market penetration of EVs from 2018-2023 as presented in equation 4.4.

$$DR\ = \frac{EVs\ 18}{RVs\ 18} \times \frac{RVs\ 23}{EVs\ 18} \tag{4.4}$$

Where,

DR	Rate of Decline
EVs 18	Number of registered electric vehicles in 2018
RVs 18	Total number of registered vehicles in 2018
EVs 23	Number of registered electric vehicles in 2023
RVs 23	Total number of registered vehicles in 2023

The adoption of electric HGVs was assumed to be similar to how the electric vehicles were adopted in 2018. This evaluated based on equation 4.5.

$$ROA\ = \frac{EVs\ 18}{RVs\ 18} \tag{4.5}$$

Where,

ROA	Rate of adoption of electric HGVs
EVs 18	Number of registered electric vehicles in 2018
RVs 18	Total number of registered vehicles in 2018

The rate of growth of electric HGVs is a function of the average growth rate of diesel HGVs. The adoption of electric vehicles in the Kenyan Market and average growth rate of electric vehicles. This is presented in equation 4.6.

$$AGR\ EHGVs = AGR\ HGVs \times \frac{AGR\ EVs}{AGR\ PCs} \tag{4.6}$$

Where,

AGR EHGVs	Average growth rate for electric Heavy Goods Vehicles.
AGR HGVs	Average growth rate for Heavy Goods Vehicles (1968 – 2023)
AGR EVs	Average growth rate for Electric Vehicles (2018 – 2023)
AGR PCs	Average growth rate for Passenger cars (2018 – 2023)

The average growth rate of HGVs from 1968 to 2023 was computed using equation 4.7.

$$AGR\ HGVs = \left(\frac{Number\ of\ Registered\ HGVs\ 2023}{Number\ of\ Registered\ HGVs\ 1968}\right)^{\frac{1}{T}} - 1 \tag{4.7}$$

Where,

T Time difference between 1968 and 2023

The average growth rate of electric vehicles from 2018 to 2023 was computed using equation 4.8.

$$AGR\ EVs = \left(\frac{Number\ of\ Registered\ EVs\ 2023}{Number\ of\ Registered\ EVs\ 2018}\right)^{\frac{1}{T}} - 1 \tag{4.8}$$

Where,

T Time difference between 2018 and 2023

The average growth rate of passenger cars from 2018 to 2023 was computed using equation 4.9.

$$AGR\ PCs = \left(\frac{Number\ of\ Registered\ PCs\ 2023}{Number\ of\ Registered\ PCs\ 2018}\right)^{\frac{1}{T}} - 1 \tag{4.9}$$

Where,

T Time difference between 2018 and 2023

The increase in electric HGVs was computed using the compound interest formula as presented in equation 4.10.

$$Final\ value = Principal\ \times (1 + rate)^T \qquad (4.10)$$

Where,

Final value	Number of electric HGVs in the projected year
Principal	Number of electric HGVs in the previous year
Rate	Computed by equation 4.6.
T	Time period

4.4 Results

This section presents the results for the three scenarios considered; the business as usual (BAU), the centralise scenario that uses BD 20, and the improve scenario that shows a seamless transition between the introduction of electric HGVs and the current diesel trucks.

4.4.1 Projection of Registered HGVs

In this study, the projection of registered HGVs was estimated using equation 4.1. Table 4.4 presents the data projected by equation 4.1 and the results are presented in Figure 4.5.

Table 4.4: Presents the projection of registered HGVs from 2010 to 2050

Year	HGVs registered/year	Cumulative (from 1968)
2010	4,924	95,628
2015	13,785	142,732
2020	6,476	179,332
2025	11,220	232,045
2030	13,763	295,775
2035	16,306	372,220
2040	18,850	461,382
2045	21,393	563,259
2050	23,936	677,852

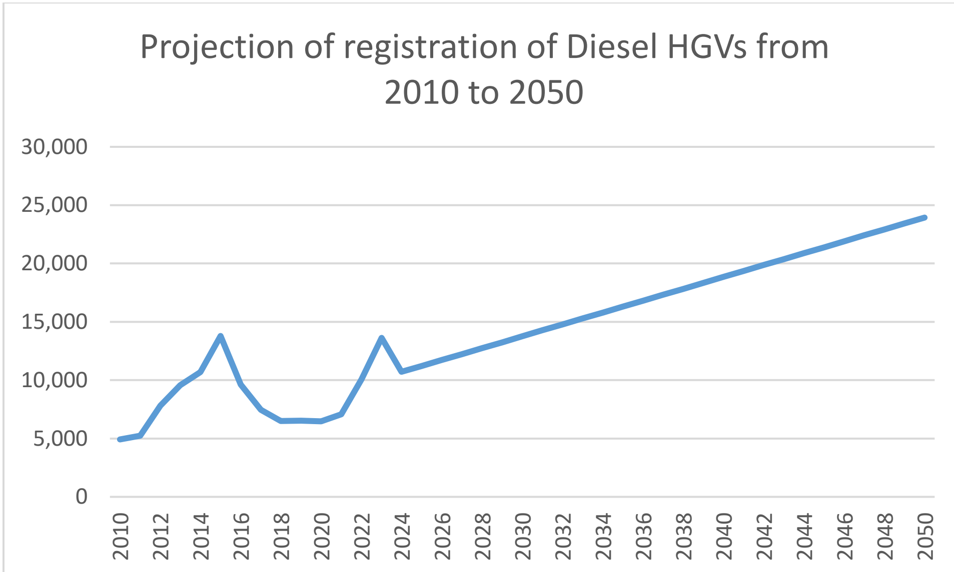

Figure 4.5: Projection of Diesel HGVs from 2010 to 2050

Figure 4.5 presents the projection of diesel HGVs from 2024 to 2050 which have been estimated using equation 4.1. Equation 4.2 gives the average growth rate of HGVs to be 4.2% based on the historical data. The trend-line analysis results are similar to the HGV projections by the Kenya Energy Transition & Investment Plan (2030-2050) that approximates around 23,000 registered vehicle by 2050. In 2010, there were 4,920 registered HGVs, and by 2015, there were 13,785 registered HGVs. In 2016, there was a decline in the number of registered vehicles as only 9,632 were registered. This is because of the East African Community Vehicle Load Control Act, 2016 that limited the amount of HGVs that can be imported (The East African Community, 2016). From 2019 to 2020 the number of registered vehicles moves from 6,518 to 6,476. This slow uptake can be attributed to the COVID 19 pandemic and its negative effect on the economy (UNCTAD, 2021) . A steady rise is observed up to 13,635 in 2023 indicating a recovery in the economy.

4.4.2 Business as Usual Scenario (BAU)

The BAU scenario shows projects the CO_2 emissions from HGVs up to 2050 if all trucks use diesel as their primary fuel source. This study considered both Wheel to Well (WTW) emissions as presented in Figure 4.6. WTW emissions is the sum of well to tank (WTT) emissions and tank to wheel (TTW) emissions. Table 4.5 presents the emission results that were calculated using equations 3.5 and 3.6.

Table 4.5 Projected CO_2 emissions in $MTCO_2e$ from 2015 - 2050 in the BAU scenario

Year	**Well to tank (WTT) Emissions in $MTCO_2e$**	**Tank to Wheel (TTW) Emissions in $MTCO_2e$**
2015	2.90	0.75
2020	3.64	0.94
2025	4.71	1.21
2030	6.00	1.55
2035	7.55	1.95
2040	9.36	2.41
2045	11.43	2.94
2050	13.75	3.54

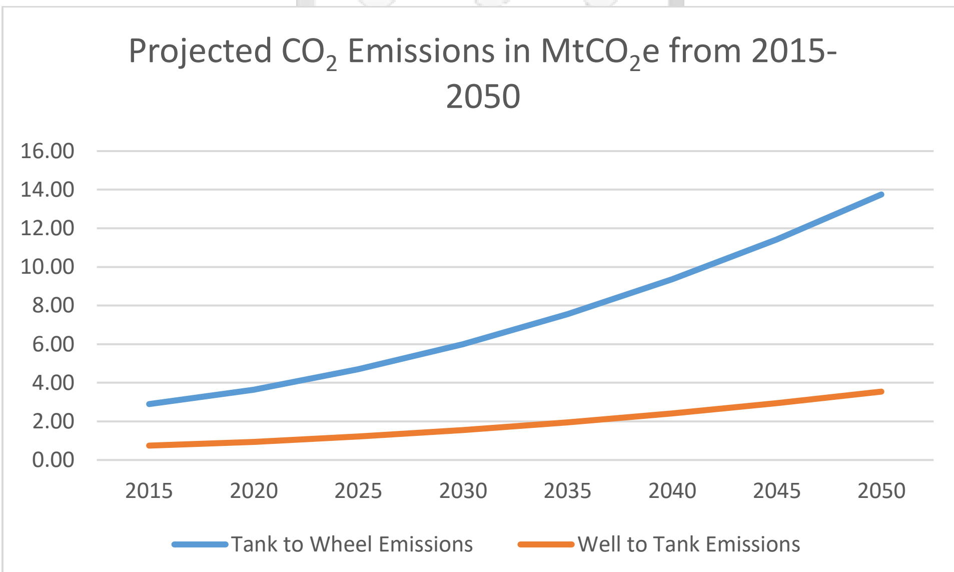

Figure 4.6: CO_2 emissions in $MtCO_2e$ from 2015 projected to 2050

Figure 4.6 show a steady rise in emissions from HGVs from 2015 to 2050. In this scenario, well to tank (WTT) and tank to wheel (TTW) were calculated using equations 3.5 and 3.6. WTT emissions cover the emissions associated with extracting, refining and delivering the fuel before it reaches the vehicles tank. TTW emissions on the other hand are a measure of the energy emissions associated with the point where the fuel is stored to the HGVs propulsion. From Figure 4.6, the tank to wheel (TTW) emissions, "tail-pipe emissions" are higher than the well to tank (WTT) emissions. From the analysis, in 2015 the TTW emissions from HGVs were 2.9 $MtCO_2e$ and the

WTT emissions were are 0.75 $MtCO_2e$ which adds up to are 3.64 $MtCO_2e$. If the current situation remains unchanged, the emissions are seen to be constantly rising. For instance, in 2030, the TTW emissions are projected to be 6 $MtCO_2e$ and the WTT emissions are 1.55 $MtCO_2e$. The projected rise in CO_2 emissions is unacceptable and is not in-line with Kenya's Nationally Determined Contributions. According to Ministry of Environment and Forestry (2020), Kenya modified its Nationally Determined Contributions (NDCs) to reduce GHG emissions by 32% from its initial target of 30% by 2030 in December 2020. Therefore, the rise of the CO_2 emissions must be mitigated in order to meet the NDCs. To this end the centralise scenario and the improve scenarios have been presented to mitigate these emissions.

4.4.3 Centralise Scenario

The centralise scenario shows projects the CO_2 emissions up to 2050 if in the current situation we change the fuel from diesel to BD 20. The amount of expected CO_2 emissions has been presented in Figure 4.7. Table 4.6 presents the emission results that were calculated using equations 3.7 and 3.8.

Table 4.6: Projected CO_2 Emissions in $MtCO_2e$ using BD 20 from 2015 to 2050

Year	**Well to tank (WTT) Emissions in $MTCO_2e$**	**Tank to Wheel (TTW) Emissions in $MTCO_2e$**
2015	2.90	0.66
2020	3.64	0.83
2025	4.71	1.07
2030	6.00	1.36
2035	7.55	1.72
2040	9.36	2.13
2045	11.43	2.60
2050	13.76	3.13

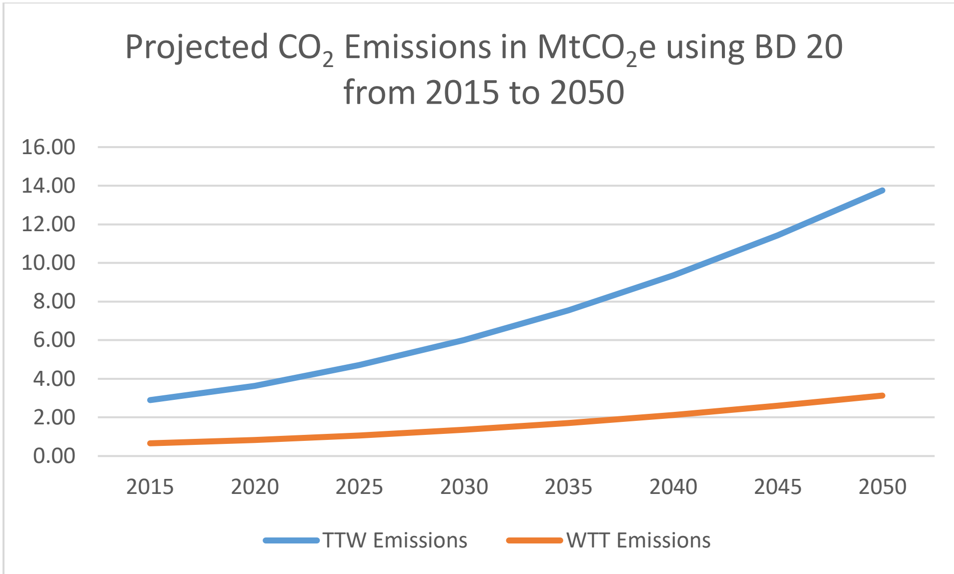

Figure 4.7: CO_2 Emissions in $MtCO_2e$ using BD 20 from 2015 to 2050

Figure 4.7 presents the TTW emissions using BD 20 are largely identical with those in the BAU scenario as shown in Figure 4.2. In this study, it was found that these emissions are expected to increase steadily. In 2015, the TTW emissions from were 2.9 $MtCO_2e$ projected to increase 6 $MtCO_2e$ up to 13.76 $MtCO_2e$. The WTT emissions however, are lower than those in the BAU scenario. These emissions were projected to be 0.66 $MtCO_2e$ in 2015. 1.36 $MtCO_2e$ in 2030 up to 3.13 $MtCO_2e$ in 2050. According to Figure 4.2, in the BAU Scenario, the subsequent WTT emission are 0.75 $MtCO_2e$ on 2015, 1.55 $MtCO_2e$ in 2030 and 3.54 $MtCO_2e$ in 2050. This slight decrease in emissions shows that BD 20 is a slightly better alternative than diesel.

4.4.4 Improve Scenario

In the improve scenario, the study focused on a fuel switch from the current diesel HGVs to electric HGVs. The transition from diesel HGVs to electric HGVs was projected to start in 2030 and the adoption of these HGVs is similar to the adoption of EVs in 2018, in Kenya. The projected adoption of electric trucks is presented in Figure 4.8. Table 4.7 presents the data computed by equations 4.4 and 4.6.

Table 4.7: Projection for adoption of electric HGVs from 2030 to 2050

Year	**Adoption of electric HGVs registered/year**	**Cumulative electric HGVs registered**
2030	48	48
2035	78	372
2040	125	893
2045	201	1,732
2050	324	3,083

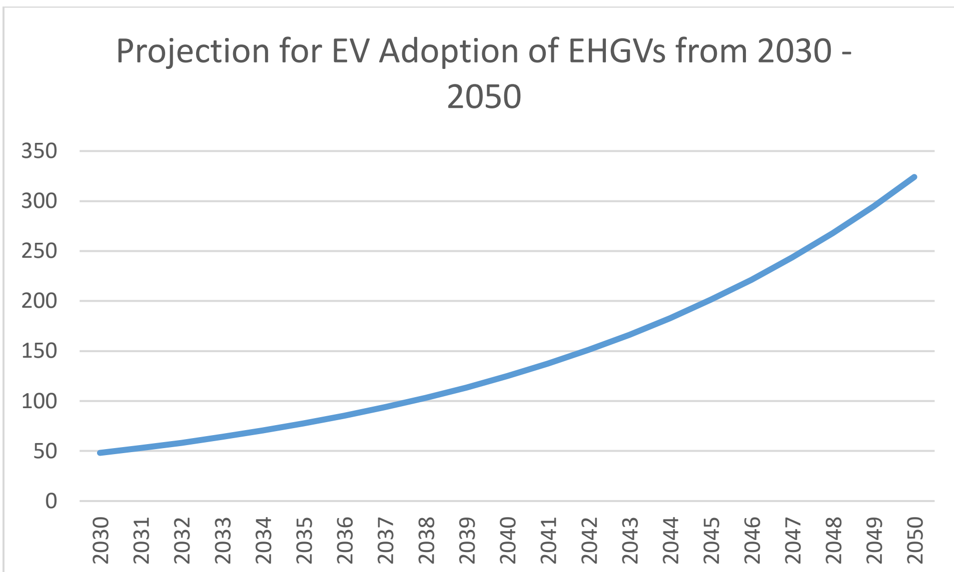

Figure 4.8: Projected adoption of electric HGVs from 2030 to 2050

Figure 4.8 presents the projected adoption electric HGVs from 2030. Year 2030 marks the projected entry of electric HGVs in the Kenyan market. In this study, 48 electric HGVs as computed by equation 4.4. The average growth rate of the projected HGVs was computed using equation 4.6. The adoption of electric HGVs was computed using Equation 4.7. In 2050, the model projects that 324 electric HGVs will be registered following the computed average growth rate in equation 4.6. This shows that the number of registered HGVs will have increased by 575% from the initial adoption year, 2030. The data projected in Figure 4.8, however, did not take into consideration any changes in policy and market demand, the rate computed by equation 4.4 was based on historical data.

To ensure a slow and seamless transition from diesel HGVs to electric HGVs, Figure 4.9 shows the projected decline in the use of diesel HGVs. Table 4.8 shows the results obtained from equations 4.3 and 4.4.

Table 4.8: Projected decline in use of diesel HGVs

Year	**Diesel HGVs**
2020	6,476
2025	11,220
2030	13,763
2035	12,679
2040	11,680
2045	10,760
2050	9,912

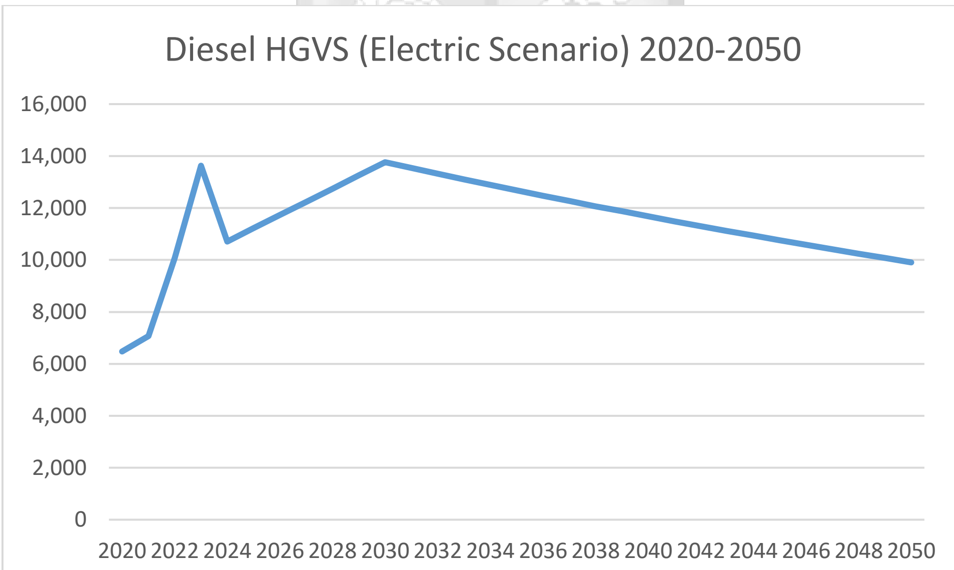

Figure 4.9: Projected decline in Diesel HGVs from 2020 – 2050.

Figure 4.9 presents data on the expected decline in diesel HGVs when the electric HGVs are adopted from 2030. The number of registered HGVs from 2020 – 2023 represents actual data collected from the KNBS (2024). From 2024 – 2030, the values presented are projected using trend-line analysis as shown in equation 4.1. Finally, the values expressed from 2030 – 2050 show the projected decline in the registration of diesel HGVs due to the adoption of electric HGVs. The values have been simulated using equation 4.3 and the rate of decline was computed using equation 4.4. The rate of decline in the registration of diesel HGVs from 2030 to 2050 has a significant impact in the amount of emissions projected in this scenario. The rate of decline is projected to be approximately 10% with the number of registered vehicles projected to be 9,912 by the year 2050 from the 13,763 that were registered in 2030. This reduction signifies a change in emissions from the BAU scenario by 2050. In the BAU scenario, projected emissions in 2050 were found to be 17.29 $MtCO_2e$ while in this scenario, the projected reduction in diesel HGVs gives projected emissions of 14.54 $MtCO_2e$ by 2050. This shows 2.75 $MtCO_2e$ reduction in emissions.

In the electric scenario, since electricity is a clean energy source, only well to plug (WTP) emissions were considered. WTP emissions refer to the emissions associated with the production of electricity to the charging stations. These emissions were considered equal to grid emissions (Notter et. al, 2018). Figures 4.10 shows the projected WTP emissions using the current system losses, 23.16%. (EPRA, 2024) Figure 4.11 shows the projected WTP emissions using the Ministry of Energy & Petroleum (2023) objective of having system losses reduced to 15% by 2025.

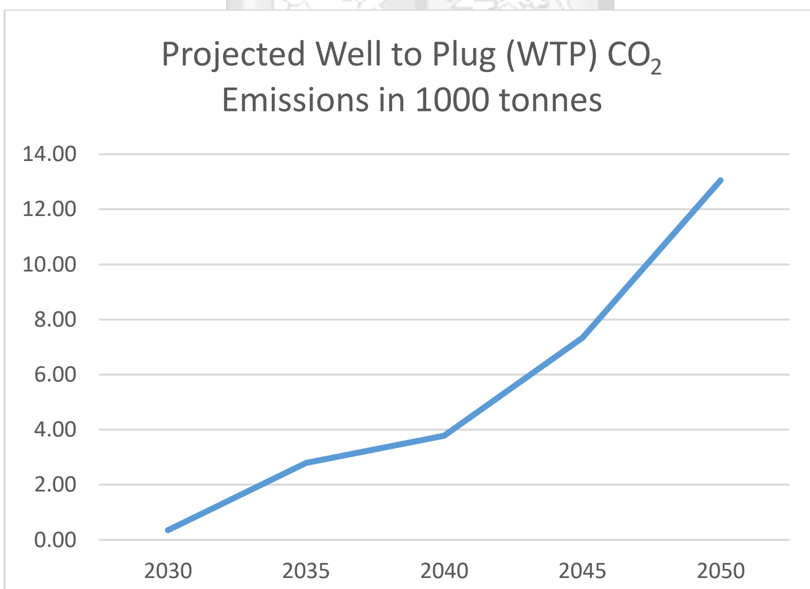

Figure 4.10: Projected WTP CO_2 Emissions in 1,000 tonnes (23.16% system losses)

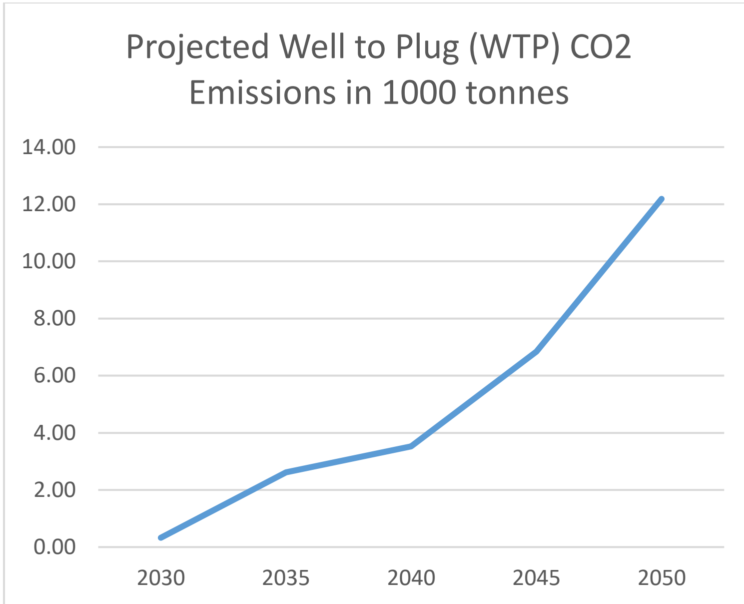

Figure 4.11: Projected WTP CO_2 emissions in 1,000 tonnes (15% system losses)

In this study, the electric scenario considered well to wheel (WTW) emissions for the remain diesel trucks as shown in Figure 4.9 and the well to plug (WTP) emissions associated with powering the adopted electric trucks. The data presented in Figure 4.10 shows the WTP emissions from 2030 to 2050 with system losses at 23.16%, while Figure 4.7 presents the WTP emissions from 2030 to 2050 with system losses at 15%. This is in line with the Ministry of Energy & Petroleum (2023) goal that aims at reducing system losses to 15% from 23.16% from 2025. The projected WTP emissions are largely similar despite the reduction in system losses. Figure 4.6 shows that the emissions with the current system losses projected WTP emissions are 0.35 1,000 tonnes of CO_2 in 2030 up to 13.05 1,000 tonnes of CO_2 in 2050. In comparison, Figure 4.7 shows that, if the target by Ministry of Energy & Petroleum (2023) is achieved, the WTP emissions are reduced to 0.33 1,000 tonnes of CO_2 in 2030 up to 12.19 1,000 tonnes of CO_2 in 2050.

4.5 Model framework

In this study, a model framework was created in order to achieve the necessary the scenarios presented. This framework shows the policy changes and the relevant assumptions made to transition from the Business as Usual (BAU) scenario to either the Centralise BD 20 scenario and to the Improve scenario. Two frameworks were considered; Transition framework 1 refers fuel switching from low sulphur diesel to BD 20, while Transition Framework 2 refers fuel switching from low sulphur diesel to electricity. These frameworks were considered to aid in policy formulation in Kenya should the country decide on only one fuel switch methods relative to the current situation.

4.5.1 Transition Framework 1

In this case, the transition from the BAU scenario to the Centralise BD 20 scenario is presented in Figure 4.12 which showed the total projected emissions up to 2050 for both scenarios.

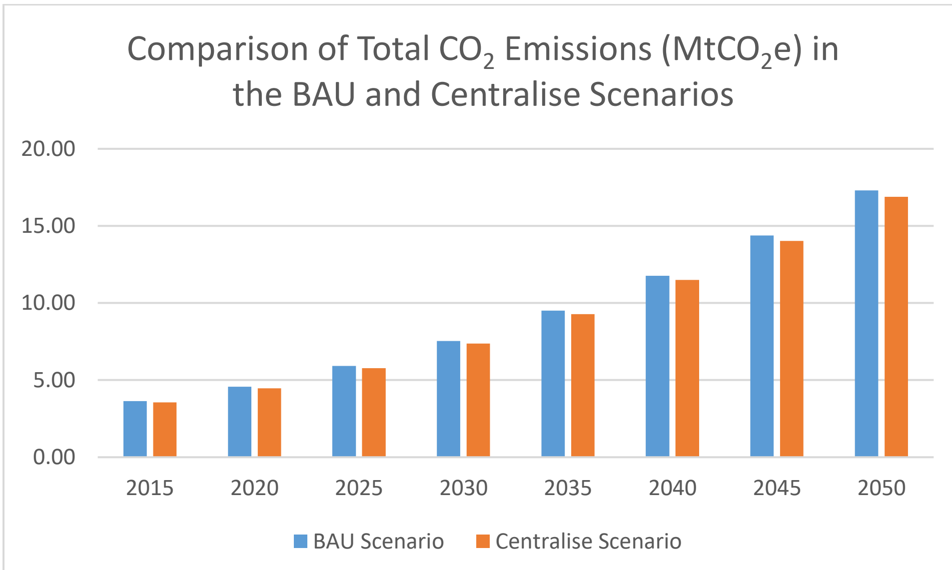

Figure 4.12 Comparison CO_2 emissions in the BAU and Centralise scenarios.

Figure 4.12 presents a comparison between the projected CO_2 emissions from HGVs in the Centralise and the BAU scenarios up to 2050. From the bar chart, in the BAU scenario, the emissions were projected to increase steadily over the years from 3.64 $MtCO_2e$ in 2015, to 7.55 $MtCO_2e$ in 2030 up to 17.29 $MtCO_2e$ in 2050. In comparison, the centralise scenario showed a similar increase in the amount of emissions over the same time period. In 2015, the projected emissions were found to increase from 3.56 $MtCO_2e$ to 7.37 $MtCO_2e$ by 2030 up to 16.89 $MtCO_2e$ in 2050. The difference in amount of emissions was computed to 0.09 $MtCO_2e$ in 2015, 0.18 $MtCO_2e$ in 2030 and 0.41 $MtCO_2e$ in 2050. The difference in these emissions is explained by Figure 4.3 in section 4.4.3.

The following assumptions were made in this study to actualise this transition framework.

i. Ready and steady availability of BD 20 similar to the current availability of diesel.

ii. A government policy that mandates the use of BD 20 as a replacement for diesel for all HGVs.

4.5.2 Transition Framework 2

In this case, the transition from the BAU scenario to the Improve scenario which is presented by. Figure 4.9 which showed the total projected emissions up to 2050 for both scenarios.

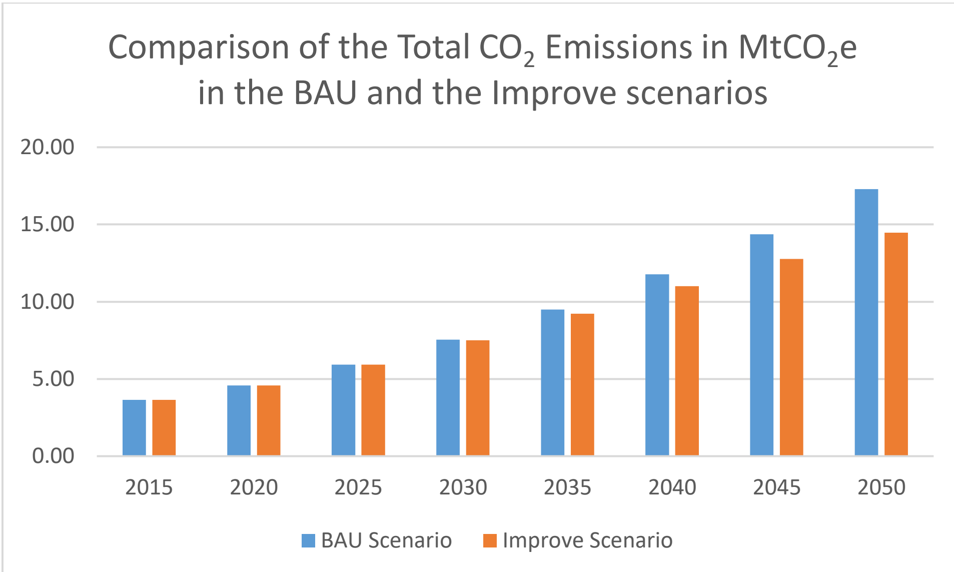

Figure 4.13 Comparison of the Total CO_2 Emissions in $MtCO_2e$ in the BAU and the Improve Scenarios

Figure 4.13 shows a comparison of CO_2 emissions from the current situation and the improve scenario. The emissions are seen to be exactly the same in 2015 up to 2025. This is because the study's projection of adoption of electric HGVs was expected to begin in 2030. From the 2030, the emissions were seen to increase but at a slower rate than in the BAU scenario, indicating the effect the adoption of electric HGVs and the subsequent reduction of diesel HGVs had on the total emissions in the freight industry. In the BAU scenario the study found that 7.55 $MtCO_2e$ in 2030 gradually rise to 17.29 $MtCO_2e$ in 2030. In the improve scenario, however, in 2030 the HGV emissions are 7.51 and 14.47 $MtCO_2e$ in 2050. Though the amount of emissions is still rising in the Improve scenario, it is shows a decrease a slight decrease when it was compared to the BAU scenario. In 2030, the difference in amount of projected emissions is 0.03 $MtCO_2e$ in 2030, to 0.77 $MtCO_2e$ in 2040 up to 2.83 $MtCO_2e$ in 2050. This means that in 2050, it was projected that there would be a 16.4% reduction in CO_2 emissions as compared to the BAU. The increase in emissions is because, the Improve scenario projects that 9,912 diesel HGVs will still be in service by 2050. This 16.4% reduction shows a how important the adoption electric HGVs has on the environment and the potential positive implications towards the Nationally Determined Contributions. (NDC)

The following assumptions were made in this study to actualise this transition framework.

i. According to Ministry of Energy & Petroleum (2023) Kenya plans to have EVs comprise of 5% of cars by 2025. Given the electrification required to actualise the Improve scenario, this study assumes that electric HGVs will be adopted by 2030.
ii. A policy that cuts taxes and provides subsidies and incentives to encourage the electric HGVs while restricting imports of diesel HGVs. (Briand, et al., 2023)

4.6 Validation of Model Results

Researchers have carried out similar studies in decarbonisation of freight transport using fuel switching and other decarbonisation methods.

In Colombia, Valderrama et.al (2019) analysed decarbonisation of the transport sector and the associated challenges in greenhouse gas mitigation. The study followed fuel switching and modal shift as the primary decarbonisation pathways with projections from 2030 to 2050. The study found an 8% reduction in CO_2 emissions by 2030 and an 18% reduction in emissions by 2050. Likewise, in the model presented in this study, the improve scenario projected a 16.4% decrease in emissions should the model recommendations be adopted. It is worth noting that in his study, Valderrama considered a variety of fuel switch options such as liquefied natural gas (LNG), use of compressed natural gas trucks and modal shift to rail.

Salvucci et.al (2019) used modal shift as the primary method for decarbonisation for the Scandinavian transport sector. The study encompassed the three countries, Denmark, Norway and Sweden. The fuel switch option analysed for freight transport was from road to rail. It found a cost-effective mitigating measure, the modal shift, is expected to reduce cumulative transportation-related CO_2 emissions by 2.2%. This results are similar to those of the centralise scenario conducted in this study that show a 2.3% reduction in CO2 emissions by 2050.

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

In conclusion, this study set out to develop a decarbonisation model that uses fuel switching in freight transport sector in order to reduce CO_2 emissions. It set out evaluate the emissions related to freight transport and to quantify the energy demand for the transportation of freight goods in Kenya. Furthermore, in this research, we modelled fuel switching options and finally create a model framework to which these fuel switching options can be achieved. The study considered three (3) scenarios; business as Usual (BAU), centralise and improve scenarios in relation to the Avoid-Shift-Improve (ASI) theory. This section presents the summary and conclusion of the study findings as follows;

i. In the business as usual (BAU) scenario, the study reported a marked increase in current emissions and projected emissions. In the current situation, the total well to wheel (WTW) emissions were computed to 3.64 $MtCO_2e$, increasing steadily to 7.55 $MtCO_2e$ in 2030 up to 17.29 $MtCO_2e$ in 2050, This means that if Kenya is to achieve its Nationally Determined Contribution (NDC) by 2030, the current situation should not be allowed to continue and policy changes may have to be effected to mitigate these emissions,

ii. In the centralise scenario, the study found that a slight reduction in the total CO_2 emissions which was attributed (WTT) emissions. The figures in the tank to wheel (TTW) emissions are similar to those of the BAU scenario while those of the well to tank (WTT) in the centralise scenario are considerably lower. The TTW emissions in the BAU scenario were found to be 2.89 $MtCO_2e$ in 2015, 6.00 $MtCO_2e$ in 2030 up to 13.75 $MtCO_2e$ projected for 2050. Similarly, in the centralise scenario, the TTW emissions were found to be 2.90 $MtCO_2e$ in 2015, 6.003 $MtCO_2e$ in 2030 up to 13.76 $MtCO_2e$ projected for 2050. However, the study found that in calculating the WTT emissions in the BAU scenario, they were found to be 0.745 $MtCO_2e$ in 2015, 1.55 $MtCO_2e$ in 2030 up to a projected 3.52 $MtCO_2e$ in 2050. In contrast, the study found that the WTT emissions in the centralise scenario to be 0.66 $MtCO_2e$ in 2015, 1.36 $MtCO_2e$ in 2030 up to a projected 3.13 $MtCO_2e$ in 2050. This reports a 2.3% reduction in the overall emissions and shows that if the NDC is to be achieved with the switch to BD 20 would not be the best approach.

iii. Finally, the improve scenario modelled a blend of the decline in the use of diesel HGVs and the projected adoption of electric HGVs. The total well to wheel (WTW) emissions in the improve scenario were found to be slightly lower than WTW emissions in both the BAU and centralise scenarios from 2030 to 2050. Quantitatively, the improve scenario projects a 16.4% reduction in CO_2 emissions as compared to the BAU scenario. In the BAU, the WTW emissions were found to be 7.55 $MtCO_2e$ in 2030, 11.77 $MtCO_2e$ in 2040 up to 17.29 $MtCO_2e$ in 2050. Likewise, in the centralise scenario, the WTW emissions were found to be 7.37 $MtCO_2e$ in 2030, 11.49 $MtCO_2e$ in 2040 up to 16.89 $MtCO_2e$ in 2050. However, in the improve scenario the projected findings over a similar time period were found to be 7.51 $MtCO_2e$ in 2030, 11.00 $MtCO_2e$ in 2040 up to 14.47 $MtCO_2e$ in 2050. This shows that while there is some decrease in projected emissions in the improve scenario, stringent policies on vehicle emissions and tax on electric HGVs may have to be put in place in order to increase the CO_2 abatement.

5.2 Recommendations

In this study, the following are recommendations for potential areas of study to improve the model and other areas of research.

i. This study was limited to HGVs in Kenya. This study can be expanded to included passenger cars, busses, trucks and motorcycles. According to Government of Kenya (2019), HGVs were responsible for 2.89 $MtCO_2e$ in 2015 of a total of 6.9 $MtCO_2e$ all road subsector emissions. Therefore, there is need to mitigate all other emissions associated with the road sub-sector.

ii. In this study, the centralise scenario focused on using BD 20 as the biofuel option. Further research can explore using BD 100, which is 100% bio-fuels, and project the CO_2 abatement.

iii. This study was limited to consider the quantity of CO_2 emissions only. Further research on other emissions such as methane (CH4), nitrous oxides (NOx) and sulphur oxides (SOx) to improve the model.

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Appendices

Appendix A: Similarity Report

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Appendix B: Ethical Clearance Release Letter

Strathmore
UNIVERSITY

1st October 2024

Mr Kariuki David,
njoroge.kariuki@strathmore.edu

Dear Mr Kariuki,

RE: Decarbonisation using Fuel Switching in Freight Transport

This is to inform you that SU-ISERC has reviewed and **approved** your above **SU-masters** proposal. Your application reference number is **SU-ISERC2331/24**. The approval period is from **1st October 2024 to 30th September 2025**.

This approval is subject to compliance with the following requirements:

i. Only approved documents including (informed consents, study instruments, MTA) will be used.
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 72 hours of notification.
iv. Any changes anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 72 hours.
v. Clearance for the export of biological specimens must be obtained from relevant institutions.
vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) https://research-portal.nacosti.go.ke/ and obtain other clearances needed.

Yours sincerely,

Mr Ambrose Rachier,
Chairperson; SU-ISERC

Appendix C: Data Collected

Number of HGVs registered.

Year	HGVs registered/year	Cumulative (from 1968)
2010	4,924	95,628
2011	5,247	100,875
2012	7,821	108,696
2013	9,570	118,266
2014	10,681	128,947
2015	13,785	142,732
2016	9,632	152,364
2017	7,460	159,824
2018	6,514	166,338
2019	6,518	172,856
2020	6,476	179,332
2021	7,071	186,403
2022	10,075	196,478
2023	13,635	210,113

Data on Diesel Trucks

Category (Rigid Truck)	CO_2 Emission Factor (kg/TJ)	Average VKT km/year	Fuel Density (kg/l)	LHV (TJ/tonnes)	Avg, Fuel Consumption (litres/100km)
<7.5t	74,100	48,383	0.84	43.00	13.15
7.5-12t	74,100	35,823	0.84	43.00	19.89
12-14t	74,100	35,823	0.84	43.00	21.69
14-20t	74,100	25,588	0.84	43.00	26.34
20-26t	74,100	19,831	0.84	43.00	33.45
20-28t	74,100	63,205	0.84	43.00	33.30
28-34t	74,100	63,205	0.84	43.00	35.33
34-40t	74,100	64,620	0.84	43.00	41.04

Specifications for Bio-diesel 20.

Category (Rigid Truck)	CO_2 Emission Factor (kg/TJ)	Fuel Density (kg/l)	LHV (TJ/tonnes)	Avg, Fuel Consumption (litres/100km)
<7.5t	73.400	0.86	42.00	13.28
7.5-12t	73.400	0.86	42.00	20.09
12-14t	73.400	0.86	42.00	21.91
14-20t	73.400	0.86	42.00	26.60
20-26t	73.400	0.86	42.00	33.78
20-28t	73.400	0.86	42.00	33.63

28-34t	73.400	0.86	42.00	35.68
34-40t	73.400	0.86	42.00	41.45

Projected CO_2 Emissions in $MtCO_2e$ using BD 20 from 2015 to 2050

Year	**Well to tank (WTT) Emissions in $MTCO_2e$**	**Tank to Wheel (TTW) Emissions in $MTCO_2e$**
2015	2.90	0.66
2020	3.64	0.83
2025	4.71	1.07
2030	6.00	1.36
2035	7.55	1.72
2040	9.36	2.13
2045	11.43	2.60
2050	13.76	3.13

Grid Emission Factors. Government of Kenya (2015) and ERC (2018).

Year	**"Basic" Grid EF from Kenya's Second National Communication**	**"Alternative" Grid EF from Least Cost Power Development Plan (LCPDP)**
2015	33.4	22.0
2020	96.1	5.3
2025	104.6	9.3
2030	103.2	38.2
2035	90.3	39.6
2040	89.3	41.4
2045	88.6	41.4
2050	87.6	41.4

Appendix D: National Commission for Science, Technology and Innovation (NACOSTI) research certificate.

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: 979088

Date of Issue: 20/March/2025

RESEARCH LICENSE

This is to Certify that Mr.. David Njoroge Karioki of Strathmore University, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Nairobi on the topic: A Decarbonisation model using fuel switching in the Petroleum Industry for the period ending : 20/March/2026.

License No: NACOSTI/P/25/417381

979088

Applicant Identification Number

Director General

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

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See overleaf for conditions