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A Path to Low Carbon and Climate Friendly Transport Sector in Addis Ababa: System Dynamics Approach

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Abstract:

Urban transportation system is a complex system with multiple variables and nonlinear feedback loops and influenced by transportation, social, economic, and environmental factors. Conventional transportation modeling approaches are unsuitable to simulate and evaluate its performance. This paper presents a system dynamics approach based on the cause-and-effect analysis and feedback loop structures. The proposed SD model comprises population, economic development, number of vehicles, environmental influence, travel demand and transport supply. The model runs in Vensim PLE software using the data from Addis Ababa, Ethiopia. The impacts of different policy scenarios on transportation system related carbon emission are analyzed. Ban imports of used vehicle, Energy shift and setting emission standard have the capacity to reduce carbon emission with the magnitude of 17%, 59% and 43% respectively by 2030. The study suggests that a combination of policies to achieve a low carbon and climate-friendly transport sector which will result a 74% decrease in carbon emission by 2030.

***Keywords*: transport, carbon emission, system dynamics, Addis Ababa**

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Thank you

Kaleab Enyew

ADDIS ABABA UNIVERSITY

This is to certify that the thesis prepared by Kaleab Enyew, "A path to low carbon and climate friendly transport sector in Addis Ababa: System Dynamics approach" and submitted in Partial Fulfilment of the Requirements for the Degree of Masters of Science in in Economics complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

1. Supervisor --------------------------- Signature ------------ Date--------------------
2. Internal Examiner --------------------------- Signature ------------ Date---------------------
3. External Examiner --------------------------- Signature ------------ Date---------------------

Declaration

I, undersigned, declare that this thesis entitled “A path to low carbon and climate friendly transport sector in Addis Ababa: System Dynamics approach” is my own and original work and has not been presented for a degree in any other university, and that all sources of material used for the thesis have been duly acknowledged, following the scientific guidelines of the institute

Declared by:

Name: Kaleab Enyew

Date: 19 June 2023

Signature: ________________

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Chapter One

1.1. Background of the Study

The transition from old growth models to green growth or sustainable growth is now an important shift for many economies around the world. Environmental issues are now a priority for governments and companies around the world due to rising concerns about global warming and corporate social responsibility. In essence, green growth or sustainable growth replaces conventional models of economic development with policies that create value from the use of natural capital, protect the environment, and promote poverty eradication and improved living conditions for all (Getu, 2020; Sundarakani et al., 2014)

This issue of Environment pollution and climate change has turned out to be one of the main challenges for mankind and the natural environment in the 21st century. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) underlined the urgency of addressing climate change and the need for urgent global action(IPCC, 2022). It is acknowledged that this change is caused by carbon emissions, which are being released into the atmosphere in ever-increasing amounts following an increase in human activities. The Earth is in danger from global warming, rising sea levels, extreme temperature swings, and the extinction of numerous species. By identifying the causes and barriers, as well as solutions to reduce emissions, carbon footprint analysis, quantification, and reduction are essential to prevent this and ultimately, attaining carbon-neutral economic growth(Sundarakani et al., 2014).

The Intergovernmental Panel on Climate Change (IPCC) Working Group III (WG3) has identified five major sectors as the primary drivers of global greenhouse gas emissions: energy systems, industry, buildings, transportation, and AFOLU (agriculture, forestry, and other land uses). Following the rapid increase in emissions from these sectors, in 2015 Paris Agreement was signed to keep the rise in global temperature between 1.5 and 2 degrees Celsius over pre-industrial levels. Yet, the Paris Objectives are at risk due to present trends in emissions, planned infrastructure, and national policy commitments(Höhne et al., 2020; Lamb et al., 2021).

The current development strategy of Sustainable development depends on high energy consumption and the International Energy Agency predicts that 46.47% of the increase in oil demand between 2018 and 2040 will come from the transportation sector. The transportation sector accounted for 43.55% of crude oil consumption and 24.5% of CO_2 emissions in 2018(Abergel and Brown, 2017). Even while mobility and road transportation have improved, the results show that increased usage of motor vehicles contributes to resource depletion and global warming(Østergaard et al., 2020; Zhang et al., 2019).

The size of the transport vehicle population in the Ethiopia and kilometers traveled have also increased substantially. According to the federal transport authority (2019_2021), in 2007, the vehicle population was 244,256 and grew to 1,071,345 in 2018, which is about a 338.6% increase(Addis Ababa City Administration, 2012). A total of 596,084 vehicles were reportedly registered in Addis Ababa in 2019 which is more than half of the 1.1 million vehicles registered in Ethiopia. The road network increased from 26,550 km to 126,773 km starting from 1997 through 2018(Federal Transport Authority, 2019) As a result, road density per 1,000 sq. km increased significantly, from 24.1 km in 1997 to 115.2 in 2018.

Addis Ababa is the largest city both in population and business activities in Ethiopia and out of the total number of vehicles in the country, more than 50% are found in it. However, the transport sector is not receiving enough attention in climate change mitigation efforts in the city. Despite the fact that cities are now emphasizing the changing climate through various adaptation and mitigation measures, they must work to enhance the greenhouse gas mitigation measures by providing a solution to the growing number of motorized vehicles. Therefore, the main objective of this study is to search for the best mechanism of mitigating carbon emission in road transport of Addis Ababa city for a sustainable transport system.

1.2. Problem statement

Emissions of greenhouse gases (GHGs) continue to endanger both the environment and humanity. In recent years, it is being observed that emissions have decreased in certain historically high-emitting sectors such as industry, but have increased in other areas, such as transportation(Getu, 2020; IPCC, 2014b). The transport sector which is primarily reliant on fossil fuels, presently accounts for 28% of global final energy consumption, 23% of global energy-related CO_2 emissions, and 25% of overall GHG emissions, with approximately 7.9 $GtCO_2$ annual emissions(Abergel and Brown, 2017; Gota et al., 2019). In addition, according to IEA report (Abergel and Brown, 2017). it is indicated that transportation emission will continue to grow by 2.5% yearly, and this trend will last until 2050.

Researchers warned that low-income countries will increase their transport emissions at a faster rate than high-income nations. According to the Intergovernmental Panel on Climate Change (IPCC) report, the total transport emissions from non-OECD nations will likely surpass OECD emissions by 2050 due to motorization, increasing population, and higher travel demand(Getu, 2020; Gota et al., 2019). This indicates that the current mitigation efforts are not aggressive enough to decarbonize the transport sector, and bringing the motorization tendencies seen in high-income nations into developing countries will speed up the carbon emissions even more. Investigating the root causes and potential mitigation strategies for transport emissions in developing countries is therefore fascinating.

Ethiopia’s overall emission of 0.5% has made essentially little difference to the world's greenhouse gas emissions. But, Ethiopian conventional economic development runs the danger of having the same environmental effects as those seen globally. If present trends continue, Ethiopia's greenhouse gas emissions, which were 150 megatons in 2010, CO_2e (carbon dioxide equivalent), would more than quadruple to 400 megatons CO_2e by 2030. The country currently emits the third-highest amount of CO_2 in East Africa(ECRGE, 2011; Taka et al., 2020).

In Ethiopia, the entire vehicle fleet has grown at an annual rate of greater than 10%, from 95,925 vehicles in 1996/1997 (Dagnew, 2012) to 831,265 motor vehicles in 2017/2018 and around 1.2 million in 2021 (FDRE Transport Authority, 2018), as a result of the emergence of urbanization and the development of trade-related activities. The alarmingly rising number of motor vehicles will be a major problem in tackling climate change unless preventative and adaptive measures are done. Ethiopia’s transportation sector is currently dominated by internal combustion engine vehicles running using imported petroleum oil and vehicles.

In line with the increase in vehicle stock, Ethiopia imports all of the fossil fuel it needs each year, using more than 80% of its revenues in foreign currencies(Benti et al., 2021). According to NBE annual report (2022) annual report, Ethiopia imports up to 3.8 million tons of petroleum annually, the bulk of which is consumed by the transportation industry, placing a significant burden on the nation's economy. Moreover, the burning of fossil fuels in the transportation sector results in greater GHG emissions, which have an adverse impact on the environment.

The sharp rise in urban transportation is accelerating greenhouse gas emissions, which worsen global warming's effects. If the pattern holds, urban road transportation's share of the city's overall greenhouse gas emissions will significantly rise. When combined with the little efforts being made to reduce greenhouse gas emissions from vehicles, the unsustainable increase of vehicles in cities might increase the negative effects of climate change both worldwide and in the city.

The concentration of people, infrastructure, and commercial activity in urban areas leads to high energy consumption and high greenhouse gas (GHG) emissions, placing cities at the frontline of the fight against climate change. They occupy barely 2% of the land, but they contribute up to 70% of GHG emissions(Grafakos et al., 2020; Liu et al., 2018) and 75% of all global emissions of carbon dioxide from anthropogenic sources(Addis et al., 2022; Bulkeley, 2010).

One of the Ethiopian cities distinguished by a rapid urban transportation boom is Addis Ababa. The majority of the city's transportation network is comprised of roads. Almost 596,084 vehicles were registered in the city in 2020, which is more than half of all vehicles registered nationwide(Federal Transport Authority, 2019; Force, 2018). Addis Ababa's CO2 emission is 4-8 times higher than WHO standards. Addis Ababa's greenhouse gas (GHG) emissions is projected to reach 32 million tons by 2030(Teshome, 2023).

In Ethiopia, attention is given to the green economy and the Climate Resilient Green Economy Strategy (CRGE) is one, which was set into practice in 2011 and outlines the priorities for decreasing greenhouse gas emissions. In line with it, a national adaptation plan was launched aiming at producing zero level of net emission in general and to cap 2030 greenhouse gas emissions at 145 mtco2e, a 64 percent reduction from projected business-as-usual emission levels of more than 400 mtco2(ECRGE, 2011). A review of existing strategies revealed that Ethiopian mitigation strategies are ineffective to decarbonize the sector, and instead, other government policies and decisions have fuelled motorization and hence carbon emissions.

Some research has been done on transport-related emission mitigation and related areas with varying objectives and methodologies in Ethiopia. Some researchers focus on single policy options like the Contribution of light rail Sekasi and Martens (2021), biofuel energy Berta and Zerga (2015), and eco_routing Busho and Alemayehu (2020) on reducing emission from transport sector and most of which are descriptive. Others for example Zegeye (2018), Kebede et al. (2022b), Desta et al. (2022) assessed the trend of carbon emission and climate change mitigation at country level and major cities.

The transport system in Addis Ababa is very complex as it is the center of major economic, and social activities as well as the city owns over half of countries registered vehicles. To the best of our knowledge, no study has been identified with a broader system approach that simultaneously considers feedback linkages between climate change, the economy, travel time, transportation mode choice shares, and population pressure. Coordination between many sectors and actors is essential if the city is to become carbon-neutral and climate-change-resilient. System dynamic models are highly recommended models to take into account the complex interactions of the sub-sectors. There is a lack of comprehensive understanding of the interaction, feedback loops, and drivers that shape the behavior of the transport sector and its carbon emission at the country in general and specifically Addis Ababa level. Many studies have focused on technological solutions to reduce carbon emission such as Biofuel and electric vehicles, but have not fully considered the systemic changes required to achieve sustainable transport system.

Hence, this study differs in the following ways: First, methodological-wise, it uses a system dynamic model which captures holistic interactions over time. Adopting such an approach will fill the methodical gap of being unable to consider the dynamism, non-linearity, and complexity of interactions observed in the previous study. Second, this study plan to come up with different scenarios and investment options as mitigation against the emissions. Third, it focuses on a specific case, Addis Ababa which is considered as the major emitter urban area in the country. This might help to come up with a specific policy perspective.

The aim of this study is thus to explore the complex dynamics of the transport sector and identify strategies to transition towards a low-carbon and climate-friendly transport system. Hence, the study will address the following questions:

- What are the system components that build carbon emission from road transport?
- What are carbon emission mitigating mechanisms from road transport to attain the national emission target level?

1.3. Objective of the study

The main objective of the study is to develop a system dynamics model for evaluating the interaction between the transport sector and its carbon footprint in Addis Ababa. Specifically, this study intends to:

- To explore factors influencing the transport system and investigate its causality with the environment.
- To identify measures that has to be taken to make the transport sector climate-friendly.
- To find the leverage point in mitigating carbon emissions from road transport.

1.4. Significance of the study

The study would contribute to the ongoing national policy on the environment and climate friendly transport sector in reducing the greenhouse gas (GHG) emission. Furthermore, it informs the mitigation and options for better management practices to create a transport system that promotes output and socioeconomic growth while minimizing greenhouse gas (GHG) emission.

1.5. Organization of the study

The study is structured into five chapters. The first chapter introduces the topic, research problem, and study objectives, while the second chapter provides a brief overview of the transport sector and related carbon emission at the country and city level. The third focused on the model's data and methodological aspects. In chapter five, the findings have discussed and analyzed various policy scenarios for future policy implications. Finally, in the fi, the study provides conclusions, and policy implications.

Chapter Two

2. Review of Related Literature

2.1. Introduction

This chapter focuses on reviewing the literature in the area of the transport sector. The issues discussed include the theoretical and empirical studies of the existing literature and an overview of the transport sector and carbon emission at a country level and in Addis Ababa. The theoretical framework helps to understand the current state of knowledge on the research topic. An empirical review of studies of different scholars has been done to guide the research gaps for this study. Altogether, the reviews will be used to develop conceptual framework in the third chapter.

2.2. Theoretical literature review

Human activities such as the production of goods, the provision of services, and transportation all contribute to environmental pollution and carbon emission (Nathaniel, 2021). The separate relationships between transportation activity, population, economic growth, and environmental concerns have been studied in earlier research. Carbon emissions are frequently brought up when talking about these linkages. The following sub-section presents literature streams demonstrating the relationship between the variables of interest.

2.2.1. Environment and Transportation

The first body of research focuses on the relationship between transportation and carbon emissions. The fundamental theory is that increased transportation capacity and infrastructure lead to fuel consumption and higher carbon emissions. In the decades following World War II, oil was considered abundant and cheap, and this contributed to the sharp increase in car use and the emergence of new driving practices (especially solo driving) in the world (Ferguson, 1997).

Timilsina and Shrestha (2009), analyzed the main causes of carbon dioxide emissions in a group of Asian economies, came to the conclusion that the energy used by the transportation industry was the main driver of CO_2 emissions. The authors state that, the overall contribution of transport energy consumption to carbon dioxide emissions in the region has remained constant over the past 25 years at around 10%.

In a study for Pakistan, Danielle and Masilela (2020) looked at the relationship between energy use in the transportation sector, GDP, and CO2 emissions. The results of ARDL and VECM showed a significant positive relationship between carbon dioxide and energy consumption by transportation services. Similarly to this, Shahbaz et al. (2015) looked into the connection between Tunisia's transportation infrastructure, energy use in the industry, and carbon emissions from transportation. The VECM results showed a decoupling between energy consumption and carbon emissions.

2.2.2. Urbanization and Environment

Several empirical studies have indicated that the link between urbanization and environmental deterioration is very strong. Urban areas become the source of environmental issues with wider spatial dimensions as a result of consumption of natural resources and wider variety of human activities. Rapid urbanization, as seen in Ethiopia, will have a big impact on the environment, mainly through higher emissions from businesses, vehicles, power plants, and a loss of vegetation due to residential and industrial growth.

Rapid urbanization in Sub-Saharan Africa has not been accompanied by enough industrialization and job creation. The truth is that a lot of people move to cities because farming doesn't pay well and depends on unreliable environmental conditions. Rapid urbanization causes unemployment and unchecked urban growth with the development of slums and high transportation demand (UN HABITAT, 2017). Another prevalent trait is the population's rapid growth, which is associated with family planning knowledge, education levels, and poverty. This results in population growth that exceeds the capacity of the environment to sustain it, creating a vicious cycle of population growth and environmental deterioration.

2.2.3. Economic growth and Environment

Economic growth has historically had a significant impact on vehicle ownership rate. As economies grow more people tend to have higher disposable income and which allow them to purchase and maintain vehicles. Additionally, economic growth often leads to improvement in infrastructure including roads and highways which makes owning a vehicle more practical and convenient. These factors tend to increase demand for vehicle and ownership rate which leadst to increase in fuel consumption and carbon emission.

Nature serves as a sink for harmful air, water, and solid pollutants. It also serves as the final resting place for millions of tons of trash and the unlucky location of many toxic chemicals. Environmental quality declines when the capacity of the environment to disperse or absorb wastes is exceeded, and the policy response to this decline in quality may limit growth. Alternatively, growth may be constrained when human activity damages the ecosystem to the point where it deteriorates beyond repair and settles into a new, lower, less productive steady state (Brock and Taylor, 2005).

Loo and Banister (2016) investigate the relationship between economic and transportation-related activities and carbon emissions. They found that economic and transportation-related activities significantly increased energy demand, which led to an increase in CO_2 emissions.

2.3. Empirical studies on transport sector of Ethiopia

The transport system in Ethiopia, its sustainability, carbon emission mitigation from the sector, emission assessment and measurement and related issues has been the subject of several studies. In the past few years, a large number of studies have researched into the problem of urban transport energy consumption and emissions.

Engdaw (2020) has conducted descriptive methods of data analysis using quantitative data ranging from1990–2013. The study was aiming at what the trend of emission looks like among different sectors. The paper revealed that Ethiopia has shown increasing trends of emission in most sectors, except land use-land use change, and forestry.

Desta et al. (2022) conducted an analysis applying Well-to-wheel (WTW) method to investigate sustainability of transportation by blending biodiesel to the conventional petroleum fuel. In the finding the researcher showed that flexible fuel vehicles (FFVs) fuelled with a blend of 85% ethanol and 15% gasoline could save 65% fossil fuels and 29% of GHG emission reductions compared to neat gasoline vehicle.

Wondifraw et al. (2018) used an Emission calculator software (COPERT) to estimate the total annual emission released from road vehicles in Addis Ababa from 2005 through 2015. The study found that emission from vehicles in Addis Ababa increases significantly in the recent years. He showed that the total vehicles population which is considered in this study releases a total of 7.4 Megatons.

Busho and Alemayehu (2020) applied 3D_eco routing to find ways of mitigating the impacts of climate change. He found that there is emission reduction potential from fuel and CO2 up to 39.81% and 25.65% from other pollutants. The study emphasize that Eco_routes have the ability of reducing fuel consumption, CO2 and other air pollutant emission rate.

Kebede et al. (2022a) analyzed data for 358 diesel-fueled vehicles collected randomly at different locations in Addis Ababa city to investigate the emissions generated by different categories of public transport vehicles. The study revealed that 243 (67.9%) of them had emission levels beyond the standard threshold with their smoke opacity being greater than or equal to 41%. Of these, 45 (18.52%) registered 100% smoke opacity.

Research gap and contribution of the study

According to the reviewed empirical literature, several studies looked at various nexuses between transportation, economy, population, and carbon emissions,. These studies range from examining the relation between economic growth and transportation to examine the relation between emissions of carbon emission and transportation.

In Ethiopian case, most researchers like Biruk (2018), Engidaw (2020), had assessed the causes and trend carbon emission, estimated level of emission from urban transport expansion and its possible impacts on environment. Other researchers like, Borrego and Kebede (2022), Deslta and lee (2022), and Busho and Alemayehu (2020) assessed the effectiveness of various climate change mitigation measures most of which are descriptive. However, methodologies used in some of the papers done in Addis Ababa failed to absorb the interaction of variables and check different policy scenarios simultaneously. Therefore, this study will try to fill this gap by using system dynamics model. As far as the author is aware, no studies have looked into the complex dynamic relationship between transportation, urbanization, economic growth, and GHG emissions in Addis Ababa. The model is good at handling complex system and testing for best policy scenario among different policy scenarios.

2.4. Overview of global GHG emission and transportation

According to Lamb et al. (2021), greenhouse gas (GHG) emissions can be traced to five economic sectors: energy, industry, buildings, transport and AFOLU (agriculture, forestry and other land uses). GHG emission levels in 2018 were approximately 11% (5.8 GtCO2eq) higher than in 2010. Energy systems (1.9 GtCO2eq) accounted for one-third of the increase in GHG emissions between 2010 and 2018, followed by industry (1.8 GtCO2eq, or 30% of the increase), transport (1.2 GtCO2eq, or 20%), and the remaining by other sectors. Since 1990, global transport emissions have grown at a constant rate of about 2% per year. The road subsector accounted for most growth since 2010 (+0.9 GtCO2eq, at 1.9% per year).

Since 2010, Asia Pacific Developed (+0%/yr) and Europe (+0.4%/yr) have been able to maintain relatively stable transport emissions. All other regions, however, have experienced emissions rise. South-East Asia (+4.5%/yr, +0.1 GtCO2eq), Eastern Asia (+5.6%/yr, +0.4 GtCO2eq), and Africa (+3.3%/yr, +0.08 GtCO2eq) experienced the fastest growth since 2010. Since 92% of transportation energy is derived from oil-based fuels, the percentage of total final energy used in transportation (28%) and its rapid growth over time have a significant negative impact on climate mitigation efforts(IEA, 2020c).

Since 1990, there has been an increase in travel distances and a switch from low- to high-speed modes of transportation, both of which are correlated with GDP growth(Gota et al., 2019; Schafer et al., 2009) Energy efficiency has only slightly improved, on average 1.3% annually, while carbon intensities have remained constant. Overall, improvements in energy efficiency and fuel economy have lagged behind increases in passenger and freight travel activity levels, continuing a long-term trend for the transportation sector(McKinnon, 2016).

In the OECD countries, passenger-km growth has significantly slowed, rising by just 1% between 2000 and 2017(SLoCaT, 2018) It is unclear whether the so-called "peak car" in developed economies reflects merely economic stagnation and rising fuel prices or a more profound change in lifestyle and demographics(Bastian et al., 2016).

While public transportation fails to provide appropriate service, rising nations in the global South are becoming more dependent on cars as a result of rapidly expanding motorization, urban sprawl, and local automobile manufacture(Lamb et al., 2021; Pojani and Stead, 2017). Starting from a low basis, worldwide passenger travel climbed by 169% in non-OECD nations between 2000 and 2017(SLoCaT, 2018).

The energy structure of the world's transportation system is still highly dependent on fossil fuels, where using gasoline and diesel fuels accounting for 92% of total energy consumption in the vehicles market(Figueroa et al., 2014; IEA, 2019a). From 2010 and 2018, the carbon intensity of the transportation industry stayed constant across the globe. This is partly attributed to the growing popularity of larger, heavier combustion-powered vehicles, whose sales have tended to surpass those of electric and hybrid vehicles. Overall, transport trends reveal a steady increase of emissions, overwhelmingly driven by growing motorization and road transport activity. This global trend is opposite to what is needed, with a shift from lower to higher-carbon modes only minimally offset by efficiency gains.

2.5. Transport System in Ethiopia: An overview

According to a recent estimate, the landlocked nation of Ethiopia has a population of more than 110 million people (trends, 2022) and heavily relies on a few mechanized transport modes, primarily road transport(ECRGE, 2011; Getu, 2020). With the exception of international passenger and cargo transportation, air and water transportation barely contribute to national transportation services. Similarly, the country has one rail line used for freight transportation connecting its capital with the port city of Djibouti, and a light-rail transit (LRT) in Addis Ababa which only 5% of Addis Ababa’s daily public transportation use (Kozicki, 2015). The most prevalent modes of transportation are then road transportation and non-motorized transportation (NMT).

Ethiopia, which has 117 million citizens as of 2021, is the second-most populous country in Africa after Nigeria and continues to have the fastest-growing economy in the continent (WB, 2020). The country is one of the lowest rates of overall vehicle penetration in the world, with forklift trucks). Lacking a domestic auto industry, Ethiopia imports a wide range of automobiles, about 85% of which are secondhand cars, from other industrialized regions. Just one in five Ethiopians live in metropolitan regions, which is one of the primary causes of this along with the nation's income levels and the heavy import taxes levied on automobiles(Gorham et al., 2017).

Due to the low road penetration, the availability of transportation options, and the associated costs, studies have shown that commuters travel a significant portion of their distances using non-motorized modes of transportation and public transportation. For instance, in Addis Ababa, which is home to about 60%(Addis et al., 2022) of the country's registered vehicles, the majority of commuters (54%) use walking, followed by public transportation (31%) and only a small percentage (15%) drive their own cars. In addition, non-motorized transportation modal shares are higher in regional cities and rural areas with sparse populations and restricted access to private automobile ownership than in urban areas(Addis Ababa City Road and Transport Bureau, 2020)

There are five major categories of vehicle ownership in Ethiopia: private, public transportation, commercial, governmental, and international/nongovernmental organizations. When we look at vehicles average age, compared to other east African countries, Ethiopia's fleet is older. According to a UNEP report from September 2009, Tanzania's vehicle population had an average age of 15 years. Similar average ages have also been reported for Ethiopia (20 years), Kenya (20 years), and Uganda 13 years. (UNEP, 2009 September) Passenger cars typically stay shorter than light and heavy trucks as cited by(Kebede et al., 2022a)

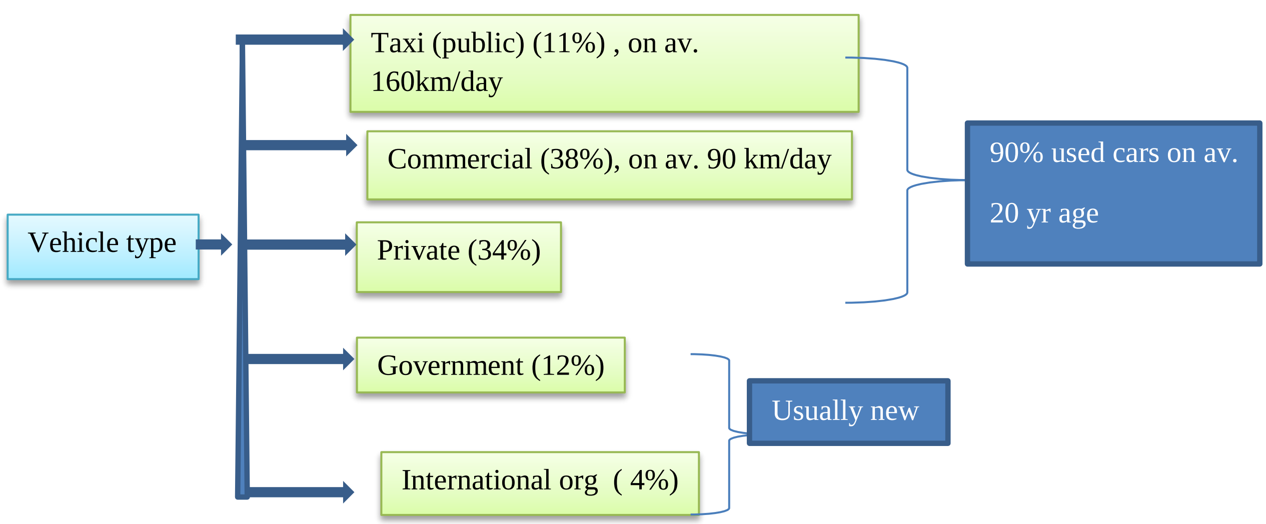


Figure 1: Classification of Ethiopian vehicles ownership, age structure and average km per day

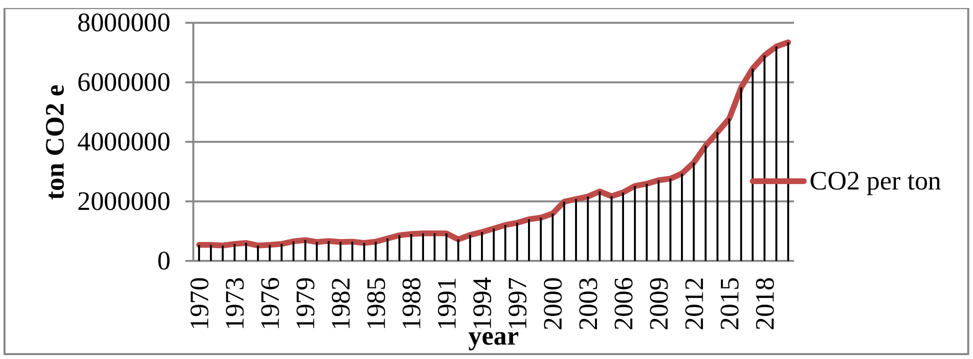
2.5.1. Ethiopia’s International Obligation/Participation

As a member of the international community and the global environmental system as a whole, Ethiopia actively contributes to environmental protection on a global scale. The number of international environmental agreements that the Ethiopian government has already ratified through legislative action is evidence of this. The UN Framework Convention on Climate Change (ratified in 1994) and the Kyoto Protocol (ratified in 2005) is a couple of the international environmental agreements dealing to atmospheric environment that the Ethiopian government has ratified.

2.5.2. Transportation and GHG emission in Ethiopia

Ethiopia's economic growth is closely tied to developments in sectors like transportation, which depends totally on imported gasoline and diesel fuel. According to the Ethiopian Panel on Climate Change, the key factors influencing the expansion of vehicles in urban areas and, subsequently, the rise in greenhouse gas emissions, are the subsidized fuel price, rising personal income, and the demand for transportation(IPCC, 2014a). The import of used cars, a lack of fuel efficiency and emission standards/certificates for imported cars, a lack of comprehensive policies to encourage the production of biodiesel and the import of hybrid and electric vehicles, a lack of laws requiring the use of catalytic converters on vehicles, and more are the main causes of the transportation sector's greenhouse gas emissions.

Figure 2: CO2 emission per ton from transport sector



Source: World Bank (2022)

In the figure above the emission level from transport sector shows an upward exponential growth. The increase trend of GHG emission from transport sector of Ethiopia is largely due to the growth in demand for vehicles in the country. The rise of income level has resulted in the rising affordability and preference for cars over other forms of transportwhich make seginificant contribution to the total emission from the sector. With the increase in number of vehicles the amount of fossil fuel consumed also increases resulting more emission. Also, lack of awarness about renewable resource of transportation such as electric/hybrid vehicles has further increased the dependency on petrol and desiel as a major source of fuel.

The rise of urbanization coupled with economic development in Ethipia require adequate transportation method of goods and services across different cities contributing high energy consumption followed by high emission. Reliance on outdated public transportation system like buses is one of the prime reaseons for additional reason for additional reason emanating from this sector.

2.5.3. Urban Transport and Related Systems in Addis Ababa

Addis Ababa is the capital city of Ethiopia and one of the largest cities in Africa. The city has road oriented transport system with several routes leading in and out of the city. In a metropolitan area of Ethiopia, there are now more and more vehicles on the road every day. The category of road vehicle includes motorbikes, heavy duty trucks, and light commercial vehicles and the like. In extremely densely populated urban regions like the capital city Addis Ababa, the increase of these vehicle populations is growing very high. Road vehicles in Addis Ababa make up over half of all road vehicles in Ethiopia, according to the Ethiopian Road Transport Authority.

Addis Ababa as a primary commercial center is quickly growing in many aspects. Every ten years since the 1980s, population has expanded by more than doubling. According to the Central Statistical Agency, Addis Ababa’s population is currently estimated to be more than five million. Motorization rate of the city was 130 vehicles per 1,000 people, with a total registered vehicle fleet of about 426,500 in 2015 which is projected that a large increase in vehicle ownership will result from the city's recent and rapid economic growth(Haji, 2020).

For the majority of population, standard city buses and mini-bus taxis are the most readily available and reasonably priced forms of public transit. Also, there are public and private limited enterprises that distribute goods by road to customers in a city. There were 596,084 different types of vehicles available as of 2019(Federal Transport Authority, 2019).

To accommodate the fast-growing demand, the Addis Ababa City administration developed major transportation projects, which are currently in the expansion stages. Nevertheless, the environmental impact of these road network developments was not taken into account. The road sector must be held accountable for its part in achieving environmental sustainability.

2.5.4. GHG Mitigation assessment and policy measures in Ethiopia

Ethiopia is making substantial efforts to cut GHG emissions even though it is not required to do so by the climate change convention. Despite contributing only a paltry 0.5% of global GHG emissions, the nation is willing to reduce its GHG emissions because of its green growth policies and low-carbon development paths. Ethiopia has contributed 368.8 Mt CO_2e and removed 108.4 Mt CO_2e from the total worldwide GHG emissions in 2018(Benti et al., 2021), produced a net emission of 260.4 Mt CO_2e, or almost 0.5% of the total global emissions (49.7 Bt CO_2) in 2018. In the business-as-usual scenarios, the total anticipated GHG emission was calculated to be 404.4 Mt CO_2-eq in 2030 given the growing trend.

Ethiopia has implemented a number of projects that could help with climate change mitigation and assessment strategies to lower GHG emissions and/or improve their sinks. As stated in the CRGE, the nation is dedicated to minimizing vulnerability to the effects of climate change by enhancing the comprehensive integration of adaptations to the change in development plans and strategies at the national as well as regional levels.

Regardless of the implementation and effectiveness, changing the energy system to electricity generation from renewable sources (solar, wind, and hydropower), improving resource and energy efficiency in manufacturing processes, and using efficient improved stoves at the household level are a few of the suggested mitigation measures in the energy sector. As part of the CRGE strategy, the nation is also building an intra-urban electric rail with the overall goal of replacing 50% of the transport of goods with electric rail(ECRGE, 2011). The use of efficient vehicles (such as an electric car), alternative fuels (such as bio-diesel), increasing the percentage of ethanol-gasoline blends (also known as "gasohol"), improving rural and urban transportation infrastructure, promoting mass transit, and the use of non-motorized transport, such as bicycles and various forms of intermediate transport, are some of the additional options.

Chapter Three

Method

3.1. Description of the study area

Addis Ababa, the political capital and the most important commercial and cultural center of Ethiopia, is geographically located at the heart of the country, $9^{o}2'$N latitude, and $38^{o}45'$E longitude occupying a total of 540 sq. km land area. Addis Ababa is one of the fastest-growing cities in Africa and a primate city in Ethiopia with an estimated population of approximately 7 million in 2019, which is roughly 25% of the total urban population of the country(CSA, 2017; Erena, 2017).

Owing to its central geographic location, Addis Ababa is on the crossroad linking all the corners of Ethiopia. Following the Growth and Transformation Plan I (2011- 2015) and GTP II(2016-2020), Addis Ababa has shown an impressive macroeconomic performance significantly exceeding the national average. Based on data from the city administration's Bureau of Finance and Economic Development (2016), the GDP of Addis Ababa has grown, on average, by more than 15% over the five years of the first GTP; much faster than the national GDP over the same period. The city's GDP account for 29% of all the urban centers and generate on average a quarter of the national GDP(Spaliviero, 2017).

It is worthwhile to remember that Addis Ababa is the city most closely associated with the quick changes in technology, lifestyle, and societal transformation, rapid urbanization and economic expansion, and rising energy consumption and carbon emissions. For this reason, the researcher chose the case area for dynamic modeling of road transportation and CO2 emission.

3.2. Model

System dynamics is a popular modeling approach that is widely used in various fields, including economics, engineering, and management. One of the main advantages of system dynamics is its ability to model complex dynamic systems, which are characterized by feedback loops, delays, and nonlinear relationships. This makes it a powerful modeling tool for analyzing the behavior of complex economic systems, such as markets, industries, and economies.

Compared to macroeconomic models, CGE and DSGE model system dynamics models provide a more detailed and realistic representation of the underlying dynamics of the system. In macroeconomic models, the economy is usually represented as a set of equations that describe the relationships between different variables, such as output, inflation, and unemployment. However, these models often make simplifying assumptions that may not capture the true complexity of the system. In contrast, system dynamics models allow for a more realistic understanding of the system, by explicitly modeling the feedback loops and nonlinear relationships that exist in the system.

CGE models are often used to analyze the impacts of policy changes on the economy, by simulating changes in prices and quantities across different sectors of the economy. However, these models may not capture the dynamic interactions between different sectors and the feedback loops that arise as a result. DSGE models, on the other hand, are often used to analyze the business cycle and the effects of monetary and fiscal policy on the economy. However, these models may not capture the long-term dynamics of the economy, and may not be suitable for modeling complex systems with multiple feedback loops and delays.

System dynamics is a powerful modeling approach that offers several advantages over other modeling techniques. Its ability to capture the complex and dynamic nature of economic systems makes it a valuable tool for analyzing the behavior of markets, industries, and economies, and for designing effective policies and interventions. In real terms, the dynamic interaction between the economic, social, and environment is a complex interaction and the relationship is not linear and has feedback. Therefore, the model applied in this study has to be able to absorb complexity, dynamics, and nonlinearity.

The transport sector is a complex system with many variables, feedback loops between subsystems, and influencing factors. The conventional linear quantitative technique should not be used to characterize the properties of this complex system. To simulate the development of the urban transportation system, specifically the effects of road transport on carbon emission in Addis Ababa city, this study uses the system dynamics approach. The degree to which the system is sensitive to changes in a policy or the system's structure can be determined using the system dynamics model. It can demonstrate how much the system reacts to disturbances brought on by the environment outside. Creating models in this way offers helpful insight into the road transportation sector's sustainability.

3.2.1. Overview of Systems Dynamics Methods

The discipline of system dynamics was created in the late 1950s as a result of efforts to address dynamically challenging long-term policy issues in both the public and private spheres. Its foundations are found in the fields of mathematics, physics, and engineering, specifically nonlinear dynamics and feedback control theory. One reason why simulation-based analysis of the transport sector and carbon emission problem is required is due to the dynamic complexity of the real world. According to some theories, the real world functions as a multi-loop, multi-state, non-linear feedback system that reacts to decisions in both expected and unexpected ways(Kamp et al., 2016). The model is a simplified representation of the real-world phenomenon to make it easier to understand. System dynamics modeling is a powerful tool for understanding complex dynamical systems. it provides an approach for simulating and analyzing the behavior of dynamic phenomena like public policy, environmental sustainability, and others. This approach uses a mathematical equation to represent the structure and behavior of a system allowing users to explore different scenarios or change in the underlying system. By simulating model scenarios, stakeholders can gain insights into the likely outcome of their decision.

System dynamics model involves constructing diagrams with feedback loops to demonstrate how various variables interact within a system over time. Furthermore, these models allow for parameter estimation and tuning which help refine model predictions and identify trajectories that lead to different outcomes. Overall, system dynamics modeling offers a powerful method for exploring uncertain systems through visualization, simulations, and scenario analysis.

The system dynamics model contains two parts. The first part is a causal–loop diagram that describes an idea, both conceptually and as a set of simplified cause–effect relationships between the different systems developed during model construction. The second part is a stock–flow diagram that represents the quantitative relationships among variables. (Jan, 2003)

3.2.2. Dynamic hypothesis

The dynamic problem is an increase in vehicle emissions into the atmosphere in Addis Ababa from 2010. Sulfur dioxide (SO_2), particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO), and nitrogen oxides (NO_x) are the five pollutants that make up these emissions.

The notion that system behavior Predominantly results from system structure" (Chen et al., 2006; Jan, 2003) is one of the tenets of system dynamics. This study offers a model to replicate the causes surrounding the accumulation of carbon into the atmosphere to better understand how carbon emission has changed through time.

The primary premise of this study is that the increase in used vehicle imports into the country has had the biggest impact on the rise in vehicular emissions over time. The model thus connects four areas that are thought to be related, namely, carbon emissions, vehicle population, population growth, and economic growth, and it has a simulation duration that spans from 2010 to 2030.

Over the years, Ethiopia has neglected to take a comprehensive approach to environmental challenges. The country's environmental policies primarily concentrate on enhancing environmental performance and human activities like industrialization and land use, while downplaying the significance of other related issues that also have an impact on the environment, such as economic growth, the rate of expansion of the transportation sector, and the quality of vehicles that are permitted to operate on the road.

According to Todaro and Smith (2009), rural-to-urban migration is a key feature of growing economies. As a result, as more people find jobs, the gross domestic product (GDP) per capita rises. People tend to prefer material possessions that improve their quality of life when they have more purchasing power. Addis Ababa’s unreliable public transportation system makes private vehicle ownership extremely necessary. Due to the strong demand for affordable imported used vehicles, they have flooded the market. As cars got aged, their emission capacity rises, which causes an increase in atmospheric gas accumulation.

3.2.3. System structure

It is crucial to identify the primary causes of rising car pollution concentrations because taking steps to affect these causes becomes a key policy concern. Urban population growth and per capita GDP are the key factors influencing the demand for vehicles. Numerous economic studies have proposed a link between rising car demand and rising GDP(OECD and Rozwoju, 2001).

Urban transportation is a complex system that is influenced by the economy, population, and environment. The system's model can be disaggregated into sub-models of population, the economy, the number of vehicles, and the environment. The interaction between these sub-models creates nonlinear causal relations and feedback loops.

The population sub-model depicts the stage of urban development. Both economic development and total transit demand are impacted by population density and the GDP per capita has a significant impact on the net migration rate. The expansion of the economy and rising demand for transportation are likely to be blamed for the rise in the number of vehicles.

The economic sub-model has a direct impact on net migration and it determines the ownership of private vehicle which in turn affect the total motor vehicle. There is a strong correlation between economic growth and a rise in the need for transportation, especially for road vehicles(Dargay et al., 2007). Investment in transportation is also influenced by the economy since, to maintain excellent traffic conditions, the government must boost financial support for transportation infrastructure.

3.2.4. Causal Loop Diagram

A causal loop diagram is a conceptual framework that explains the underlying dynamic and systemic reasons for the behavior in order to highlight a particular topic. It shows how the feedback system is organized and how the dynamics and underlying causes of the behavior are captured. A causal loop diagram shows both the causal connection between model variables and how they interact with feedback. The causal loop diagram also includes feedback loops that counterbalance and support one another. Although the balancing loop depicts how the system generates goal-seeking or self-regulating actions, the reinforcing loop illustrates how the system achieves growth.

An initial step in modeling is to create a causal loop diagram. The connections between each predefined variable are shown in the causal loop diagram as a feedback cycle. Each relationship explains how these variables are related causally. Each relationship has a polarity to indicate how the relationship between these variables affects one another, which can be positive (+) or negative (-). Additionally, there are two types of feedback in the causal loop diagram: the reinforcing loop, which describes how a cycle is reinforced, and the balancing loop, which describes how a cycle is stable.

The causal loop diagram shown below makes an effort to grasp the system structure of the transport sector and related emission, and its relation with other sub-models like economy and population. In this CLD, main variables identified in each sub-model are included and tried to capture their interaction.

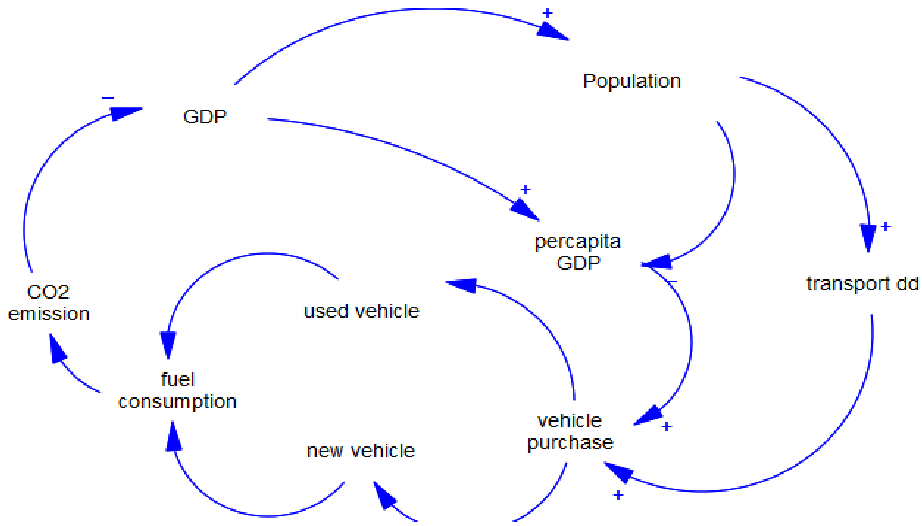


Figure 3:CLD for urban road transportation and related carbon emission

The above CLD show balancing and reinforcing feedback interactions among the variables identified variables. Economic growth generally urges the demand for mobility and private vehicles. The growth of vehicle ownership leads to an increased population of motor vehicles and fuel consumption followed by carbon emission. The deterioration of the environment has a negative effect on economic growth. This forms a balancing loop.

Economic development and rise in per capita income attract more immigration population. The growing population generates more travel demand and aggravates traffic congestion. Serious congestion results in a decrease in economic development through deteriorating environment. Percapita income growth leads to population growth through high net migration and once again increases in population lowers per capita income.

Population size is also an important factor in urban passenger transport systems. A large number of population movements have brought huge challenges to the urban passenger transport system. At the same time, large carbon dioxide emissions can also have adverse effects on the population.

The carbon emission of new vehicles is lower than that of used/old fuel vehicles, so the increase in the proportion of new vehicles will reduce the carbon emission of urban passenger transport.

To a certain extent, it protects the urban environment and promotes the development of urban economy. With the development of the urban economy, a new vehicle has also been further promoted and developed.

3.2.5. Stock Flow Diagram

The model structure on the dynamic issue of carbon emission from the transport sector is illustrated in this section. The arrangement of stock, flows and auxiliary variables used to depict any system is referred to as a stock-flow diagram. Through the causal tying of variables and integrated equations connecting them, the stock flow diagram characterizes the qualitative and quantitative features of the system. Stocks are represented by rectangles and are described as variables that accumulate over time. On the other hand, flows are the factors that affect stocks and cause them to accumulate or deplete.

3.2.5.1. Population and Economy Sub-Model

The economy sub-model reflects the driving forces of urban transportation development. The level of economic development is one of the city's competitiveness indicators and directly affects the in- and out-migration of people. It stimulates the ownership and utilization of private cars, and public transport too and leading to an increase in the number of vehicles.

The size of the population and the economy has a significant impact on urban transportation systems. As a result, the stock flow diagram of the population and economy is constructed in this study as it is seen in the figure above. As a general rule, economic growth can pull more people to dwell in this city; hence it is tied to population growth. Addis Ababa’s population will continue to grow through migration as a result of the high demand for cheaper labor and cities' generally has higher salaries as compared to rural areas. In the model, the population is represented as the sum of natural increase and net immigration. GDP and carbon emissions both have an impact on migration volume.

Per capita GDP is a crucial economic indicator for assessing the level of regional development since it connects the population and economy sub-models with vehicle demand. Residents will think about purchasing private cars as the per capita GDP increases in order to facilitate travel or other personal hobbies.

3.2.5.2. Vehicle Stock model

The number of the vehicles sub-model is the focus of this study because it is the core interest of the proposed model and related to all other sub-models. The increase in the number of vehicles probably results from the development of the economy and transportation demand which resulted from population pressure. Environmental pollution caused by excessive use of vehicles will react to economic development and the total number of vehicles.

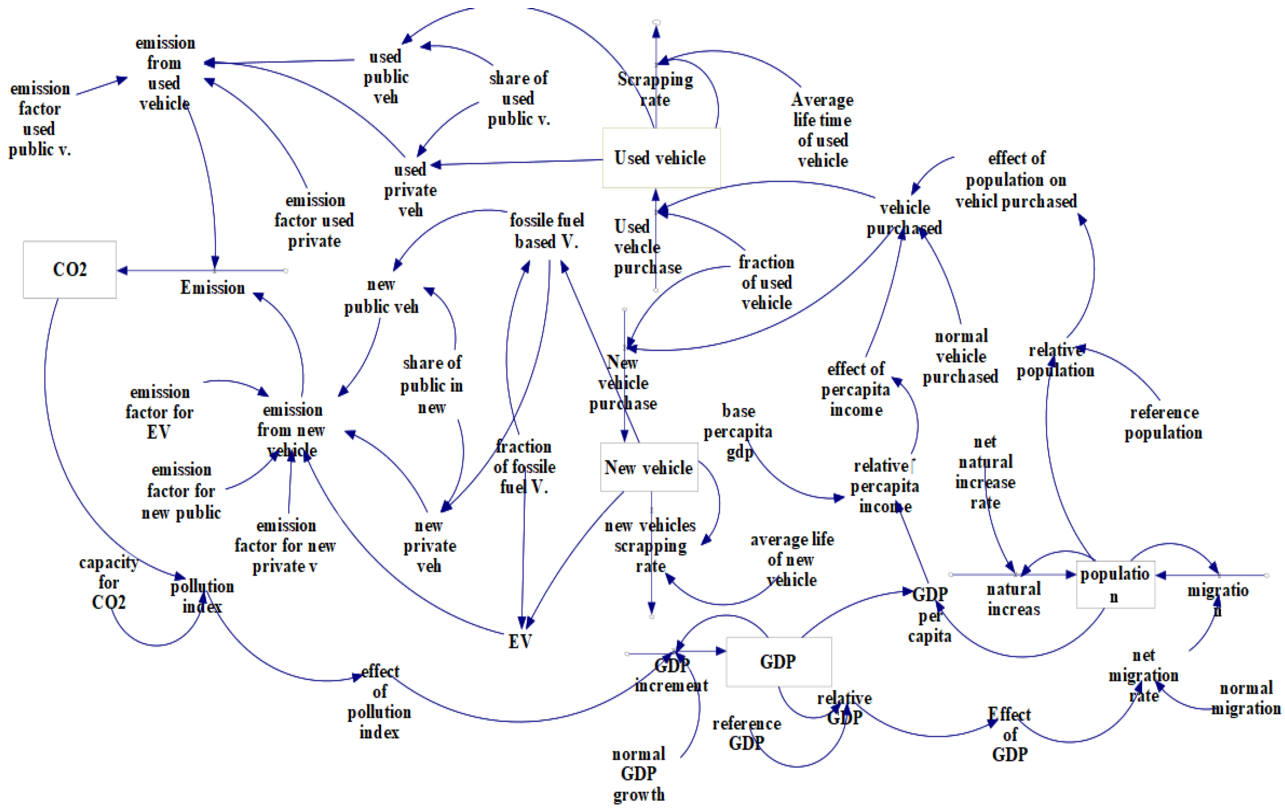


Figure 4: Stock_flow diagram for the transport sector

The total number of cars and the total emissions produced by each vehicle are multiplied to produce the emission rate. The total number of vehicles is calculated by adding the first registrations of new vehicles and used imported vehicles.

The demand for vehicle purchases is determined by economic growth and population pressure and the market share determines the stock of new and used vehicles. The average lifespan of new cars determines how much of this stock is reduced through scrapping. Used imports also grow in the same way, with the stock falling due to scrapping, which is defined by the average lifetime of used cars, and the demand being multiplied by the market share of used imports. Total emissions per vehicle depend on both newly registered vehicles and used vehicles, multiplied by the average emission of both stocks.

3.3. Data Description

3.3.1. Data source and types

For this study, data from several sources was collected. Addis Ababa transport bureau, and Addis Ababa city government environmental protection authority were the main sources of vehicle and emission-related data. World Bank and ESS were used to retrieve data for population and regional GDP and related data. Because of the nature of the variables used, the data used in this study was secondary.

3.3.2. Description of relevant variables and measurements

Before starting the simulation for the stock-flow model, the equations must be specified and the variables must be parameterized. The values of the model's variables and parameters are listed in the table below, along with details on the unit of measurement and equation.

Table 1: Description of variables and measurement

Variable	Type	equation	value	unit	Source
Population	Stock	NTEG (migration+natural increase, 3e+06)	3million	person	CSA(2014)
Co2	stock	INTEG (Emission, 900000)	900000	ton co2	FAO (2020b)
Emission	flow	emission from new vehicle+ emission from used		ton/Year	
GDP	Stock	INTEG (GDP increment,8e+09)		$	WB (2020)
Percapita GDP	Auxiliary	GDP/population		$/person	
GDP increment	flow	GDP*normal GDP growth rate*effect of pollution index		$/year	WB (2020)
Migration	flow	population*net migration rate		person	CSA (2021)
net natural increase rate	Auxiliary		0.015	1/Year	UN HABITAT. (2017).
netmigration rate	Auxiliary	Effect of GDP*normal migration		1/Year	CSA (2021)
Natural increase	flow	net natural increase rate*population		person	CSA (2021)
New vehicle	stock	INTEG (New vehicle purchase-new vehicles scrapping rate,)	30000	vehicle	AACRTBureau. (2020).
Used vehicle	stock	INTEG (Used vehcle purchase-Scrapping rate)	100000	vehicle	AACRTBureau. (2020).

Used vehicle purchase	flow	fraction of used vehicle*vehicle purchased		vehicle/Year	
vehicle purchased	flow	normal vehicle purchased*effect of population on vehicle purchased*effect of percapita income		vehicle/Year	Transpot bearue
Average emission per vehicle	Auxiliary			Vehicle/year	
Scrapping rate	flow	vehicle/Average life time of used vehicle		vehicle/Year	
New vehicles purchase	flow	(1-fraction of used vehicle)*vehicle purchased		Vehicle/year	
average life of new vehicle	Auxiliary		40		Kebede, (2022b).
base percapita gdp	Auxiliary		1000	dollar/person	WB (2020)
emission factor for new private v	Auxiliary		4.5	ton/vehicle/Year	Teshome.(2023).
emission factor for new public	Auxiliary		7	ton/vehicle/Year	
emission factor used private	Auxiliary		7	ton/vehicle/Year	Force, (2018).
emission factor used public v	Auxiliary		14	ton/vehicle/Year	Force, (2018).
emission from new vehicle	Auxiliary	(emission factor for new private v*new private veh)+(emission factor for new public*new public veh)		ton/Year	
emission from used vehicle	Auxiliary	(emission factor used private*used private veh)+("emission factor used public v*used public veh)		ton/Year	
fraction of used vehicle	Auxiliary		0.4	Dmn	AACRTBureau. (2020).
Migration	flow	population*net migration rate		person/Year	

3.3.3. Definition of variables

Used vehicle: A used vehicle refers to a previously owned or pre-owned vehicle that has been sold or traded in for another vehicle. It can include vehicles that have been previously registered and driven by one or more owners and are also considered to be of an older model or year. Used vehicles are often sold at a lower price than new vehicles and may have some wear and tear, mileage, and history of repairs or accidents.

New vehicle: Typically refers to a motorized vehicle that has not been previously owned or used by anyone else before. It may be purchased directly from a dealership or manufacturer and comes with a full warranty and all the latest features and technology

Co2 stock: greenhouse gas in the atmosphere that is attributed by the major ruminants directly through the burning of fossil fuel from vehicles. It is measured in terms of the tons of CO_2 equivalent emission level. This is mainly affected by the emission growth due to the emission contributed by used vehicle stock and new vehicle stock.

Private vehicle: Private vehicle refers to a mode of transportation that is owned and operated by an individual or a private entity for personal use. Examples of private vehicles include cars, motorcycles, bicycles, and boats. These vehicles are typically used for commuting, running errands, leisure activities, and personal travel. Private vehicles are distinct from public transportation, which is operated by government agencies or private companies for the general public.

Public vehicles: public vehicles are modes of transportation that are owned and operated by government agencies or private companies for the general public. Public transportation is designed to provide affordable and accessible transportation options for everyone, regardless of their income or physical abilities. Public vehicles are regulated by government agencies to ensure safety, reliability, and accessibility for all passengers.

3.4. Methods of Analysis

System Dynamics is a methodology that helps to understand the behavior of complex systems over time. This study will use system dynamics to analyze and simulate the behavior of systems that change over time. After creating a model of the system using causal loop diagrams (CLDs) and stock-and-flow diagrams, the model is then simulated and analyzed using Vensim software to understand how the system behaves over time and search for the leverage point. The simulation is illustrated using graphs or charts that show how the variables in the system change over time.

3.5. Possible scenarios

Scenario planning and modeling can be used to explore different pathways towards a low-carbon and climate-friendly transport sector using a system dynamics approach. Some possible scenario planning and modeling approaches for this thesis are proposed below:

1. Baseline scenario: This scenario would provide a reference point for the current state of the transport sector and its carbon emissions. It would consider factors such as population growth, economic development, level of fuel consumption and carbon emission, transport demand and supply, and use these to project future emissions levels without any additional policy interventions.

2. Technology-driven scenarios: These scenarios would explore the potential impact of different technological advancements in the transport sector, such as electric vehicles and biofuels.

3. Policy-driven scenarios: These scenarios would focus on the impact of different policy interventions to reduce carbon emissions in the transport sector, such as fuel taxes, carbon pricing, incentives for low-carbon technologies and investment in public transit, and a limit on the age of cars imported.

4. Combined scenarios: These scenarios would combine different technology and policy interventions to explore the potential interactions and trade-offs between them. For example, a scenario could explore the impact of a policy package that includes a carbon price, incentives for electric vehicles, and investment in public transit.

Chapter Four

Result and Discussion

4.1.Descriptive analysis

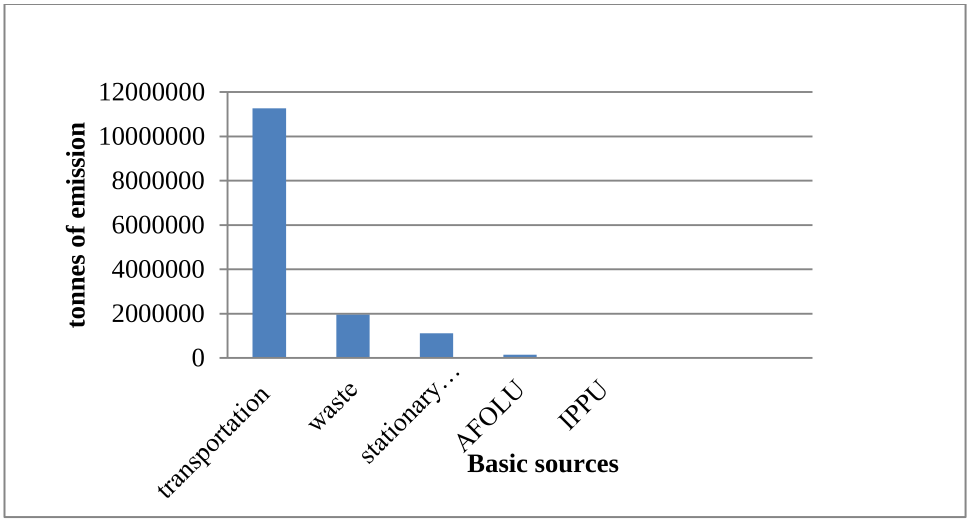
4.1.1. Carbon Emission Trend in Addis Ababa City

Greenhouse Gases (GHG) emissions must decrease globally to keep within a "well below 2 degrees" climate change trajectory, according to the Paris Agreement and SDG13 on Climate Action. Cities are crucial to achieving this because they are thought to be responsible for 60 to 80% of the world's GHG emissions(Fuso Nerini, 2019). One of the eleven African cities doing bravely to fulfill the objectives of the Paris Accord is Addis Ababa. The city is currently working to cut greenhouse gas emissions and harden the city against climate change's consequences. To make the city carbon neutral and climate change adaptable, all sectors and stakeholders must work together.

Adopted from the national CRGE, the Addis Ababa City Administration has also stressed the achievement a vision of middle-income status by 2025 in a climate-resilient green economy and net carbon zero economic growth by 2030, indicating a 64% reduction against the BAU scenario(ECRGE, 2011). In 2012 Addis Ababa GHG inventory was conducted on the basis of activities taking place within the city, assessing GHG emissions that occur inside the city boundary as well as outside the city boundary. The inventories identified sources of emissions and serve as a baseline for setting emission reduction goals and future benchmarking.

The city's climate action goals and targets have demonstrated that it is committed to achieve its climate-resilient and net zero emission reduction targets by 2030. A quarter of Ethiopia's urban population resides in Addis Ababa, and according to the city's GHG inventory report of 2012, the city has emitted 4.89 Mt CO_2e in total and per capita emission of 1.6 tCO_2e in 2012(Addis Ababa City Administration, 2012; Haji, 2020). In the report it is also indicated that around 47% of the city's total emissions are attributed to transportation, followed by stationary energy (35%), waste (13%), and agricultural, forestry, and other land use (AFOLU) (5%), according to a breakdown of these emissions by subsector.

Figure 5: Level of CO2 emission by sub sectors in 2016 in Addis Ababa

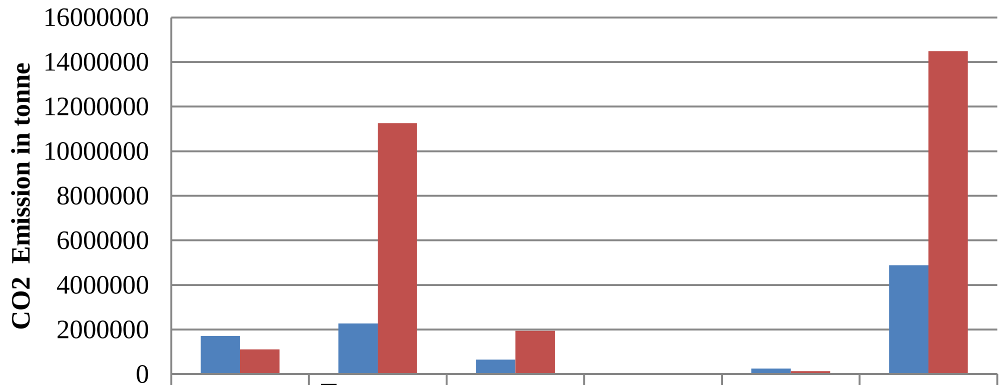


Source: Addis Ababa city emission inventory report

The city produced 14.48 million tonnes of CO_2e in total in 2016, according to the city's second round of the GHG inventory. The city's per-person emissions were found to be 4.3 tCO_2e. The breakdown of the city's total emissions by sub sectors indicates that transport sector has the lions share accounting 78%, waste (13%), stationary energy (8%), and agricultural, forestry, and other land use (AFOLU), which contributes 1%(Haji, 2020).

Compared to the level emission in 2012, the overall GHG emission in the city has risen significantly during 2016 and continues to rise till now as it is summarized in Figure 3 below. Next to transport sector, the waste industry, which accounts for 13% of total emissions, and the stationary energy sector, which accounts for 8% of total emissions, was found to be the second and third greatest emitters next to transportation. About three times increase in total GHG emission in AA City is observed in 2016 the inventory year compared to the first emissions inventory created in 2012.

Figure 6: Comparison between 2012 and 2016 emission inventory in Addis Ababa



	Energy	Transportation	Waste	IPPU	AFOLU	Total
2012	1710586	2273138	647898	10514	246541	4888677
2016	1116195	11263787	1946389	11434	141327	14479132

Source: Addis Ababa city emission inventory report

In figure 6 above, it is observed that transportation emission has increased by almost 9 MtCO2e. The increase in fuel consumption coupled with the presence of old vehicles, has been blamed for the significant increase in emission level in the sector. Due to a decrease in the amount of waste generated and sent to landfills and an increase in composting, emissions from waste are approximately 1.3 MtCO2e higher in 2016 than it was in 2012. Emission from the stationary energy has shown a decline approximately by 594,391 tCO2e through improvements in generation efficiency and increase in electricity consumption. In addition, emissions from AFOLU are approximately 105,214 tCO2e lower in 2016 than in 2012 as a result of a decrease in the overall quantity of cattle and little fertilizer application(Haji, 2020) This indicates that the Green House Gas emissions of the city in an increasing trend mainly because of the transport sector.

4.2. Model Validation result

The validation results for the model, which must demonstrate that the model is suitable for policy implementation and testing, must be presented before the entire creation of the model is complete. To put it another way, a model must be valid and accurate about the relevant literature and historical data before it can be utilized for prediction. In this study, structural and behavioral validations are considered.

4.2.1. Structural Validation

Model structure tests help us to assess the structure and parameters of the model without studying the relationships between structure and the resulting behavior. Various tests can be carried out to assess the structure of a model. For this study, structure, and parameter verification tests, dimensional consistency, and extreme condition test are carried out to build confidence in the structure.

4.2.1.1.Structural verification test

This test is all about checking whether the model is a sufficient representation of the real-life situation being represented. This test compares the structure of the model to the structure of a real system.

It is safe to say that this model incorporates all of the essential factors that affect the modeled system in reality. The model's causal-loop diagram demonstrates that it has feedback loops that have an impact on the reference mode. Additionally, the produced stock and flow diagram was created using variable relations and formulas that function clearly on VENSIM. Because of this, the model also passes the structural verification test.

4.2.1.2.Parameter Verification Test

This test evaluates constant parameters against the knowledge of a real system. The parameter verification test is passed since the model parameters were obtained from trustworthy sources.

4.2.1.3.Dimensional Consistency Test

One method of testing the validity of a model is to look at the consistency of the units used in the model's construction. The model's units are constant throughout and accurately reflect the variables they are meant to represent. This test is checked through the software.

4.2.1.4. Extreme Condition Test

Extreme condition testing is one of the model structure tests used in system dynamics. It is a technique that helps in evaluating the model's response to extreme parameter values, shocks, and policies by contrasting the behavior generated by the model with the behavior that the real system would exhibit under the same extreme circumstances. If we make a complete ban on used vehicles, the initial stock of used vehicle will continue with an outflow of scrapping rate.

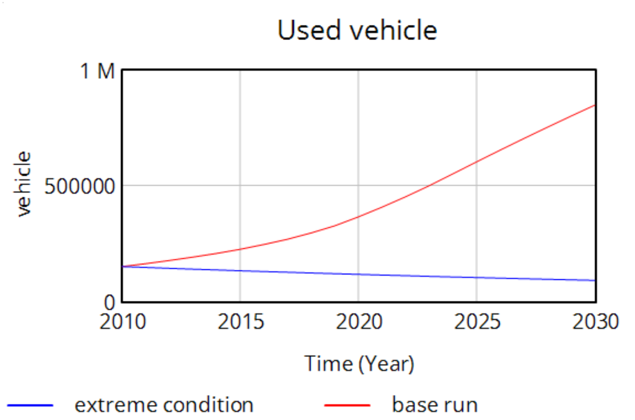


Figure 7: Extreme condition test

4.2.2. Model Behavior Test

Testing behaviors generated by the structure of a model help us evaluate the adequacy of the structure. In this section, the model simulation behavior test and sensitivity analysis are considered.

4.2.2.1. Model Simulation Behavior Test

The structural validation procedure verifies the model's development and functionality, but it does not ascertain if the model behaves in a manner consistent with the reference mode's historical data. Model validation test in system dynamics is the process of comparing the behavior of a simulation model to real-world data or observations to determine the accuracy and reliability of the model. This involves testing the model against historical data, experimental results, or other sources of information to ensure that it accurately represents the behavior of the real system(Barlas, 1996; Ercan, 2019). Model validation is an important step in the modeling process because it helps to establish confidence in the model's ability to predict future behavior and inform decision-making. If a model fails validation tests, it may need to be revised or improved before it can be used for practical purposes.

The behavioral reproduction test results with regard to used vehicle stock and new vehicle stock are shown in Figure 7 where the simulation was run from the year 2010 to the year 2022. Addis Ababa Transport Bureau Statistics (2023) provided accurate information for the share and stock of used and new vehicles. It is evident from the figure that the simulation behavior of the model captures the behavior of the historical data.

The historical data for new and used vehicles was collected from the Addis Ababa transport bureau and regional GDP and population data for the city was retrieved from World Bank and ESS data center. The Addis Ababa city emission inventory reports in 2012 and 2016 are the basis for the transportation emission data.

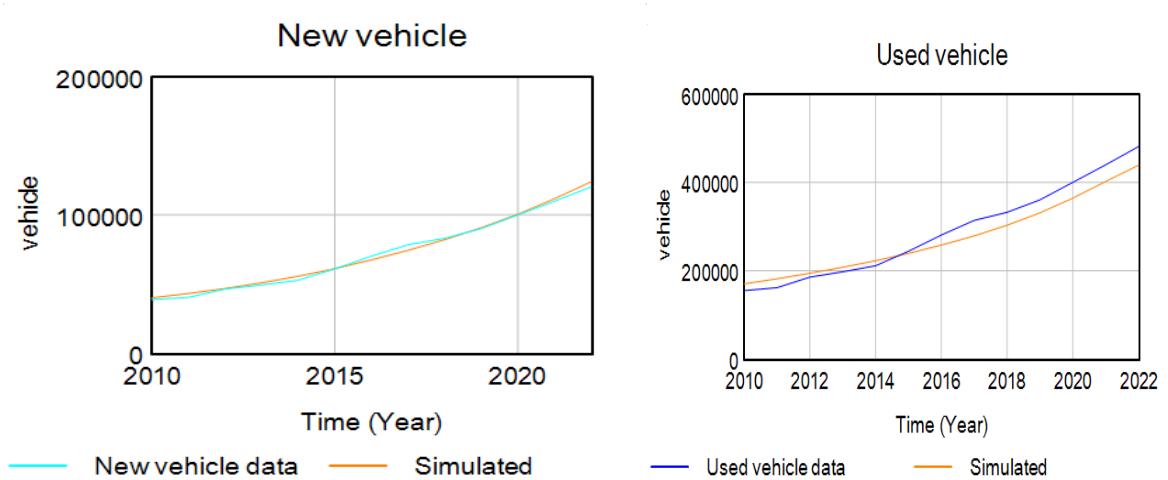


Figure 8(a): Behavioral reproduction of the new and used vehicle

Figure 8 shows the behavioral reproduction test results for new and used vehicles. The simulated value fits the actual data and the model well captured the behavior of vehicle stock. Age and manufacturing year are key components of the model, as it generates the energy consumption and CO2 emissions previously discussed concerning the modeled system.

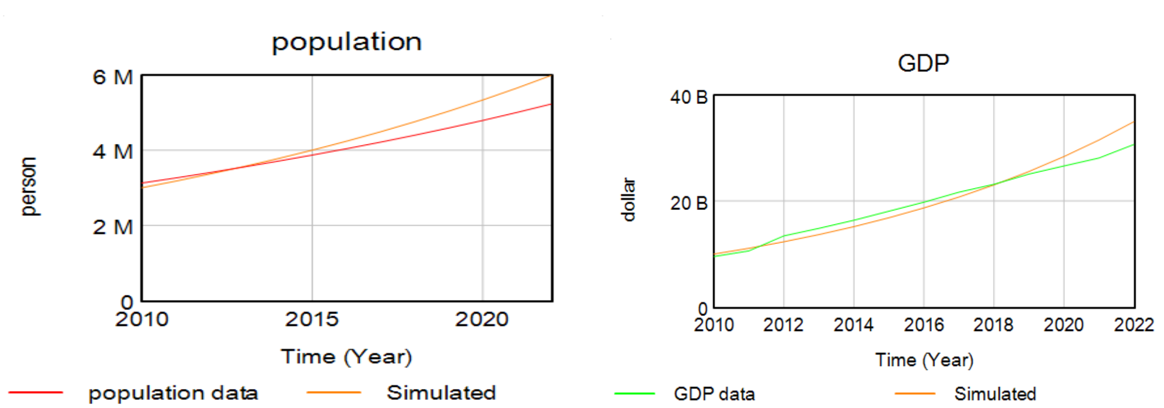


Figure 8(b) : Behavioral reproduction population and GDP

The findings in Figure 9(b) make it very evident that the simulated model compares well. The time series data indicates that taken at face value, the model passes the visual fit test with reasonable results. It suggests that the chosen variables' simulated behavior closely matches the data and the model has well absorbed the behavior of the variable.

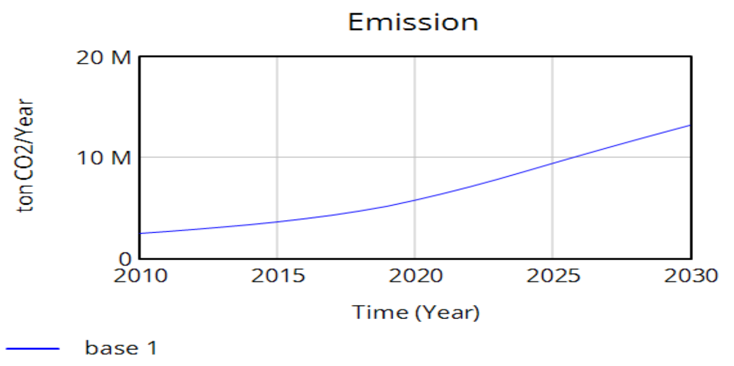


Figure 8(c): Behavioral reproduction for carbon emission

Figure 9(c) above is used to see the behavioral correlation for annual transportation-related CO2 emissions between the simulated findings and the real data. Because of the difficulty of data, two years of real data are used to validate the model. Data retrieved from the Addis Ababa city carbon emission inventory report shows that the 2012 and 2016 yearly emission was around 2 million and 6.6 million tons of CO2 carbon equivalence. Although the simulated result above didn't exactly fit with the two years of real data, it is visible that it has captured the behavior of carbon emission.

Sensitivity analysis is used in system dynamics to determine whether or not the model is sensitive to certain factors. Particularly, parameter values that are calculated based on statistical data and professional understanding, or parameter values coming from previous studies, are the subjects of sensitivity analysis. The purpose of the sensitivity test is to offer additional, insightful information about the model and its many parameters. This offers information on the model's leverage points and where policy adjustments are necessary. Some of the important model variables underwent sensitivity analysis to determine how sensitive they are to the model's behavior.

In this model, to observe the simulated behavior, the sensitivity analysis was carried out by adjusting the parameter value by 50% below or above the base case run value.

a) Fraction of used vehicle

The fraction of used vehicles has a causal relationship with new and used vehicles and hence with the total CO2 emission level. Hence it is a crucial variable in this model. A lower share of used vehicles leads to a decrease in emission levels as used vehicles have the largest emission factor. On the other hand, the increase in share of used vehicles causes the opposite effect on the other variables. Used cars have failed to meet the safety and environmental standards in the country they were exported from.

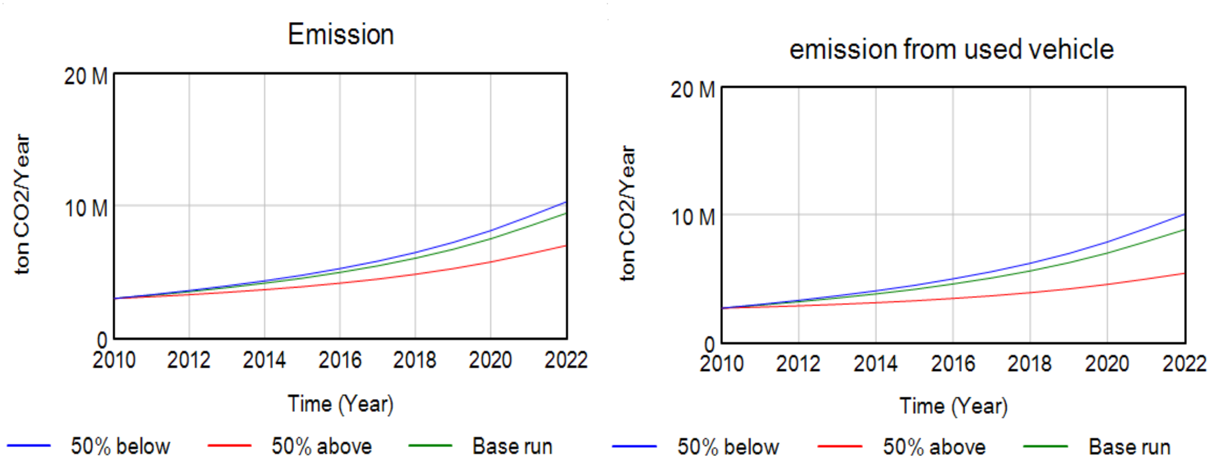


Figure 9(a): Sensitivity analysis of carbon emission to change the fraction of used vehicle

b) Emission standard

The following figure shows the results of the sensitivity analysis of the parameter emission standard. The model considers sensitivity analysis with 50% of the parameter below or above the base case value and depicted in the simulated behavior of carbon emission.

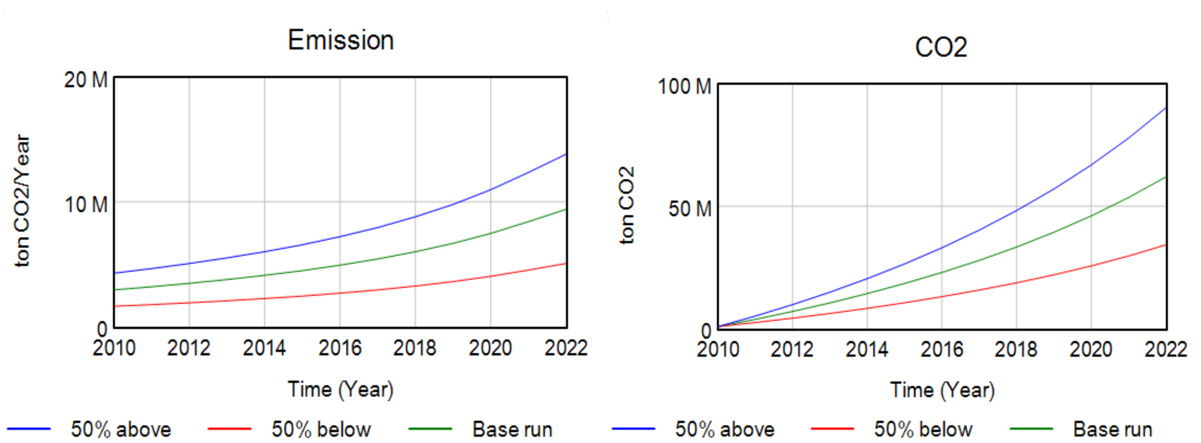


Figure 10: Sensitivity analysis of carbon emission to change in emission standared

4.3. Policy Scenario Analysis

Policy scenario is a typical activity in system dynamic modeling for evaluating future outcomes and simulating alternative approaches. This study aims to simulate how the sector interacts with the environment. The study also intends to uncover potential policy cases that lower the sector's carbon footprint. The scenarios include banning used vehicle imports, set emission standard, energy shift, and combining all policy scenarios. The policy possibilities are put into effect after 2022, and the simulation period included the years between 2010 and 2030.

4.3.1. Base run

The model's base run, which spans the years up to 2030 and represents business-as-usual results in the outcomes is the simulation result of the model, with present policies in place and exogenous variables assuring that current progress continues in the future. The base run of a few selected variables, including yearly emission, vehicle stock, population, and GDP are shown in Figure 9 below.

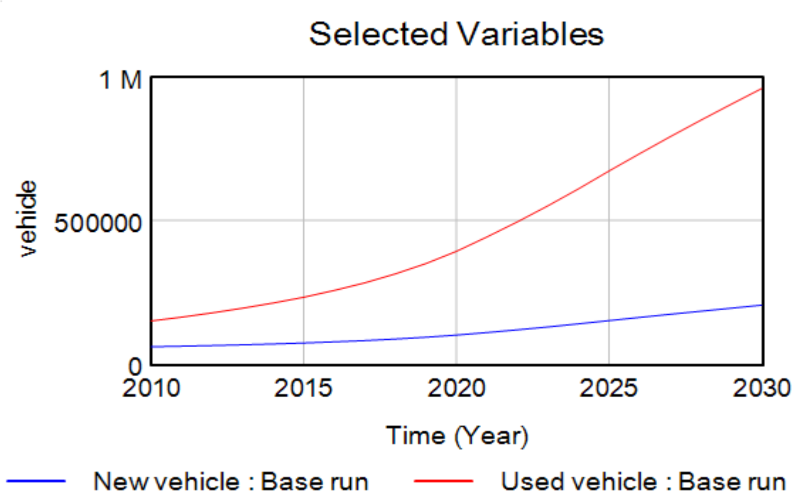


Figure 11(a): The simulated value of used and new vehicles under base run

As is seen from the Figure 11(a) above, the number of both new and used vehicles is increasing over time. The number of used vehicles is forecasted to reach nearly one million by 2030. This could be attributed to the increase in economic growth and population pressure.

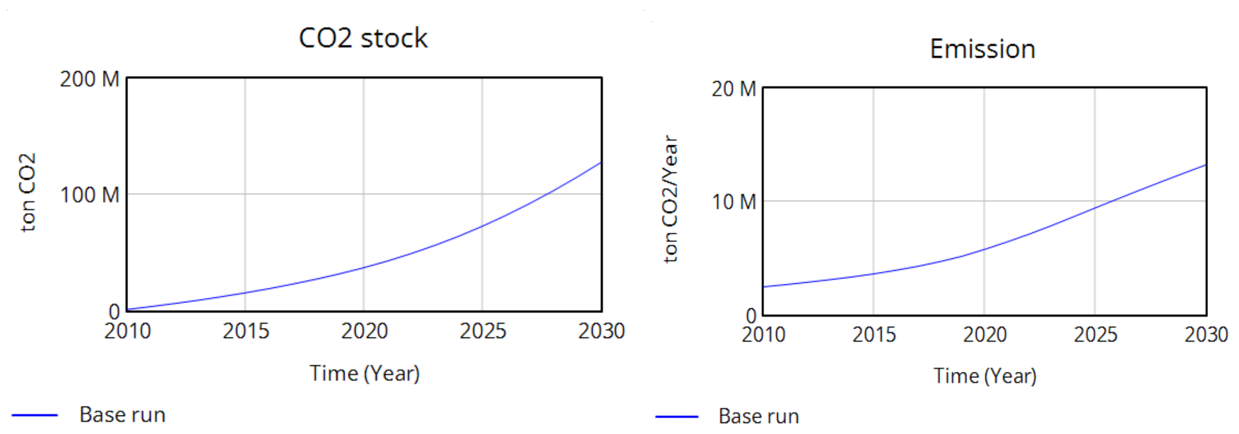


Figure 12: The Simulated value of carbon emission and accumulated carbon stock from the transport sector

The concentration of greenhouse gases has increased, and the sector's emissions are estimated to reach around 13 million tons by 2030. The reason for this includes, among other things, an increase in the number of used vehicles, the absence of emission standards, and pure dependency on fossil fuel. Population pressure and economic growth play their role in increasing transport demand and vehicle ownership.

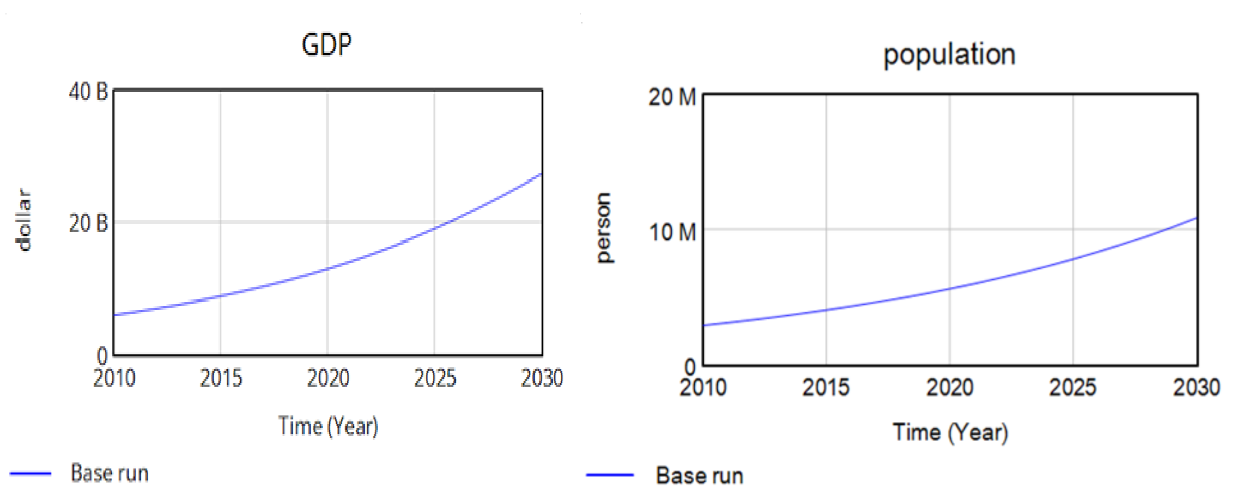


Figure 13 : The Simulated value of population and regional GDP

The population of the city which is mainly migration driven, will rise to above 10 million by 2030. This population pressure with relatively better per-capita income will have significant demand on transport demand and vehicle ownership.

Scenario1. Ban used vehicles

Used vehicles have a significant impact on Carbon emissions. Compared to newer vehicles that meet the current emissions requirements, used vehicles typically have lower fuel efficiency and higher emissions. This is due to the possibility that older vehicles lack advanced technologies and emission control systems which are currently installed in new vehicles. Developing counties like Ethiopia are being dumped with unsafe, highly polluting cars by rich nations. According to OECD and Rozwoju (2001), 80% of used cars have failed to the safety and environmental standards of the nation from which they were imported. Like many other African countries, Ethiopia lacks a solid grading standard when it comes to approving imported vehicles.

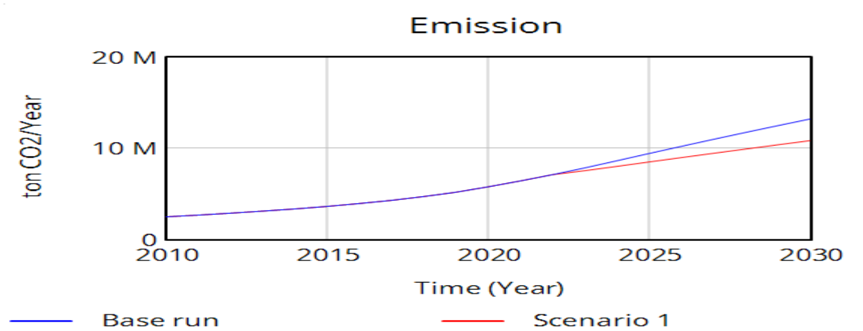


Figure 14: Carbon emission under scenario 1

In this policy scenario, reducing used vehicle consumption by imposing bans on the import of vehicles is considered to see emission reduction potential of the transport sector.

Scenario 2: Energy shift

To mitigate emission from the transport sector, an energy shift is necessary, which involves transitioning transport away from fossil fuels to cleaner and more sustainable energy sources. This shift can include a variety of strategies, such as promoting the use of electric or hybrid vehicles, developing more efficient transport systems, improving public transport infrastructure, and encouraging the use of sustainable fuels like biofuels or hydrogen. Additionally, technology such as vehicle-to-grid systems, where electric vehicles can contribute to the grid's energy needs, can also play a role in reducing emissions. Beyond just the transport sector, an energy shift throughout all sectors is critical in addressing climate change. However, given the significant role of transport in emissions, making this shift in the sector is especially crucial to achieving global mitigation goals.

Public transport is an important factor in shifting energy in the transport sector. By increasing the share of public transport, we can reduce the number of cars on the road, which will ultimately reduce carbon emissions. Public transport produces fewer emissions per passenger than private cars, and it can also reduce traffic congestion, which can lead to further reductions in emissions.

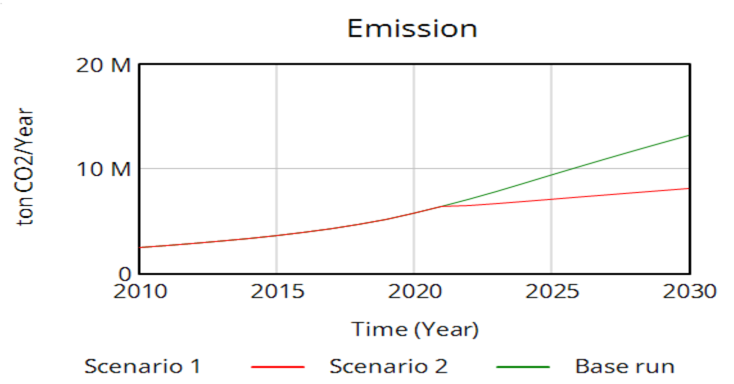


Figure 13: Carbon emission under scenario 2

In this policy scenario, increasing public transport share and shifting to electric vehicles is considered to see the emission reduction potential of the transport sector.

Scenario 3: Applying emission standard

Emission standards for vehicles in the transport sector are a crucial way to mitigate carbon emissions. By implementing strict emission standards, governments can reduce the amount of greenhouse gases being emitted by these vehicles. There are several ways to implement emission standards for vehicles. One way is through vehicle efficiency standards. This can be done by setting a minimum fuel efficiency standard for cars, trucks, and buses. Vehicles that do not meet the standard will not be allowed to be sold or imported into the country. Another way to implement emission standards is through tailpipe emissions standards. This can be done by setting limits on the amount of pollutants that can be emitted from a vehicle's exhaust. This can be achieved through the use of emission control technologies, such as catalytic converters. Implementing emission standards for vehicles in the transport sector is essential for mitigating carbon emissions. By reducing the amount of greenhouse gases being emitted by vehicles, we can take significant steps toward combating climate change.

Scenario 4: Applying all scenarios simultaneously

In this policy scenario, all policy options are put into practice simultaneously to see the effect in reducing carbon emission and other variables.

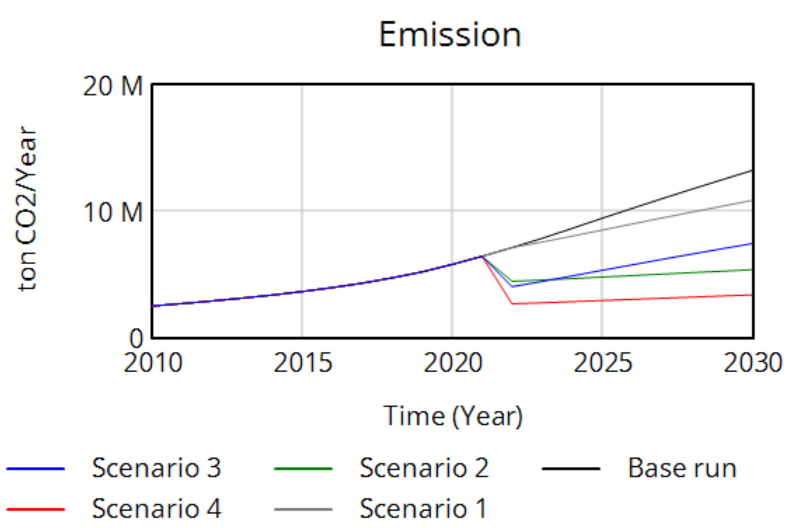


Figure 15: Yearly Carbon emission under different policy scenarios

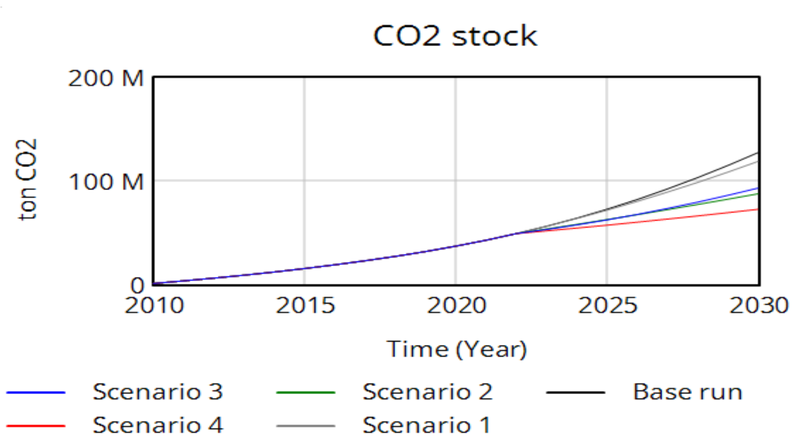


Figure 16: Carbon emission under different policy scenarios

As can be seen from the Figure 1**6** above, scenario 2 and scenario 3 have resulted in the highest decrease in carbon emission from the transport sector in reference to the base run. Scenario 2 considers energy shift from the usual fossil fuel and scenario 3 considers applying emission standards for vehicles operating in the city.

scenario	emission in 2030	percentage change from base scenario
scenario 4	3.3312	-74.717285
Scenario 3	7.39559	-43.869898
Scenario 2	5.32197	-59.607993
Scenario 1	10.8062	-17.984487
Base run	13.1758	

Table 2: Comparison of policy scenarios from the base

The table above table shows the effect of different policy scenarios on emission in reference to the base run. As it is seen clearly applying all policy scenarios could result in a significant reduction in yearly emission from the transport sector. With a business-as-usual scenario, emission from the sector will rise to 13 million ton carbon equivalence by 2030. But, if we activate the three scenarios simultaneously, emission will decrease by about 72% to 3.3 million tons of carbon equivalence. Energy shift (away from the usual fossil fuel) alone could reduce emission by 59% compared to the business-as-usual scenario. The proportion of new vehicles to used vehicles currently is 20:80 indicating that the city is flooded with used vehicles. To ban the import of used vehicles and making the proportion 80:20, vehicle emissions could decrease by 17% by 2030.

4.4. Discussion of result

The transport sector contributes significantly to greenhouse gas emissions, which is an important contributor to climate change. Therefore, there is a need for action to be taken to transition towards a low-carbon and efficient transport system. This thesis aims to explore the potential pathways towards achieving a low-carbon and climate-friendly transport sector through the implementation of four potential policy scenarios: banning used vehicle imports, setting emission standards, and shifting towards low- or no-carbon energy sources and finally simultaneous activation of the three.

The total number of vehicles in Addis Ababa increase exponentially between 2010 and 2030. The main reason for this increase is the increase of new registrations, which is developing in parallel with the projected population growth, along with increase in percapita income. This leads to a strong increase in emissions of road transportation by 2030.

One of the most effective measures is the ban on used vehicle import, which can significantly reduce the number of high-emission vehicles on the road. This approach has been successfully implemented in several countries, and can be adapted to suit local conditions and needs. In Africa, four countries (including South Africa, Egypt, Sudan and Seychelles) have completely banned used vehicle imports and 10 countries have banned the import of vehicles over five years old(Ayompe et al., 2021). From Table 2 above we can observe that shifting the proportion of used and new vehicles to 20:80 will result in 17% reduction in carbon emission by 2030.

Another important strategy is the setting of emission standards for new vehicles. This can encourage manufacturers to produce and importers to import more fuel-efficient and low-emission vehicles, and can also provide consumers with greater choice in terms of environmentally-friendly options. Governments can play a key role in setting and enforcing these standards, and can also provide incentives for manufacturers to comply with them.

Finally, the shift towards renewable energy sources such as electric or hydrogen-powered vehicles can also make a significant contribution to reducing carbon emissions from the transport sector. This will require significant investment in infrastructure and technology, as well as changes in consumer behavior and attitudes towards alternative energy sources. CO2 emissions in East Africa are growing exponentially at 6.5% per year, but the process of energy clean-up is slow with little emission reduction(Sun et al., 2022). According to Sun et al. (2022), overall the CO_2 emissions in East Africa show a 'two-stage exponential growth' pattern and that is mainly because in terms of the energy mix, these countries are the lowest.

Overall, the findings of this study suggest that a combination of these strategies is needed to achieve a low carbon and climate-friendly transport sector. While each approach has its strengths and limitations, together they offer a comprehensive and effective path towards a more sustainable future. Further research is needed to explore the potential impacts and challenges associated with these strategies, and to identify additional measures that can be taken to promote sustainable transportation.

Chapter five

Conclusion and policy implications

5.1. Conclusion

Every year, the number of vehicles on the roads rises as Addis Ababa's economy and population expand and as residents make more daily travel. Furthermore, the transportation industry not only completely relies on fossil fuels but the vehicles operating in the city are used and are an average of 20 years old. Because of all these pressures, the transport sector is the first and giant contributor to GHG emission in the city.

System dynamics modeling that captures the sector's dynamics and complexity has been applied to the transport industry and the environment, in particular the emission of greenhouse gases. The model has also been used to analyze and look at different policy scenario prospects.

In conclusion, the study using a system dynamics model highlights that a path to a low carbon and climate-friendly transport sector is achievable by implementing a range of policies. This includes the ban on used vehicle import, setting emission standards, and shifting energy sources towards cleaner alternatives. The model indicates that these policies can result in significant reductions in greenhouse gas emissions from the transport sector while promoting technology innovation and investment in clean transportation. However, effective policy implementation will require sustained political will, engaging stakeholders and consensus-building around the identified policies. Overall, this study provides valuable insights for policymakers considering options for mitigating climate change impacts and transitioning to a low-carbon economy in the transport sector.

5.2. Policy implication

The findings of the thesis entitled "A Path to Low Carbon and Climate Friendly Transport Sector Using System Dynamics Model" suggest that a combination of policies including a ban on used vehicle imports, setting emission standards, and shifting to cleaner energy sources is necessary to achieve a low carbon and climate-friendly transport sector. Therefore, policymakers should consider implementing these policies in order to reduce greenhouse gas emissions from the transport sector and mitigate the impacts of climate change. Additionally, incentives for the adoption of electric vehicles and other low-carbon transportation options should be considered to further promote sustainable transportation.

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Appendex A

Variables, equation value and unit

1. average life of new vehicle= 60
   Units: Year
2. Average life time of used vehicle= 40
   Units: Year
3. base percapita gdp=1500
   Units: dollar/person
4. capacity for CO2=5e+07
   Units: ton CO2
5. CO2 stock= INTEG (Emission,900000)
   Units: ton CO2
6. Effect of GDP = WITH LOOKUP (relative GDP, ([(0,0)-(10,10)],(1,1),(1.22606,1.10795),(1.5,1.2),(1.8,1.24),(2.4,1.4),(2.78159,1.41477),(2.88385,1.47727)))
   Units: Dmnl
7. effect of percapita income= WITH LOOKUP (relative percapita income, ([(0,0)-(10,10)],(1,1),(1.13307,1.79545),(1.29002,2.42045),(1.50839,2.64773),(1.68581,2.82955),(1.92124,2.93182),(2.08501,2.98864),(2.20102,2.98864))
   Units: Dmnl
8. effect of pollution index= WITH LOOKUP (pollution index, ([(0,0)-(10,10)],(1,1),(1.13307,0.98864),(1.29002,0.98864),(1.51908,0.96875),(1.71925,0.957031),(1.89228,0.933594),(2.04156,0.917969),(2.18744,0.894531)))
   Units: Dmnl
9. effect of population on vehicl purchased = WITH LOOKUP (relative population, ([(0,0)-(10,10)],(1,1),(1.18,1.2),(1.29,1.3),(1.42578,1.6),(1.51501,1.7),(1.61445,2),(1.75467,2.3),(1.9,2.9),(2.5,3.8)))
   Units: 1
10. Emission=emission from new vehicle+emission from used vehicle
    Units: ton CO2/Year
11. emission factor for EV=1e-05
    Units: ton CO2/vehicle/Year
12. emission factor for new private v= 5
    Units: ton CO2/vehicle/Year
13. emission factor for new public= 12
    Units: ton CO2/vehicle/Year
14. emission factor used private= 8
    Units: ton CO2/vehicle/Year
15. "emission factor used public v."=22
    Units: ton CO2/vehicle/Year
16. emission from new vehicle=

(emission factor for new private v*new private veh)+(emission factor for new public *new public veh)+(EV*emission factor for EV)

Units: ton CO2/Year

17. emission from used vehicle=
(emission factor used private*used private veh)+("emission factor used public v." *used public veh)
Units: ton CO2/Year
18. EV = (1-"fraction of fossile fuel V.")*New vehicle
Units: vehicle
19. "fossile fuel based V."=New vehicle*"fraction of fossile fuel V."
Units: vehicle
20. fraction of fossile fuel V. = 0.9999
Units: Dmnl
21. fraction of used vehicle=0.8
Units: Dmnl
22. GDP= INTEG (GDP increment,6e+09)
Units: dollar
23. GDP increment=GDP*normal GDP growth rate*effect of pollution index
Units: dollar/Year
24. GDP per capita=GDP/population
Units: dollar/person
25. migration=population*net migration rate
Units: person/Year
26. natural increas=net natural increase rate*population
Units: person/Year
27. net migration rate=Effect of GDP*normal migration
Units: 1/Year
28. net natural increase rate= 0.015
Units: 1/Year
29. new private veh="fossile fuel based V."*share of public in new
Units: vehicle
30. new public veh= "fossile fuel based V."*share of public in new
Units: vehicle
31. New vehicle= INTEG (New vehicle purchase-new vehicles scrapping rate,60000)
Units: vehicle
32. New vehicle purchase=(1-fraction of used vehicle)*vehicle purchased
Units: vehicle/Year
33. new vehicles scrapping rate= New vehicle/average life of new vehicle
Units: vehicle/Year
34. normal GDP growth rate= 0.08
Units: 1/Year
35. normal migration=0.036
Units: 1/Year
36. normal vehicle purchased= 8000

Units: vehicle/Year

37. pollution index=CO2 stock/capacity for CO2
Units: Dmnl

38. population= INTEG (migration+natural increas, 3e+06)
Units: person

39. reference GDP= 1.5e+09
Units: dollar

40. reference population= 2.9e+06
Units: person

41. relative GDP=GDP/reference GDP
Units: Dmnl

42. relative population= population/reference population
Units: 1

43. relative percapita income=GDP per capita/base percapita gdp
Units: 1

44. Scrapping rate=Used vehicle/Average life time of used vehicle
Units: vehicle/Year

45. share of public in new=0.4
Units: Dmnl

46. "share of used public v."= 0.4
Units: Dmn

47. used private veh= (1-"share of used public v.")*Used vehicle
Units: vehicle

48. used public veh= Used vehicle*"share of used public v."
Units: vehicle

49. Used vehcle purchase=
fraction of used vehicle*vehicle purchased
Units: vehicle/Year

50. Used vehicle= INTEG (Used vehcle purchase-Scrapping rate,150000)
Units: vehicle

51. vehicle purchased=normal vehicle purchased*effect of population on vehicl purchased*effect of percapita income
Units: vehicle/Year