Evaluation of factors for adoption of alternative fuel-based vehicles

Varshini Venkatesh

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By: Varshini Venkatesh

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______________________________ Supervisor

Dr. Anjali Awasthi

Approved by ____

Dr. Farnoosh Naderkhani

Graduate Program Director

____________ 2025 ____

Dr. Mourad Debbabi

Dean of Gina Cody School of Engineering and Computer Science

ABSTRACT

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This thesis develops a system dynamics simulation model for evaluating five factors like customer awareness, government initiatives, cost of vehicles, cost of fuels, infrastructure developments to increase the adoption of alternative fuel vehicles like EV's, Biofuel vehicles and Hydrogen vehicles. This model also integrates other modes of sustainable transportation like bikes and public buses. This helps in providing insights about the vehicle adoption over time and the reduction of greenhouse gases from the transportation sector. System dynamic simulation technique is used in this study to evaluate these fuels. Three scenarios were modeled: A baseline scenario that follows the existing trends, Scenario 1, which prioritizes higher adoption of electric vehicles (EVs) and biofuel-powered vehicles, Scenario 2 prioritizes hydrogen fuel-based vehicles and improved biking culture. The simulation findings show that all scenarios achieve reductions in GHG emissions compared to the baseline, with Scenario 2 showing the lowest emissions because of the near-zero emissions features of hydrogen fuel-based vehicles and the advantages of enhanced bicycle transportation. It was found that cost had a huge impact in the growth of adoption of these vehicles and modes of transportation. A combination of technology developments, government initiatives that are supportive of the effort, and significant investment in infrastructure shaping customer perception is essential in reducing the overall GHG emissions which also aligns with Canada's net zero goals.

Keywords: Alternative fuel, system dynamic simulation, sustainable transportation, GHG emissions

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

When we discuss climate change, we refer to the continuous transition of weather patterns from tropical regions to the polar. This is a global hazard that has already begun to impact a diverse array of industries. In addition, the gradual decline of ecological systems has resulted in the loss of biological diversity, as the survival and existence of a significant number of species have been in peril due to the change in climate (Abbass et al., 2022). This is due to the temperature ranges that are considered to be desirable have fluctuated. An overwhelming body of scientific evidence suggests that human activities, in particular the combustion of fossil fuels such as coal, oil, and gas, are a contributor to the levels of atmospheric carbon dioxide and other greenhouse gases in the environment. This, in turn, contributes to the increase in the average temperature of the earth's surface. As a consequence of global warming, severe climatic changes are anticipated to occur, and many of these changes are expected to have a negative impact on human communities (Houghton, 2001). Anthropogenic climate change is projected to go on for a significant number of centuries, according to projections. When it involves climate change, everything we are accomplishing is putting ourselves in danger, and the consequences that could emerge from this could be disastrous (Karl & Trenberth, 2003). The usage of fossil fuels, which include coal, oil, and natural gas, is widespread and has historically been an essential element in the growth of both the economy and the industrial sector. As a consequence of this dependence, however, a variety of complex issues have arisen, including pollution, adverse impacts on health, and a weakening of the economy.

There is a limited amount of fossil fuels readily available on our planet. Additionally, conventional energy sources are considered to be contributors to the release of greenhouse gases. Alternative fuels and energy sources will need to be developed before the depletion of fossil fuels, which is inevitable. A significant amount of research is being conducted all over the world in order to find alternative fuels that have the potential to meet our energy requirements in the present as well as in the future without contributing to any additional climate change of the planet (Sangeeta et al., 2014).

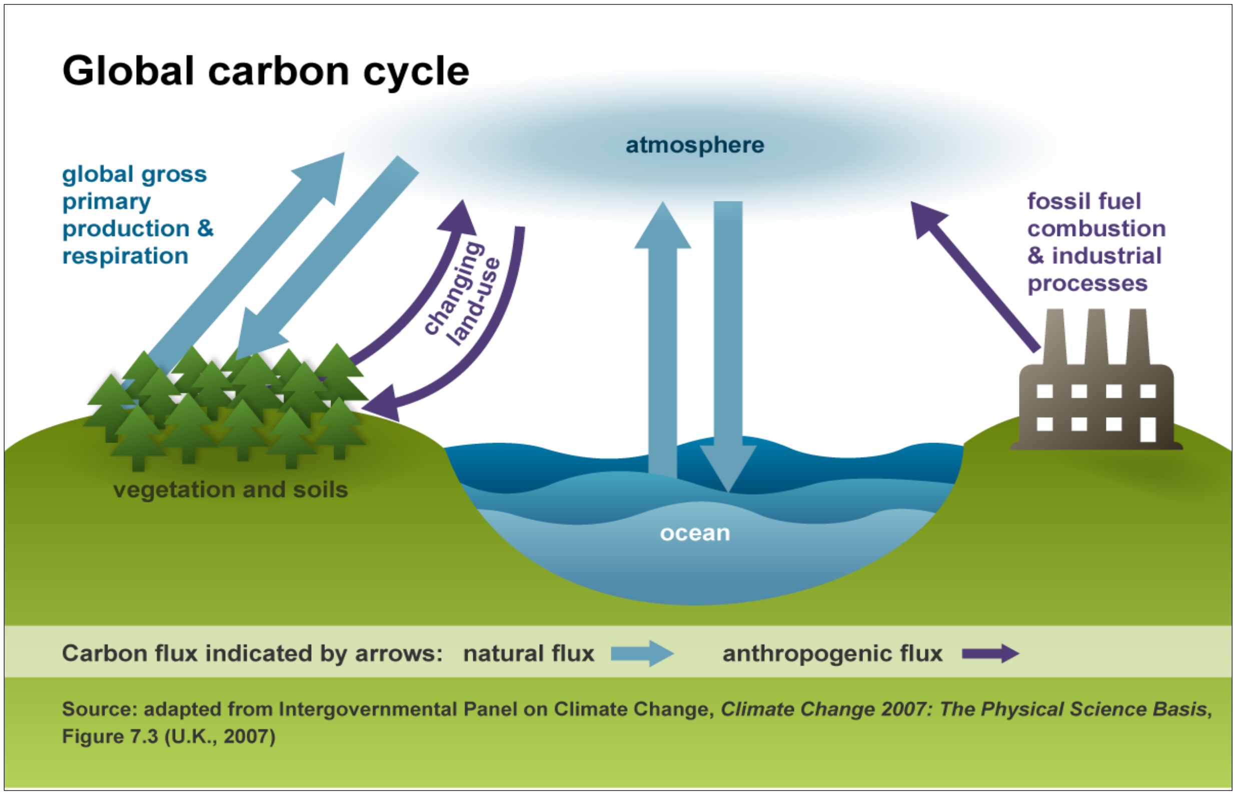

Figure 1 Carbon cycle process explaining climate change (Chukwuemeka et al., 2024).

1.2 GREENHOUSE GAS EMISSIONS IN TRANSPORTATION SECTOR

The transportation industry significantly contributes to greenhouse gas (GHG) emissions in Canada. Environment and Climate Change Canada reports that transportation accounts for around 22% of the country's total emissions, equating to around 150–170 million tons of CO_2 equivalent (CO_2e) annually (Canada, 2024). The role of this sector is primarily influenced by road transportation, encompassing passenger vehicles, light-duty trucks, and heavy-duty trucks. These cars release carbon dioxide and other pollutants during combustion, constituting a significant component of the nation's total emissions.

Besides road transportation, other modes also contribute to the emission profile, but to a lower degree. Aviation, maritime, and rail transportation contribute to the overall emissions. Aviation emissions, albeit less voluminous than those from road transportation, are significant due to their substantial impact per unit of fuel combusted. Marine transportation, especially in coastal and port communities, contributes to emissions through fossil fuel burning and operating activities. Rail is generally more energy efficient; yet, it still contributes to overall emissions when operated by diesel locomotives.

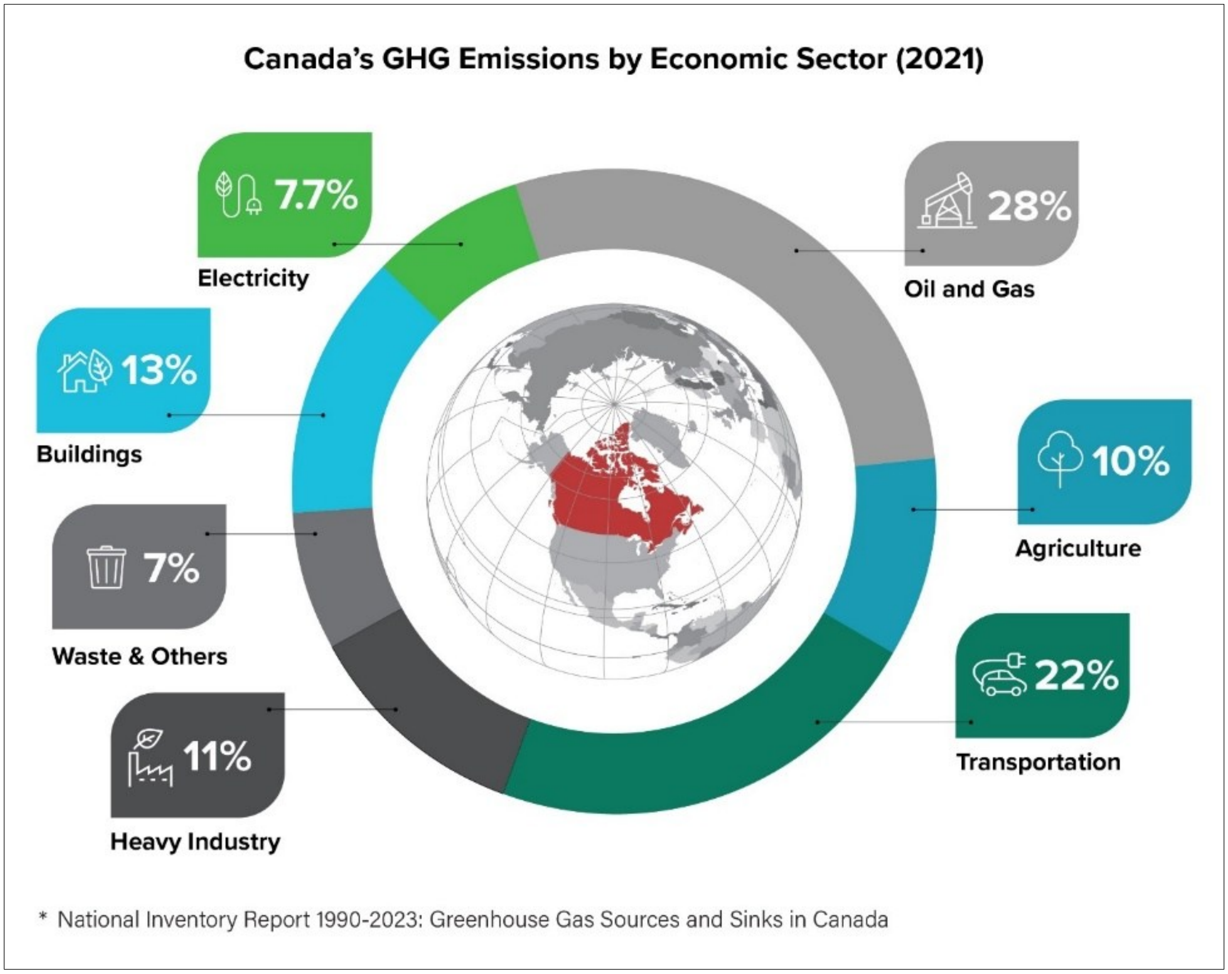

Figure 2 Breakdown of Canada's GHG emissions of various sectors (Canada, 2023).

Current trends demonstrate an increasing imperative to mitigate these emissions. The federal and provincial governments have implemented strategies to decrease dependence on gasoline and diesel fuels. This encompasses promoting the adoption of electric cars (EVs) and biofuel alternatives, investing in renewable energy sources, and enhancing public transit systems. There is a growing focus on enhancing infrastructure to facilitate active transportation modes like cycling and walking, which provide the combined advantages of decreasing emissions and advancing public health.

These findings are further supported by Statistics Canada, which shed light on fuel consumption and transportation trends. Recent reports indicate that the increasing number of automobiles on the road corresponds with a growth in total fuel consumption and associated emissions. This association underscores the necessity for a thorough shift to cleaner transportation technologies and enhanced infrastructure expenditures.

Efforts to reduce these emissions are diverse. Technological breakthroughs, like enhancements in battery storage for electric vehicles and more efficient biofuel production methods, are rendering low-emission options increasingly viable and cost-effective. On the other hand, policy initiatives such as carbon pricing, incentives for the acquisition of green vehicles, and laws aimed at emission standards are intended to alter consumer choices and industrial practices. Collectively, these initiatives are crucial for diminishing the environmental impact of the transportation sector while complying with Canada's national and international climate objectives.

1.3 POLICIES AND INITIATIVES FOR ALTERNATIVE FUELS IN CANADA

There are a number of policies and initiatives that have been implemented by the government of Canada in order to support the transition away from fossil fuels and toward other energy sources that are less harmful to the environment. These policies aim to improve public health, boost economic growth in the sector of clean energy, and reduce emissions of greenhouse gases by reducing the levels of pollution in the environment.

Clean Fuel Regulations (CFR)

Through the implementation of the Clean Fuel Regulations, which were approved by Canada in June 2022, fuel importers and manufacturers are obligated to gradually lower the amounts of carbon emissions that are produced by gasoline and diesel. By encouraging the development of fuels that are less harmful to the environment and the use of technology that is more environmentally friendly, this policy helps to mitigate the negative effects that transportation fuels have on the environment (Canada, 2022).

Clean Fuels Fund (CFF)

The federal government established the Clean Fuels Fund with the goal of encouraging the production and distribution of fuels that are derived from renewable sources. The government has committed nearly $1.8 billion to the expansion of the biofuels industry beginning in January 2025 (N. R. Canada, 2025). This is in addition to the $776.3 million that has been allocated aside for sustainable fuel efforts between the years 2024 and 2030. This investment is being made with the intention of promoting growth within the energy sector and widening access to fuels with low carbon emissions.

Program for Zero-Emission Vehicle Infrastructure (ZEVIP)

An initiative known as the Zero-Emission Vehicle Infrastructure Program (ZEVIP) after coming to the realization that zero-emission vehicles (ZEVs) require infrastructure in order to function, Canada initiated the Zero-Emission Vehicle Infrastructure Program. A significant barrier to the widespread adoption of zero-emission vehicles (ZEVs) is addressed by this program, which provides funding for the building of hydrogen refueling stations and charging stations for electric vehicles all around Canada (N. R. Canada, 2024).

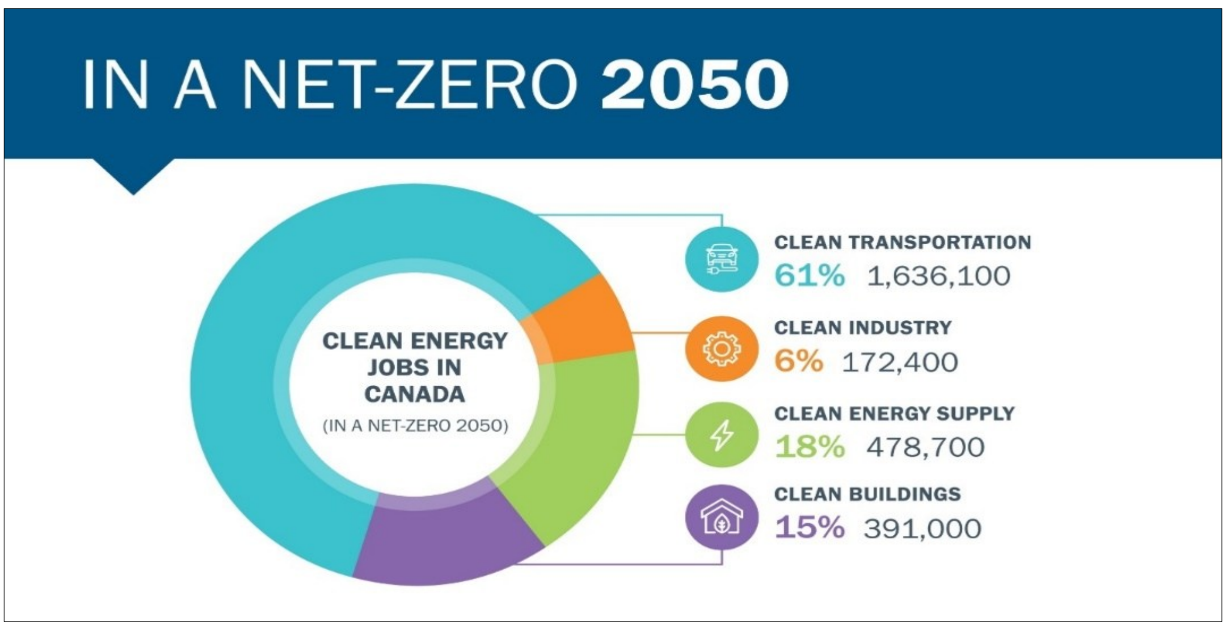

Figure 3 Shows increase in jobs boosting economic growth in alternative energy sector (*A Pivotal Moment - Clean Energy Canada*, 2023).

Electric Vehicle and Alternative Fuel Infrastructure Deployment Initiative (EVAFIDI)

Established in 2016, the Electric Vehicle and Alternative Fuel Infrastructure Deployment Initiative has the objective of building a network of hydrogen refueling stations in key cities, natural gas refueling stations along important freight passageways, and fast chargers for electric vehicles from coast to coast. This infrastructure development is absolutely necessary in order to facilitate the widespread adoption of alternative fuel vehicles (N. R. Canada, 2025b).

Hydrogen Strategy for Canada

The Hydrogen Strategy was released by Canada in December of 2020 with the intention of establishing the country as a global leader in the manufacturing, consumption, and export of hydrogen. The plan calls for the establishment of a transcontinental hydrogen corridor and provides investment tax incentives for the production of hydrogen. This is in accordance with the nation's commitment to expanding hydrogen as a source of renewable energy (N. R. Canada, 2025b).

Program for Green Freight

In an effort to reduce emissions in the transportation and logistics industry, the Green Freight Program provides incentives that are not repayable for the purpose of recharging vehicles and purchasing environmentally friendly alternative fuel vehicles. This program helps achieve a reduction in emissions on a global scale by promoting the utilization of environmentally friendly technology in the transportation of goods (N. R. Canada, 2025d).

Pricing of Carbon

In order to incentivize emission reductions across a variety of businesses, Canada has implemented a carbon price system via which carbon is priced. The federal carbon tax has been increasing at a rate of $10 per tonne since 2018, and it is expected to reach $50 per tonne in 2022. This has been the case since the tax was first implemented. For both customers and businesses, this policy encourages the use of technology and energy sources that are less damaging to the environment (Wikipedia contributors, 2024).

1.4 RESEARCH OBJECTIVES

- Design a system dynamic model to imitate the increase in alternative fuel-based vehicles like electric vehicles, biofuel vehicles, hydrogen vehicles over time due to the factors like customer perception, government initiatives, infrastructure developments, cost of the fuels and vehicles.

- Integrate public buses and bikes in the model which helps lower ghg emissions.
- To find the total reduction in greenhouse gas emissions over time.
- To understand which factors driving the increase in vehicles have the highest influence.
- To predict what if scenario analysis that finds the increase in alternative fuel-based vehicles, decrease in gasoline vehicles due to its reducing popularity over time from 2024 to 2050.
- To understand which scenarios of alternative fuel-based vehicles, bikes and public buses is optimum and best for the reduction of total greenhouse gas emissions and hence will be useful in meeting net zero goal.
- To predict the reduction in total ghg emissions from 2024-2050 to meet net zero goals of Canada.

1.5 THESIS OUTLINE

Chapter 1 provides a comprehensive background of Canada's transportation emissions challenges, setting the stage for the investigation. It begins by contextualizing climate change and the transportation sector's role in greenhouse gas (GHG) emissions. The current Canadian alternative fuels policies, that encourage biofuels, hydrogen, and electric vehicles, are examined. Finally, the Chapter describes the research objectives, which use system dynamics simulation to assess the influence of alternative fuels and sustainable transportation modes on GHG emissions by 2050.

Chapter 2 reviews the field's literature extensively. Biofuels, hydrogen, and electric power are examined for the benefits and drawbacks in sustainable mobility. The study then examines how different countries are incorporating alternative fuels into their transportation sectors, sharing successful techniques and lessons gained. The study then analyses the various methodologies to evaluate alternative fuels in transportation. The literature review summarizes the research gaps found from the existing literature to help us design effective research.

Chapter 3 outlines the research methodology, beginning with an explanation of system dynamic modeling and the classification of its primitives in Insightmaker. It details the concepts of both causal loop and stock-flow diagrams, with practical examples, and explains the systematic steps of system dynamic simulation. The Chapter further addresses the objectives and scope of the simulation, the conceptual design of the model that includes the analysis of variables, relationships and feedback loops, causal loop model of the simulation, stock and flow model, presentation of mathematical equations.

Chapter 4 explains the numerical applications of the model by first validating the model. It also includes baseline scenario, two scenario analyses scenario 1 (EV uptake), and Scenario 2 (hydrogen vehicles increase) and finally sensitivity analysis for key parameters.

Chapter 5 presents the empirical findings, beginning with the output of the baseline scenario and extending to the results of Scenario-1 and Scenario-2. It then discusses the inherent limitations of the model and provides a critical discussion that contextualizes the results within the research framework.

The final Chapter 6 summarizes the key findings and draws conclusions based on the analysis presented in previous Chapters. It also outlines conclusions of the study and suggests potential directions for future research to address identified gaps and expand on the current work.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

There has been a recent crisis involving petroleum, unexpected price increases, and uncertainty surrounding supplies, all of which represent an immediate threat to the ability of the global economy to pursue more sustainable practices. Questions about the environment and the availability of gasoline are two factors that have a significant impact on rising fuel prices for transportation vehicles. Internal combustion (IC) engines are responsible for the production of certain harmful pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), particulate matter, smoke, and others. Therefore, the most important topic of research for internal combustion engines is the concurrent generation of power and the reduction of pollutants from the engine for generations to come. As a result of the gradually increasing density of transportation vehicles and the ever-increasing need for gasoline, researchers and academics were driven to investigate the possibility of discovering new sources of fuel for transportation. Throughout the years, a number of tactics and processes have been developed, and they continue to be carried out, with the goal of increasing output, cost-effectiveness, and durability (Salvi et al., 2013).

2.2 BIOFUELS

Biofuels are a type of energy fuel that derives from organic sources, which are generally referred to as biomass. Biofuels are made from plants and other living things and can be cultivated and collected on a continuous basis. Forests, residue streams, agriculture and crucial harvests are the primary sources of biofuels that are used to replace fuels that are derived from fossil fuels (Polburee et al., 2015, Xue et al., 2018). The significance of biofuels lies in the fact that they take the place of energy sources that are derived from petroleum. A rising number of developed as well as developing nations have recognized the potential of biofuels as a means of reducing greenhouse gas emissions, decreasing their dependence on oil imported from other countries, and achieving targets related to rural development (Agency, 2004, *Pacific Food System Outlook 2006-2007: The Future Role of Biofuels 9789812307262 - DOKUMEN.PUB*, n.d.). Biofuels can be categorized into a wide variety of generations, each of which is determined by the raw material and the manufacturing procedures used. In the first generation of biofuels, corn, sugarcane, and vegetable oils are the primary sources of production. Both bioethanol and biodiesel are examples of such fuels. Second-generation biofuels are produced from non-food biomass, such as lignocellulosic resources (such as forestry residues, agricultural waste, and other similar products).

Third-generation biofuels are generated from microalgae and other lipid-rich organisms. Improved fuel production from sustainable sources of energy is the goal of fourth-generation biofuels, which are developed through the application of synthetic biology and genetic engineering (Chowdhury & Loganathan, 2019). The cracking or transesterification procedures are used to produce biodiesel, which is a well-known first-generation biofuel. Biodiesel is produced from the vegetable oils of oleaginous plants that have been refined. Glycerine and fatty acid, often known as biodiesel, are the byproducts of the process of transesterification, which typically involves the use of ethanol or methanol in conjunction with alkaline, acid, or enzymatic catalysts (Malode et al., 2020).

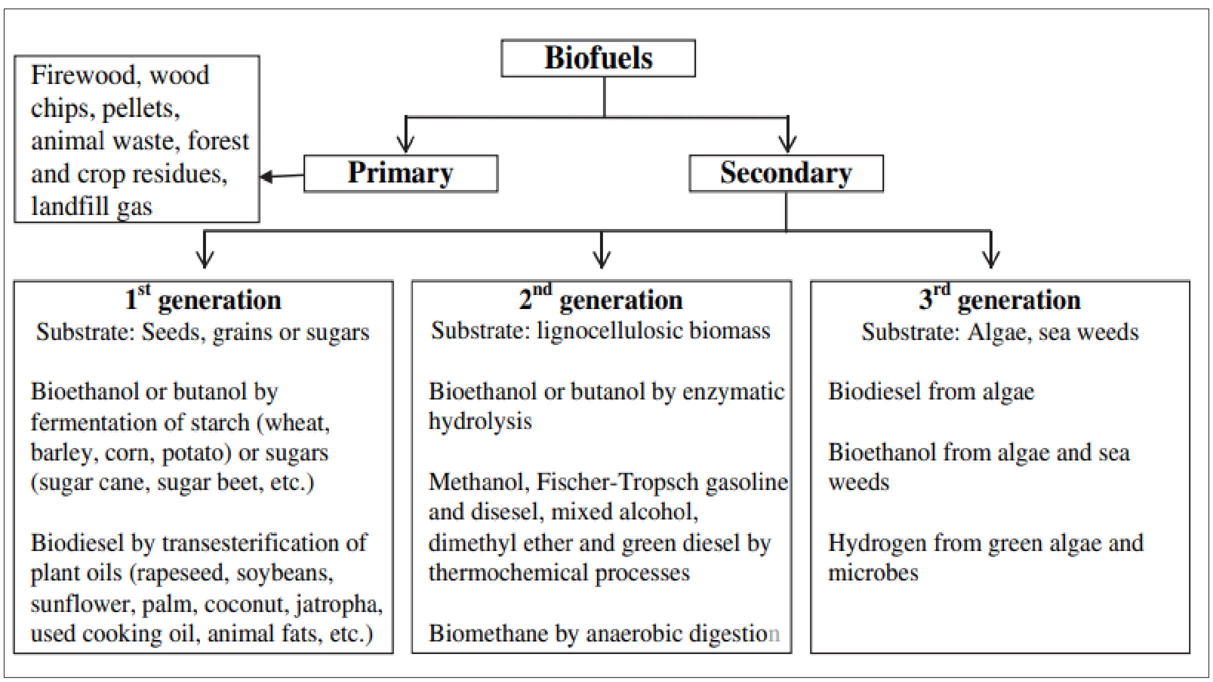

Figure 4 Different generations of biofuels (Calvey et al., 2015).

Ethanol is manufactured from cellulose materials (including wood residues, straw, and agricultural byproducts such as cellulose, mannose, and xylose), starches (such as wheat, corn, barley, and sweet potatoes), and sugars (raw sugarcane syrup, sugarcane molasses, sugar beet, and sweet sorghum syrup, predominantly comprising glucose, fructose, and sucrose) as feedstocks. It is important to note that the type of raw material influences ethanol synthesis, as well as the predominant sugars present in these materials at certain phases.

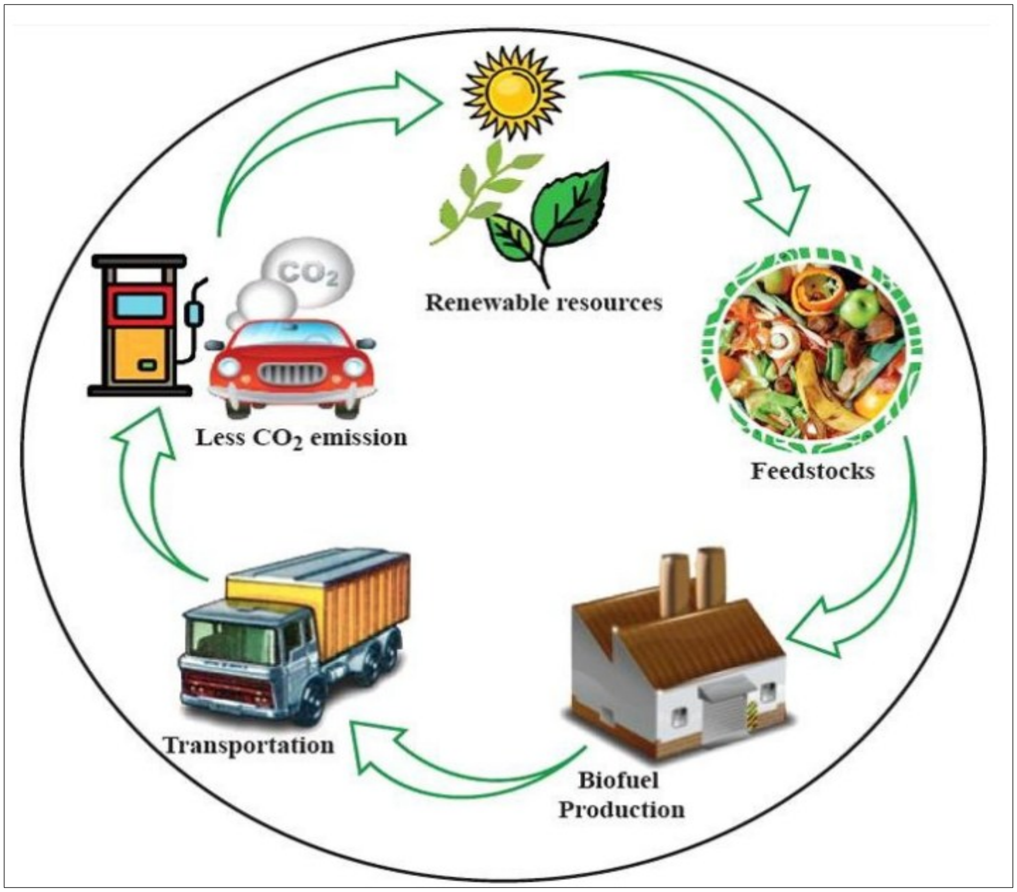

Figure 5 Shows the process of biofuel from extraction to transportation (Vedarethinam et al., 2024).

2.3 HYDROGEN

As a source of energy that is not solely efficient but also environmentally friendly and sustainable, hydrogen is rapidly becoming a key alternative fuel for automobiles. Hydrogen-powered vehicles, including fuel cell electric vehicles (FCEVs), hydrogen-powered internal combustion engines (H2-ICEs), and hydrogen hybrid systems, are garnering an increasing amount of interest as governments and businesses look for ways to reduce their dependence on fossil fuels and reduce their carbon emissions. Gasification and Thermocatalysis processes, which begin with natural gas as the starting ingredient, are responsible for producing approximately half of all hydrogen that is produced today (Iulianelli & Basile, 2014). The next largest sources are coal, followed by heavy oils and naphtha, and only 4% of hydrogen fuel that is produced comes from the generation of water through electricity.

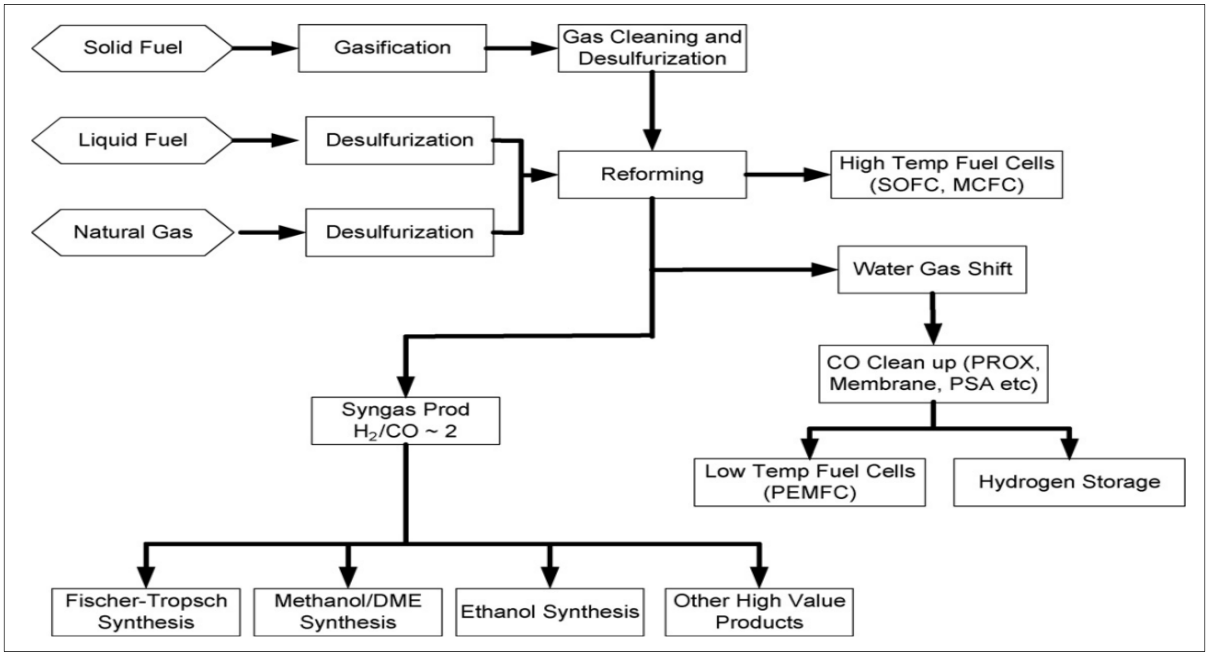

Figure 6 Fuel processing of gaseous, liquid, and solid fuels for hydrogen production (Holladay et al., 2008).

Due to the fact that hydrogen can be created from all of the feedstocks as well as many more, it is considered to be a universal fuel (Holladay et al., 2008). The majority of these fuels require a distinct engine technology in order to function well. It has been widely held that the production of hydrogen through the use of green hydrogen is the most sustainable and greenest method so far. The process of electrolysis, which involves the separation of water molecules into hydrogen and oxygen, is responsible for its generation. This process makes use of electricity derived from renewable energy sources such as solar, wind, or hydroelectric power. Due to the fact that the process does not produce any greenhouse gases, it is an excellent option for a decrease of carbon emissions in the transportation sector. It is critical that the costs associated with producing and transporting hydrogen in a manner that is both environmentally responsible and efficient be dramatically decreased.

It is necessary for building new generations of hydrogen storage technology for use in the transportation and stationary industries. Last but certainly not the least, it is essential to bring down the cost of fuel-cell and other hydrogen-based technologies (Sharma & Ghoshal, 2014b). An alternative competitive option can be achieved through the use of a hydrogen complex that is built around nuclear power stations that create hydrogen through the process of electrolysis (Aminov et al., 2024). One of the most common techniques for extracting hydrogen from natural gas is known as steam methane reforming (SMR), which in turn produces blue hydrogen. As opposed to the conventional gray hydrogen, blue hydrogen makes use of carbon capture and storage (CCS) technology in order to reduce the amount of carbon dioxide that is released into the atmosphere. Blue hydrogen provides an alternative that has a smaller carbon footprint and can serve as a temporary solution while further infrastructure for green hydrogen is constructed. Gray hydrogen is currently the most widely utilized technique of producing hydrogen, accounting for around 95% of the total hydrogen produced worldwide. As is the case with blue hydrogen, it is produced through the conversion of steam methane, but it does not include any carbon capture processes. The release of a considerable amount of carbon dioxide into the atmosphere is one of the primary ways in which gray hydrogen contributes significantly to the increase in carbon emissions.

2.4 ELECTRIC

As opposed to conventional internal combustion engines, electric vehicles (EVs) are powered by the electric energy that is stored in batteries. There is a wide variety of electric vehicles, each of which is designed to cater to a certain set of driving requirements and infrastructure circumstances.

Different kinds of electric vehicles include (Sanguesa et al., 2021):

Battery Electric Vehicles (BEVs): They are fully electric vehicles that rely only on rechargeable battery packs to power an electric motor. BEVs are also known as battery electric vehicles. In addition to being completely charged from the electric grid, they do not create any pollution from their tailpipes. Generally speaking, battery electric vehicles (BEVs) have longer driven ranges as battery technology continues to advance.

Plug-in Hybrid Electric Vehicles (PHEVs): They are vehicles that combine an internal combustion engine with an electric motor and a battery that can be recharged. The gasoline engine kicks in after a specified range has been reached by these cars, which can be charged from the electric grid and run on electric power for a given amount of time. This dual powertrain offers flexibility, which in turn expands the overall range of the vehicle, while simultaneously reducing the amount of gasoline consumed and the emissions produced.

Fuel cell electric vehicles (FCEVs): They are vehicles that generate energy on-board by utilizing a fuel cell. This fuel cell combines hydrogen and oxygen in order to produce electricity, and the only pollution that a fuel cell produces is water vapor. In comparison to charging batteries, they can be refueled in a short amount of time, making them a potentially useful option for applications that require long-range and heavy-duty capabilities.

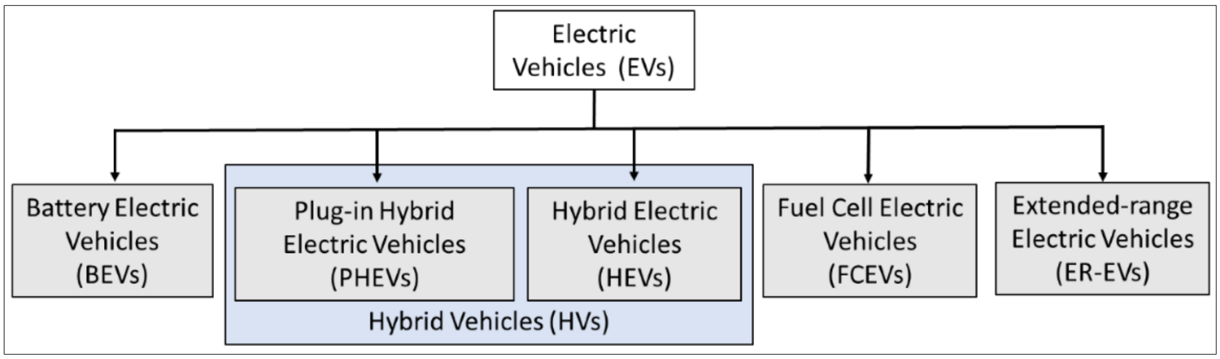

Figure 7 Types of electric vehicles (Sanguesa et al., 2021).

Electric charging is the process of transferring energy from an external power source to the battery of an electric vehicle by means of a charging station or outlet. The process is controlled by a battery management system (BMS), which is charged with monitoring and controlling the temperature, voltage, and state of charge of the battery in order to guarantee that the charging process is both safe and effective. The following are the three primary levels of charging (Sanguesa et al., 2021):

Level 1 charging: It is accomplished by plugging the device into a conventional household outlet, which is commonly 120V in North America. The charging rate is minimal, and they can add anywhere from three to five miles of range each hour. They are the choice that is the slowest. In cases where only a short daily driving distance is required, Level 1 charging is the most suitable option. It is also effective for overnight charging.

Level 2 charging: It is characterized by the utilization of a higher voltage source (often 240V in North America) and the requirement of specialized charging equipment. These electric vehicles have a faster charging rate, often delivering a range of 10 to 60 miles per hour, which makes them acceptable for use at public charging stations, as well as at home and in the workplace. When it comes to day-to-day use, level 2 charging is typically utilized in urban and suburban settings.

Level 3 charging: DC Fast Chargers are devices that convert alternating current (AC) to direct current (DC) outside of the car. They then send high power levels directly to the battery, which frequently reach 50 kW. In as little as twenty to thirty minutes, this technology may charge an electric vehicle to eighty percent of its capacity, making it a great method for long-distance travel as well as for rapid refueling on highways. On the other hand, high-power charging stations need a solid infrastructure and thus incur higher costs for installation and operation.

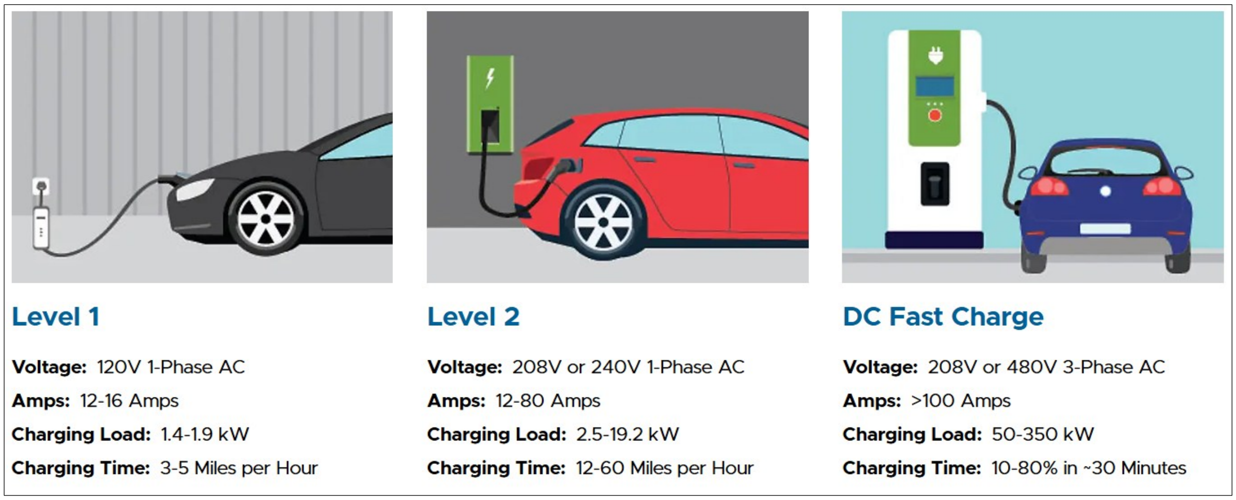

Figure 8 Types of EV charging infrastructures (*Charging 101*, 2023).

2.5 ADVANTAGES OF ALTERNATIVE FUELS

The advantages of biofuels encompass a reduced risk of global warming, an improved environment, and the elimination of harmful gases and toxic substances. They combust efficiently, are biodegradable, and are environmentally sustainable. Biofuels receive government assistance and can reduce greenhouse gas emissions by around 50%. Employing agricultural residues and waste substrates as raw materials will mitigate the possible conflict between food and fuel while also generating biofertilizers and biopesticides. Biofuels derived from lignocellulosic materials yield minimal net greenhouse gas emissions, hence mitigating environmental impacts (Calvey et al., 2015). High-yield energy crops, including switchgrass, giant miscanthus, sorghum, and other species, serve as feedstock for cellulosic ethanol production and other biomass conversion processes. In comparison to many other perennial grass species and traditional agricultural crops, switchgrass (Panicum virgatum), acknowledged as an energy crop, exhibits resilience to diverse environmental conditions and produces substantial biomass in both favorable and adverse growth environments.

Genetic enhancement of switchgrass is essential to reduce the cost of delivered feedstock as a specialist bioenergy crop (Vedarethinam et al., 2024).

Domestic production of hydrogen from renewable energy sources, including wind, tidal, and biomass, may be feasible; but it will undoubtedly be insufficient to meet global demand. Initially, pollution resulting from global warming is alleviated by implementing renewable techniques for hydrogen production. Ultimately, it may be more advantageous considering the viability of carbon capture and storage. Advanced carbon capture techniques can mitigate 95% of CO2 emissions in the production of blue hydrogen. The use of hydrogen in transportation systems, either as fuel for internal combustion engines or as a fuel cell in electric vehicles, has received great positive attention as an energy policy issue. The sole result of hydrogen utilization is water vapor; no toxic gasses or CO2 emissions are generated. Hydrogen-powered vehicles significantly decrease dependence on fossil fuels and substantially diminish exhaust pollutants (Sazali, 2020).

Electric vehicles (EVs) have numerous benefits over internal combustion engine automobiles. Their environmental impact is a major advantage. EVs release no tailpipe pollutants like nitrogen oxides or particulate matter, which can pollute the air and cause respiratory issues (Alanazi, 2023). They emit less carbon than gasoline or diesel automobiles when fueled by renewable energy. Energy efficiency and environmental benefits are EVs' trademarks. Inherently more efficient than combustion engines, electric motors convert more battery energy into vehicle movement. This reduces energy usage per mile, saving fuel over the vehicle's lifetime. Another benefit is lower maintenance (Alanazi, 2023). EVs feature fewer moving parts than typical cars, minimizing oil changes and brake wear owing to regenerative braking. Lower maintenance expenses and more dependable driving can result. EVs tend to perform well. Many electric vehicles accelerate quickly and run quietly, improving the driving experience. Electric motors' quick torque makes driving exciting and responsive. Improved air quality, energy efficiency, minimal maintenance, and outstanding reliability make EVs a popular sustainable transportation option.

2.6 DISADVANTAGES OF ALTERNATIVE FUELS

Biofuels have a number of challenges, including the high cost of labor, the enormous storage requirements, the growing demand for agricultural land, and the consumption of water. The viscosity of biofuel has the potential to reduce the efficiency of the engine, which is why conversion methods are needed. Despite certain physical property restrictions, such as pour point and cloud point, biodiesel has been shown to produce lower levels of pollutant emissions compared to traditional fuels (Vedarethinam et al., 2024).

In order to create a hydrogen fuel system that is both technologically and economically feasible, the most important problem that needs to be solved is the question of how to store hydrogen (Sharma & Ghoshal, 2014). There are significant financial and scalability challenges associated with green hydrogen, despite the fact that it has positive effects on the environment. The procedure of electrolysis requires an enormous amount of electricity; yet, the infrastructure required for renewable energy sources is currently slightly expensive. Furthermore, there is a possibility that certain regions will have difficulty acquiring freshwater for the purpose of electrolysis, which requires the development of new techniques for electrolysis of seawater. The future of the blue hydrogen market is significantly influenced by a number of factors, including the price of fossil fuels, the characteristics of the global energy system, and the regulations governing carbon (AlHumaidan et al., 2023). Blue hydrogen produces more fugitive methane than gray hydrogen does, though having lower carbon dioxide emissions (Howarth & Jacobson, 2021). This is due to the fact that blue hydrogen uses more natural gas to power the carbon capture process more than gray hydrogen does.

Electric vehicles have much potential, but their adoption is still low for severe reasons. Technology constraints have hampered EV dominance. Battery weight is the key problem because they add to car weight. Range and recharge time depend on the battery. Battery capacity limits EVs. The energy stored there permits them to travel a given distance. Users experience 'range anxiety', worrying about finding a charging station before the battery dies. Another drawback of EVs is their long charging time (Un-Noor et al., 2017). Depending on the charger and battery pack, charging might take minutes to hours, making EVs inept against ICE vehicles, which can be refueled in minutes. Fast charging is being explored and certain facilities are available. No-charge fuel cell EVs are also available. These cars can be filled like a fuel tank, but they need enough hydrogen refueling stations and a viable hydrogen production method to thrive. Current safety concerns are mostly about FCVs. Hydrogen, which is very flammable, may cause serious harm if it escapes tanks. Society takes time to adopt a new, immature technology and its implications since it requires habit adjustment. Using an EV instead of a normal vehicle requires changing driving habits, refilling habits, and being prepared to utilize an alternative transport in case of low battery, which is difficult. Although public charging stations have grown, they are still insufficient. This and the long charging time discourage EV adoption. Finding a public charging station to recharge the battery might be difficult because not all are compatible with all cars. EVs are more expensive than ICEs. Because batteries and fuel cells are expensive.

2.7 GLOBAL PERSPECTIVES ON ALTERNATIVE FUEL DEVELOPMENT

Developing control techniques for charging electric vehicles and incorporating these demands into smart grid infrastructures has received a lot of attention in the US. Researchers have looked into how grid energy storage and distributed renewable energy may be integrated with EV charging infrastructure to offer supplementary services. For instance, Tan et al. (2015) examine the opportunities and difficulties associated with EV integration with smart grids across the US. Vehicle to grid technology that allows bidirectional energy exchange between electric vehicles and the power grid, which benefits power grid were assessed. Zhou et al. (2020) did modeling and simulations for a study where the results show that coordinated charging schemes can lower peak loads and make the grid more reliable. Malik et al. (2024a) researched on biofuels in the United States has focused on integrating biofuel blends into the current transportation system and developing sophisticated conversion techniques. They gave an overview of recent progress in making biodiesel and bioethanol from waste feedstocks. They also focus on progress in both catalytic conversion and process optimization. The use of hydrogen fuel cells is seen as a crucial facilitator for the decarbonization of heavy-duty transportation in the United States. Hassan et al. (2023) offers a comprehensive analysis of recent advancements in water electrolysis techniques for environmentally friendly hydrogen production, including the influence of innovative electrode materials along with system architecture on overall efficiency. Veziroglu and Macario (2010) concurrently assess the advancements in storage of hydrogen, distribution, and fuel cells for vehicle performance, encompassing life-cycle evaluations and cost reduction techniques essential for the commercial implementation of hydrogen mobility.

In India, swift urbanization and the government's dedication to mitigating air pollution have catalyzed research on the integration of electric vehicles with smart grid networks. Ahmad (2019) examines the obstacles associated with the implementation of electric vehicle charging infrastructure in various urban and rural settings in India. They analyze battery performance in tropical environments and suggest flexible charging algorithms that consider fluctuating grid circumstances. Singh et al. (2021) examine the contribution of renewable energy, particularly solar electricity, to the operation of electric vehicle charging stations and explore legislative strategies that may expedite electric vehicle adoption within the Indian market. India's extensive agricultural sector offers ample feedstock for biofuel manufacturing. Arora et al. (2023) provide an overview of biofuel manufacturing technologies utilizing lignocellulosic biomass, including waste products, addressing process enhancements and scalability problems. A study conducted by Balan (2014) examines the incorporation of biofuels into India's transportation infrastructure, evaluating the performance of engines, emissions, and financial viability in urban and rural contexts. With an eye toward diversifying its energy mix, India is increasingly exploring hydrogen as a clean energy source. Qureshi et al. (2022) review the current status of hydrogen production using renewable energy in India and outline the technical challenges of scaling up water electrolysis systems. In a complementary study, Harichandan and Kar (2023) examine the development of hydrogen refueling infrastructure and assess the performance of hydrogen fuel cell vehicles in pilot deployments, providing recommendations for policy and regulatory improvements.

China's dominance in manufacturing electric cars and technology for smart grids is well established. Yuan et al. (2014) present a comprehensive assessment of the incorporation of electric vehicles with the smart grid in China, highlighting algorithms for control and the significance of vehicle-to-grid technologies in grid stabilization. Li et al. (2020) conduct a simulation-based study that assesses the influence of extensive adoption of electric cars on grid efficiency and examines coordinated charging techniques to alleviate peak load effects. Chinese research has concentrated on the conversion of agricultural leftovers and specialized energy-producing plants into biofuels. Pan et al. (2024) examine recent advancements in catalytic and thermochemical methods for biofuel generation, emphasizing enhancements in output and sustainability. Tao et al. (2011) examine field experiments of blends of biofuel in commercial cars and address infrastructure problems in modifying distribution systems to accommodate biofuels. China's hydrogen research is advancing swiftly as the country aims to establish a robust hydrogen economy. Zhao et al. (2020) conduct a comprehensive evaluation of fuel cell vehicle efficacy and the financial obstacles linked to the establishment of a national hydrogen infrastructure.

The Energiewende in Germany has catalyzed significant research on the integration of electric vehicles into an upgraded grid. Jochem et al. (2012) examine smart charging and vehicle-to-grid (V2G) solutions aimed at alleviating grid impacts due to significant electric vehicle (EV) uptake. Their work addresses both technology solutions and the legislative and market processes necessary to facilitate these advancements. Guthoff et al. (2021) conduct complementary research utilizing simulation studies to assess grid impacts and recommend coordinated charging techniques that enhance overall grid performance. Biofuels are an important part of Germany's sustainable energy plan. A thorough analysis of biofuel production systems utilizing non-food crops and waste biomass is given by Bringezu et al. (2009) who place special emphasis on process improvements and sustainability indicators. In a different study, Strzalka et al. (2017) evaluate the technical and financial feasibility of modifying traditional petroleum infrastructure to accept biofuel blends. A key component of Germany's long-term energy plan is hydrogen. With a focus on cost-effectiveness and safety, Apostolou and Xydis (2019) examine the state-of-the-art in hydrogen refueling network development and renewable hydrogen production. Studies such as those conducted by Bekel and Pauliuk (2019) that evaluate the longevity and performance of fuel-cell cars in Germany under actual driving circumstances supplement their work.

2.8 METHODOLOGIES USED TO EVALUATE ALTERNATIVE FUELS

2.8.1 MULTI CRITERIA METHODOLOGY

Zorpas et al. (2016) investigated the effects of alternative fuels (hydrogen, natural gas, bio-ethanol, and bio-gas) by analyzing various factors most likely to impact the environmental, economic, and social sectors, to assess the viability of improving their percentage relative to conventional fuels. The results demonstrated that the economic criteria of alternative fuels are regarded as a significant advantage over traditional fuels, while the comparative assessment derived from the combination of properties with optimal values demonstrates and drives the analysis of hydrogen as the 'superior' alternative fuel source.

Kim et al. (2020) conducted a to achieve the aim of GHG emissions reduction by 50% by 2050 compared to 2008, vessels could operate on alternative maritime fuels like LNG, hydrogen, ammonia, methanol, ethanol, biofuel, synthetic fuel, battery generated power, and others. Each alternative fuel has unique characteristics, which is a challenge. Alternative marine fuels may not emit

GHGs but pose a higher danger. While other alternative fuels may not emit GHGs and have low risk, their capital and operational costs may be significant. The purpose of this article is to examine selected alternative marine fuels and underline the need for integrated evaluation. They conclude that alternative maritime fuels must be assessed for environmental impact, human danger, and business value.

Brey et al. (2007) use the non-parametric method of Data Envelopment Analysis (DEA) to do a multicriteria evaluation of various current and developing technologies in the automotive industry. The findings suggest that certain technologies like hydrogen fuel cell vehicles, can be considered efficient when assessed against environmental and economic criteria, with a larger emphasis placed on the environmental factors. Their paper highlights the necessity to enhance hydrogen-based technology relative to others, particularly with vehicle sales costs and fuel prices.

Lanjewar et al., (2015) studied a hybrid multicriteria methodology employing graph theory and analytic hierarchy process methods to evaluate conventional and non-conventional transportation fuels on many criteria. The proposed fuel fit digraph shows alternate fuel selection parameters and their relationships. Fuel selection attributes are weighted using analytic hierarchy.

Kulkarni et al. (2017) presented a methodological framework for evaluating multi-criteria strategies for working energy alternatives including central grid and grid extension, solar home systems, and microgrids in India. Multiple empirical data sources were used to build the model utilizing the Analytic Hierarchy Process (AHP). MATLAB was used to evaluate and compare these multi-criteria's utilizing Saaty's AHP and Fuzzy Sets approach. The investigation included environmental and cost scenarios. Final energy generation options were ranked using AHP and Fuzzy logic. The results show that microgrid is the best centralized energy generation option and may solve the shortage of energy.

Deniz & Zincir, (2015) compared ship fuels scientifically. The environmental and economic performance of methanol, ethanol, LNG, and hydrogen was analysed. Eleven varied comparison criteria were used. Analytic hierarchy process weighed comparative criteria based on five experts' points. Liquefied natural gas is the best alternative fuel and receives the highest score. Hydrogen scored highest in bunker capability, ship adaptability, safety, commercial consequences and durability. Their study suggests that hydrogen can replace liquefied natural gas as a ship fuel, although it needs more research on emission restrictions and engine component concerns.

Tzeng et al. (2005), considered a case of public buses using alternative fuels. Evaluation criteria are weighted using TOPSIS, AHP and VIKOR and are evaluated to find the optimal alternative fuel mode compromise. Multiple attribute evaluation of alternative vehicles was done by experts from distinct decision-making groups. In the short and long term, the hybrid electric bus was the best urban bus substitute in Taiwan. If the electric bus's cruising range is adequate, the pure electric bus may be optimal. Hybrid electric vehicles will be an alternate option, at least for the period of improving the technology of electric vehicles.

Chang et al. (2015) used DEMATEL-based analytical networks to evaluate AFVs from a sustainable development standpoint. Results show that pricing, additional value, user approval, hazardous substance reduction, and dematerialization are the most important criteria. Price mattered most since it may increase alternative fuel vehicle appeal and user approval. Furthermore, energy utilization is predicted to greatly impact alternative fuel vehicle sustainability. Automakers and governments constructing alternative fuel vehicles ought to take note these results.

Tsita & Pilavachi (2012) examined alternative fuels for the Greek road transportation industry utilizing the Analytic Hierarchy Process. This research examines seven distinct fuel mode alternatives: internal combustion engine (ICE) combined with petroleum and blends of first- and second-generation biofuels, fuel cells, hybrid vehicles, plug-in hybrids, and electric vehicles. The examination of alternative fuel options is conducted based on economic and regulatory considerations. To assess each alternative fuel, one baseline scenario and 10 alternative scenarios with varying weight factors for each criterion are provided. After determining the scoring of alternative fuels against every criterion and the corresponding weights, their synthesis yields the total score and ranking for all ten potential scenarios. It is determined that internal combustion engines utilizing a blend of first- and second-generation biofuels represent the most appropriate alternative fuels for the Greek road transport industry.

Kuimov & Plotnikov (2016) calculated the efficiency of alternative fuels for minimizing economic loss and pollution was suggested. Theoretical studies validate the calculation method's functionality. The authors compared work fuel injection equipment and diesel as a whole using adjusted mean values of effective ηe and ηi efficiency measures. They also offer ways to preserve the law of heat flow in diesel engine cylinders for alternate fuels and clean diesel fuel.

Borghetti et al. (2024) suggests multicriteria-decision-methods in several nations for examining this selection. However, financial criteria, specialists, and service kind have not been sufficiently addressed. Their paper addresses these gaps by using an integrated method that includes the Analytical Hierarchy Process (AHP) to define criteria weights and to find a good fuel alternative compromise, a simple Weighted Sum Model (WSM) is used to refine ranking. A panel of experts collected data. Different fuel alternatives for urban and interurban services with and without funding are examined. The findings aid in strategies that evaluate and promote bus fuel choices when renewing fleets.

Oztaysi et al. (2017) is about US utility company's alternative-fuel technology selection challenge. It uses interval-valued intuitionistic fuzzy sets (IVIFS) and linguistic data to build a multi-expert, multi-criteria decision making (MCDM) system that determines that extended-range natural gas vehicle is ideal for the utility company.

Mukherjee (2017), Intuitionistic fuzzy sets (IFSs) similarity measurements are used to get the optimal alternative. Accurate data is hard to collect, hence intuitionistic fuzzy data is used to communicate uncertainty. The attribute weights may be known, partially known, or unknown. Normalizing the intuitionistic fuzzy data average score functions for the criterion determines the unknown weights. Various challenges are handled with algorithms and numerical demonstrations.

2.8.2 TECHNICAL AND ENVIRONMENTAL METHODOLOGY

Alonso-Villar et al. (2022) analyzed Iceland as a case study to evaluate energy security, technical feasibility, and greenhouse gas emissions. AFLEET and GREET calculate the life cycle emissions and total cost of ownership of 10 heavy-duty powertrains. Battery-electric and hydrogen trucks technical viability is assessed in terms of battery/tank required capacity for representative fuel efficiency values. The results indicate that battery-electric trucks have the greatest environmental and economic benefits, but current battery technology's limited range limits its use to delivery trucks. Regional trucks benefit from hydrogen and compressed natural gas paths, but high life cycle costs and feedstock capacity limit their use. Icelandic resources may meet 100% alternative fuel heavy-duty fleet energy demand.

Neuling & Kaltschmitt (2017) examined four northern German biokerosene manufacturing techniques using two biomass feedstocks. Data from a comprehensive simulation is used to assess these conversion processes for technical, economic, and environmental factors. Mass and energy balances, kerosene production costs, and GHG emissions for the examined conversion routes are the main findings. The criteria results are dispersing yet biomass feedstock supply has a major impact. More environmentally friendly and economically effective feedstock supply implies more promising biokerosene based on these factors.

Bilgili (2021) assessed biogas, dimethyl ether, ethanol, liquefied natural gas, liquefied petroleum gas, methanol, ammonia, and biodiesel as alternative fuels and their environmental impacts during their life cycles. Assessors utilized SimaPro V9.0.0.49 and ReCiPe 2008 V1.09. Effects on health, environment, resource use, emission inventory, and societal costs were investigated. Finally, all alternative fuels were evaluated for operating circumstances and production process. Biogas performed best in the short, medium, and long term, while methanol, ammonia, and biodiesel performed worst. Biogas was classified as the most sustainable fuel despite production, transmission, and storage issues.

Bicer & Dincer (2018) compared the life cycle assessment of electric, hybrid, and internal combustion engine vehicles fueled by hydrogen, gasoline, and other fuels. For comprehensive comparison and environmental impact assessment, vehicles using gasoline, diesel, liquefied petroleum gas, methanol, compressed natural gas, hydrogen, and ammonia; hybrid electric vehicles using gasoline and electricity; and electric only vehicles were considered. From raw material extraction to vehicle disposal, process-based life cycle evaluation is used. Electric and plug-in hybrid electric vehicles have greater human toxicity due to manufacture and maintenance. Due to their high energy density and low fuel usage, hydrogen vehicles are the greenest option.

Wagner et al. (2005) studied innovative fuel cell (FC) powertrain systems and fuels and compared to conventional systems using energetic life cycle evaluation. Process chain evaluations for compressed natural gas, methanol, and hydrogen supply at German consumption points underlie this research. To provide an integrated view, these fuels are tested in internal combustion engine and fuel cell vehicles. Their study focused on fuel cell powertrain system breakdown and energy assessment. A whole life cycle assessment includes energy and CO2-emissions for vehicle production, maintenance, and disposal.

Ashnani et al. (2015) examined the life cycle environmental implications of road vehicle fuels and technology and compares cleaner solutions with traditional fuels/technologies. A thorough fuel life cycle assessment (LCA) was done on petrol, diesel, CNG, EV, FCV, and biodiesel vehicles. The effects of vehicle technologies on climate change, air quality, and energy resource depletion are discussed. Successful vehicle and fuel policies create performance criteria and helps to reduce emissions and let the market find the best option.

McKenzie & Durango-Cohen (2011) provided a life-cycle assessment of the costs and greenhouse gas emissions of transit buses that utilize a hybrid input–output model to compare ultra-low sulfur diesel to hybrid diesel-electric, compressed natural gas, and hydrogen fuel-cell alternatives. It is found that alternative fuel buses cut emissions and operational costs but raise life-cycle expenses. Alternative fuel bus infrastructure is crucial to life-cycle emission comparisons.

Ahmadi & Kjeang (2015) studied the four major Canadian provinces investigate the FCV life cycles compared to gasoline vehicles. Hydrogen is produced by electrolysis, thermochemical water splitting, and steam methane reforming. The three hydrogen-generating methods in all four provinces reduce greenhouse gas and emissions, except for electrolysis in Alberta, where fossil fuels prevail. Thermal hydrogen synthesis works best due to renewable waste heat, followed by Quebec and BC electrolysis from sustainable hydroelectricity. Ontario's nuclear power uses waste heat and electricity, renewable production energy and low-emission compression and distribution of electricity reduce life cycle emissions significantly. Hydrogen from Canadian natural gas will be the most affordable fuel and balances pollution reductions and financial advantages for FCV adoption in all provinces.

2.8.3 COST AND FEASIBILITY ANALYSIS

In this work Hileman and Stratton (2014) offered criteria where possible alternative jet fuels are compared and investigated important drivers for alternative fuels in view of aviation's needs. Using these criteria, a broad spectrum of transportation fuels was qualitatively investigated. Alcohols and biodiesel are better suited for ground transportation because of their safe use and the energy efficiency loss. Though concerns about the economic cost of production and the present lack of feedstock availability limit their near availability in aviation.

Gül (2008) study aims to advance our knowledge by evaluating the competitiveness of alternative fuels in transportation. Three main studies are defined. Using the European Hydrogen Markal model (EHM) and the Global Multi-regional MARKAL model (GMM), scenarios are examined and cost factors and expenses of components of fuel generation and distribution are analysed.

Mitkidis et al. (2017) attempt to show that Greece has resources to enable indigenous and maybe commercial production of 2nd generation biofuels in order to meet the targets of the European Union "Renewable Energy Directive". Following a review of the biofuels market in Greece and investigating the availability of second-generation resources, a market analysis has been conducted. Economic feasibility for production has also been analysed. Given suitable technological pathways and feedstocks chosen that minimize overall supply-chain and production costs, along with strong policies, it could be an attractive choice.

Dan et al. (2023) aim to identify, rank, and determine relative weights of all factors influencing the feasibility of possible alternative vehicles by DEMATEL (Decision-Making Trial and Evaluation Laboratory). The outcome shows that infrastructure availability followed by charging/refueling time, environmental impacts, and vehicle upfront cost is the most important factor of Alternative Fuel Vehicle feasibility.

Mathur et al. (2022) examined the economic feasibility and carbon footprint and presented a whole picture of the part where alternative or biofuels used in agriculture. This paper also covers the several generations of biofuels in reaching carbon neutrality, their effects on the environment, uses in agriculture, and various constraints in implementing.

2.8.4 EMISSIONS ANALYSIS

Masuk et al. (2021) evaluated several alternative fuels with gasoline by means of analysis of their availability, engine tests, toxic element emissions, price, etc. Moreover, a selection criterion for alternative fuels is presented in several measuring scales that will be useful for selecting different fuels. Ethanol is said to cause 80% less CO emissions with proper blending with gasoline.

Beer et al. (2002) estimated alternative fuels, the expected pre-combustion and post combustion emissions of greenhouse gases from Australian heavy vehicles. Fuel-cycle emissions are the lowest in biodiesel and ethanol. Ethanol lowers emissions by 49–55%; biodiesel lowers greenhouse gas emissions from 41% to 51%.

Meyer et al. (2011) analysed total fuel-cycle (TFC) analysis for Class 8 HDVs for six fuel paths, and assesses the energy and emissions impacts of these fuels in the HDV sector. For most pollutants, results clearly show benefits from biodiesel and compressed natural gas; e-diesel has little to no effect; and liquefied natural are shown to increase greenhouse gas emissions.

Ou et al. (2010) analysed the future scenarios involving several alternative fuels/vehicles. By 2025 in the BAU scenario, GHG emissions would reach 734 million tonnes of oil equivalent and 2384 million carbon dioxide equivalents respectively, more than five times of 2007 levels. For GHG emissions, the relative reductions attained in the best case would be 15.8% and 27.6% compared to the BAU case.

Sengupta and Cohan (2017) analysed Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model for every vehicle alternative. Cost per kilometer was computed using first purchase price added with fuel and maintenance expenses. Results show HEVs can achieve 36% lower GHG emissions. BEVs and PHEVs offer still further emissions reductions. CNG sedans and trucks could only offer 11% emissions reductions. Total fuel cycle GHG and air pollutants of additional conventional gasoline vehicles, HEVs, PHEVs, BEVs, and compressed natural gas (CNG) vehicles were assessed using City of Houston data to the City's fleet.

2.8.5 SYSTEM DYNAMIC MODELING METHODOLOGY

Wang et al. (2008) introduced a system dynamics methodology grounded in cause-and-effect analysis and feedback loop frameworks. The model operates within Vensim PLE software utilizing data from Dalian, China. The coefficient of the car ownership intervention policy is selected as the control variable for simulation, and the effects of various policy scenarios on urban development and the transportation system are examined. It recommends that Dalian limit the overall number of cars in order to make the transportation system more sustainable.

Haghshenas et al. (2014), 9 urban sustainable transportation indicators were selected from the study database, 3 for each main group of environmental, economic, and social sustainability. The relevant metrics were combined using a composite index. A system dynamics model was created to investigate transportation sustainability in medieval Isfahan. Isfahan sustainable transportation metrics were monitored using future scenarios to identify effective transportation policy.

Sayyadi & Awasthi (2018) studied System Dynamics (SD) efficiently analyzes dynamic complexity and policy-resistant systems. This technique is suited for analyzing transportation issues. It is particularly useful in developing and implementing sustainable transport strategies. This research performs a thorough literature assessment to evaluate SD's use in sustainable transportation urban policy. Most of their research examines transportation strategies that reduce air pollution and traffic congestion.

Shepherd (2014) assessed the advantages and disadvantages of system dynamics (SD) as a modeling approach in the transportation sector. Their list included 12 advantages of the approach, highlighting its suitability for strategic challenges and its potential as a valuable instrument for facilitating policy research and decision-making in the transportation sector. This methodology facilitates the seamless integration of transport models with other sectors, including health, environment, and the economy, while considering temporal delays and feedback mechanisms across many scales. It is important to acknowledge that SD is not designed for accurate point forecasts.

Hu et al. (2019) used a system dynamics methodology to simulate the growth of the Urban freight transportation system, concentrating on internal processes and external influences. Various variables influencing system operations, including metrics of social and environmental externalities, pricing, investment, and subsidies, have been incorporated into two sub models. The results show that urban freight transportation system schemes with increased funding and capacity result in more significant decreases in traffic congestion, air pollution, and accidents.

Lum & Kenny (2023) analysed to comprehend the socio-economic issues of the energy transition, a System Dynamic model of Singapore's economy, energy & GHG emissions, and labor market was created. The model suggests that energy transition should be managed through a multi-pronged approach of technological changes, labor and energy use efficiency enhancements, and managing the availability of skilled local labor versus increasing the foreign worker ratio, especially when new technologies are used.

Loh & Bellam (2024) investigates Singapore's probable paths to achieving net zero goals while boosting energy security based on current and future energy plans. Using system dynamics, current and projected policies can be examined to provide new energy solutions to increase energy security. Findings suggest that Singapore should aim for >80% renewable energy by 2050.

Rafew et al. (2024) in Regina, Saskatchewan, system dynamics (SD)-based policy simulation has been used to quantify ZEV evolution and charging pile. To predict ZEV sales, SD model uses vector autoregressive model (VAR) equations and site-specific coefficients using Saskatchewan's historical vehicle registration dataset. To find the best possible fit combination, the agent-based SD model 18 with two successive scenarios was run till 2036.

Wen et al. (2016) predicted and compared Beijing's industrial carbon emissions in ten policy scenarios and makes emission-cutting recommendations. System dynamics has been used to predict and simulate numerous scenarios. The model was created using a causal loop diagram and stock flow diagram. The predicted and scenario simulation findings suggest that energy structure, carbon intensity, and heavy energy consumption organizations are essential elements, and numerous factors affect industrial carbon emissions more. Simulation results have led to low-carbon Beijing industrial carbon emission recommendations.

Sayyadi & Awasthi, 2016 studied a system dynamics-based simulation model to assess sustainable transport planning regulatory strategies has been used. Transportation system components, their interactions, and behavior development are studied using causal loop diagrams. A vehicle trip reduction numerical study is offered. The simulation analysis shows that trip-sharing policy reduces congestion while automobile ownership decreases tendency of vehicular trips and improves public transit journeys.

Redick et al. (2025) to achieve net-zero greenhouse gas (GHG) emissions by 2050, Canada aims to have 35% of new heavy-duty truck sales be zero-emission by 2030 and near 100% by 2040. System dynamic simulation is used and stock and flow model are created to estimate the adjustments needed to transition from diesel to battery electric and fuel cell electric vehicles in Alberta. With current BEV and FCEV vehicles and infrastructure, the 35%-by-2030 aim is not feasible.

2.9 RESEARCH GAP

- Not many studies focusing on modeling net zero emission goal for transportation In Canada.
- Lack of system dynamic models that analyze biofuels, hydrogen, and EV emissions together in a Canadian context.
- Lack of integrating public buses and bikes into the system dynamic model to reduce GHG emissions.
- Not enough research on comparison of various factors responsible to help increase the adoption of alternative fuel-based vehicles, public buses and bikes.
- Limited data on customer acceptance, behavior, and alternative fuel adoption challenges.
- Insufficient economic models that analyse long-term costs, benefits, and market dynamics of switching from gasoline in Canada.
- Need more dynamic models to address uncertainty and quick technology advancements.
- Not enough studies address geographic variations and social and cultural issues, especially in different socio-economic and indigenous groups in Canada.

CHAPTER 3

METHODOLOGY

3.1 SYSTEM DYNAMICS MODELING

The use of system dynamics is common in many scientific and technological domains. It is a well-constructed approach that takes cause-and-effect relationships into account when analyzing a system's constituent parts. The two primary tools for modelling system dynamics are Causal Loop and Stocks-Flow diagrams, which enable both qualitative and quantitative analysis of the system's dynamics (Pérez et al., 2002). According to Rahim, Hawari, and Abidin (2017), system dynamics is the study of complex systems' nonlinear behavior over time employing internal feedback loops, stocks, flows, table functions, and time delays. Professor Jay Forrester of the Massachusetts Institute of Technology developed system dynamics in the middle of the 1950s (Lane & Sterman, 2011). Forrester opted to become a lecturer at the recently established MIT Sloan School of Management in 1956. His first objective was to discover how his experience in science and engineering could possibly be utilized in solving the fundamental problems that determine whether a company succeeds or fails (Lane & Sterman, 2011). System dynamic models are hence thinking machines that can provide answers to "what if" scenarios involving potential futures that are challenging to develop and test in a non-virtual manner (Grieves & Vickers, 2016).

Although there are numerous tools available for simulation, Insight Maker is an innovative, free-of-charge, Web 2.0-based, multi-user, general-purpose, online modeling and simulation environment, fully implemented in JavaScript, which promotes online sharing and collaborative working (Hristoski & Mitrevski, 2017). The primitives associated with system dynamic simulation are stocks, flows, variables, links and loops.

3.2 TYPES OF PRIMITIVES

A. STOCK

Definition:

In a system, stocks stand for collections or state variables. Depending on inflows and outflows, they store quantities that fluctuate over time.

Features:

- Serve as value-holding reservoirs.
- Transform over time according to flows.
- indicate a system's states.

Examples include:

- the town's population.
- A reservoir's water.
- A warehouse's inventory.
- A bank account with assets.

Graphic representation: Insightmaker's representation of a stock is a rectangular box.

Figure 9 Image of a stock in Insightmaker.

B. FLOW

Definition:

The rates at which stocks rise (inflows) or fall (outflows) over time are referred to as flows.

Features:

- Describe the speed at which a stock fluctuates.
- It could be time-dependent or constant.
- Represent the comings and goings of a stock.

Examples:

- Include how the population stock is impacted by the birth and death rates.
- A lake is impacted by both water influx (rainfall) and outflow (evaporation).
- Sales and production rates in inventory control.

Insightmaker's Graphical Representation: An arrow that resembles a valve and points into or out of a stock is used to symbolize a flow.

Figure 10 Image of an outflow and inflow in Insightmaker.

C. VARIABLES (AUXILIARY VARIABLES)

Definition:

Intermediate values that help in articulating the relationships between stocks and flows are saved by variables, commonly referred to as auxiliary variables.

Features:

- Adjust the way flows behave.
- can stand for either dynamic values (like market demand) or constants (like the tax rate).
- Serves as the equation's input parameters.

Examples:

- the birth rate in relation to the resources that are available.
- Money growth is impacted by interest rates.
- Water loss is impacted by evaporation rate.

Insightmaker's graphic representation of a variable is a circle.

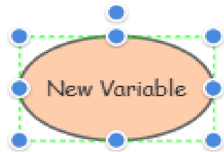

Figure 11 Image of new variable in Insightmaker.

D. CONNECTIONS (LINKS)

Definition:

Links convey connections between various components, such as variables, stocks, and flows.

Features:

- Define causal relationships.
- Make space for logical conditions and equations.
- Show how feedback loops operate.

Example:

- A birth rate variable connected to a birth flow is one example.
- Money growth is influenced by interest rates.
- Inventory management is influenced by supply chain delays.

Insightmaker's Graphical Representation: Links show up as arrows joining various primitives.

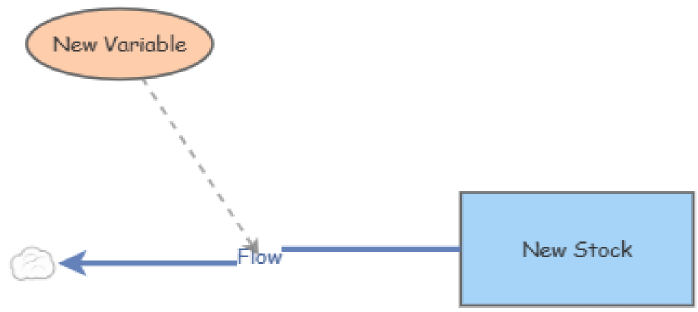

Figure 12 Connections in Insightmaker.

E. FEEDBACK LOOPS

Definition:

Feedback loops explain how components of a system affect one another through balancing or reinforcing mechanisms.

Types of Feedback loops:

- Reinforcing loop (Positive feedback)-Accelerates change, resulting in collapse or exponential expansion.
- Balancing loop (Negative Feedback)-Keeps the system balanced by stabilizing it.

Example:

More money leads to more interest, which leads to even more money. (positive loop)

As a result of scarce resources, population growth is slowing down. (balancing loop)

Insightmaker's Graphical Representation: Loops are made with variables and links.

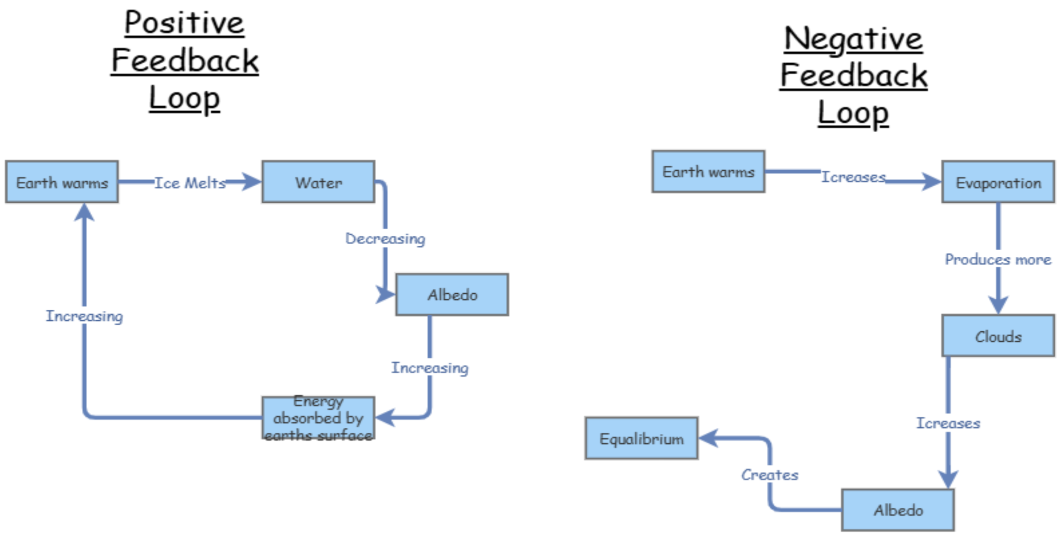

Figure 13 Image of feedback loop in Insightmaker.

F. OUTPUTS AND GRAPHS

Definition:

By showing the outcomes of a simulation, graphs assist users in identifying patterns.

Features:

- Offers visual input on the system's development.
- Possible to display several variables throughout time.

Example:

- Increase in the bank balance with compound interest.
- Ecological resource depletion.
- Population trends over time.

Insightmaker's Graphical Representation: Presented as bar or line charts.

Figure 14 Example of a graphical representation in Insightmaker (Zorpas et al., 2016).

3.3 CAUSAL LOOP DIAGRAM WITH AN EXAMPLE

In system dynamics, a Causal Loop Diagram (CLD) is a visualization that shows how several variables relate to one another. It facilitates comprehension of feedback loops, cause-and-effect relationships, and the long-term behavior of systems. In disciplines including organizational management, environmental science, healthcare, and economics, CLDs are especially helpful for understanding complex systems. For example, Davahli et al. (2020) inspected the case of healthcare, Numerous auxiliary variables, such as the number of occupied beds, patients, and empty beds, can be connected to hospital patients or patients on hospital wards. Several auxiliary factors, including treatment duration, conditions, and hospital personnel size, might be linked to and affect the patient treatment rate. The in-patient discharge, the need for additional treatment, the need for recovery, and the need for therapy are some of the auxiliary variables that might be connected to the patient undergoing evaluation for discharge.

Figure 15 displays the primary portion of the causal loop diagram. There are three balancing loops B1, if patients waiting increases, then admissions rate increases and thus it decreases the number of patients waiting. The second loop B2, if the admissions rate increases, then the patient in care increases and thus the admissions rate decreases. In the third loop B3, if patient in care increases, treatment completion rate also increases and patient in care decreases (Davahli et al., 2020).

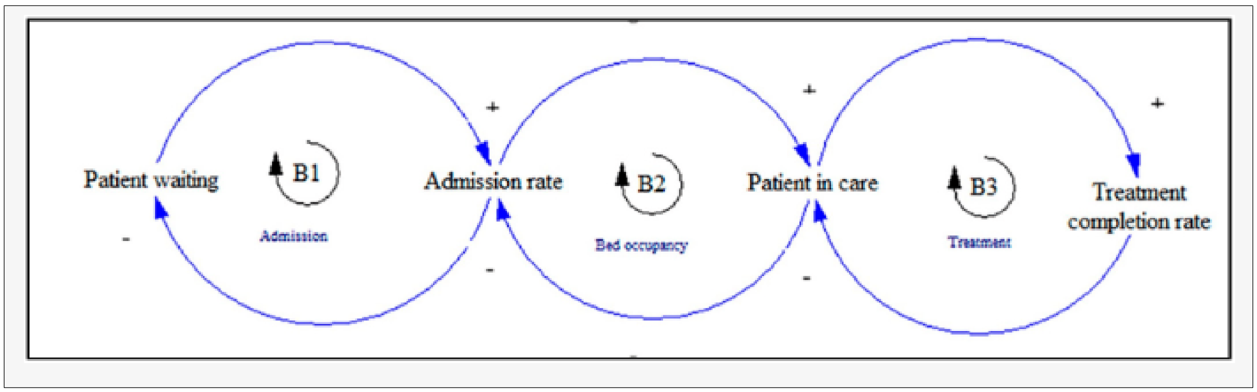

Figure 15 Causal loop diagram of example in healthcare (Davahli et al., 2020).

3.4 STOCK AND FLOW MODEL DIAGRAM WITH AN EXAMPLE

To illustrate how various variables in a system build up, deplete, and interact over time, a stock and flow diagram (SFD) is a basic tool in system dynamics modeling. By offering a more organized and quantitative depiction of the system, it goes beyond the Causal Loop Diagram (CLD) and makes mathematical formulation and computational simulation possible. According to Sulaimany et al. (2024), there are only two basic categories of variables for all complex systems: stocks and flows. While flows, which include inflows and outflows, indicate the movement of units over time and are graphically depicted as arrows, stocks, which represent accumulations of units, are shown as a rectangle in a graphical representation (Figure 16). Decision functions, which are shown as valves on the inflow and outflow, control flows, whereas stocks can only be changed by their interdependent inflows and outflows.

Decision functions, represented by valves on the inflow and outflow, govern flows, although stocks can only be altered by their interdependent inflows and outflows.

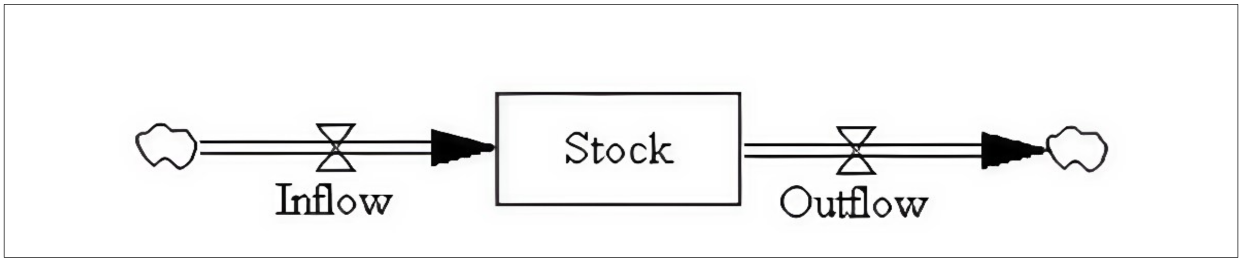

Figure 16 Stock flow model (Sulaimany et al., 2024).

The integral equation is as follows (Schoenenberger et al., 2021):

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0)$$

In the example of healthcare, patient admission rate is inflow and, patient in hospital or patient on wards (stock), patient treatment rate inflow to patient treatment in assessment (stock), and outflow is patient discharge.

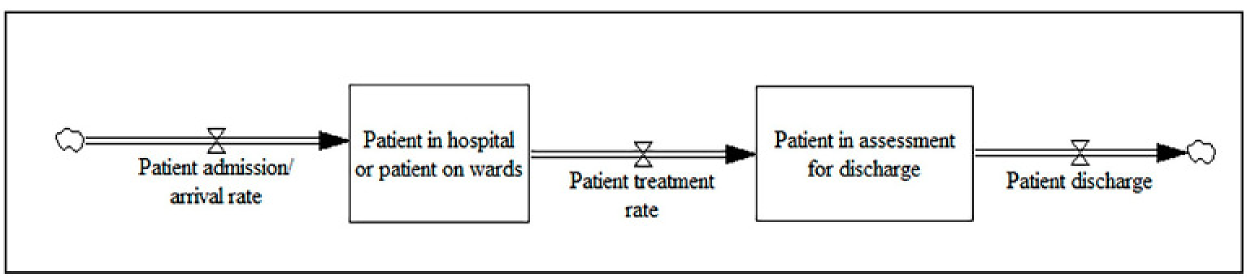

Figure 17 Example of stock flow diagram in healthcare (Davahli et al., 2020).

3.5 STEPS INVOLVED IN SYSTEM DYNAMIC SIMULATION

- The process of system dynamic simulation includes a lot of steps that all work together to help you understand and analyze how complicated systems change over time. These steps include outlining the primary objective and the scope of the goal. This stage is essential as it guarantees that the simulation concentrates on certain objectives and variables.

- The subsequent phase consists of conceptualizing the system and establishing its boundaries. This phase focuses on specifying the system's architecture by recognizing essential components and their interconnections. Researchers tend to use causal loop diagrams (CLDs) to visually illustrate the cause-and-effect linkages among variables. These diagrams identify feedback loops both reinforcing (positive) and balancing (negative) offering a qualitative comprehension of the system's evolution. Stock and flow diagrams are utilized to depict accumulations (stocks) and the rates of change of these stocks flows. These diagrams function as blueprints for the model, specifying the feedback loops and identifying the essential factors that will advance the simulation After the conceptualization phase, the simulation method grows to the formulation of the model structure.
- A crucial next stage in system dynamic simulation is validation of the model. This phase involves allocating numerical values to the variables and parameters defined in prior stages, and it is sometimes one of the hardest components of model creation. Sources for proof can consist of historical records from governmental or industrial reports, academic studies. Each stock, flow, and feedback loop are depicted using equations usually that capture the fundamental relationships among variables.
- Verification is the procedure via which researchers confirm that the model has been accurately built, devoid of computational errors, and that its logic is valid. Validation procedures include historical data matching, wherein the model's output can be compared with established trends from the past, and evaluations.
- Once the model has been tested and validated the simulation runs can be constructed. Scenario testing is a vital component of this phase, wherein researchers investigate "what-if" scenarios by modifying input parameters or external variables. This facilitates a deeper awareness of the system's potential reactions to multiple factors like government initiatives, infrastructure readiness or customer perception. Then sensitivity analysis is performed to understand how multiple factors interact in the system. Effectively conveying the simulation results in a clear and comprehensible manner is essential, particularly when the outcomes are meant to guide for strategic planning. Researchers frequently utilize visuals, including charts, graphs, and dashboards, to clearly illustrate dynamic behaviors and trends.

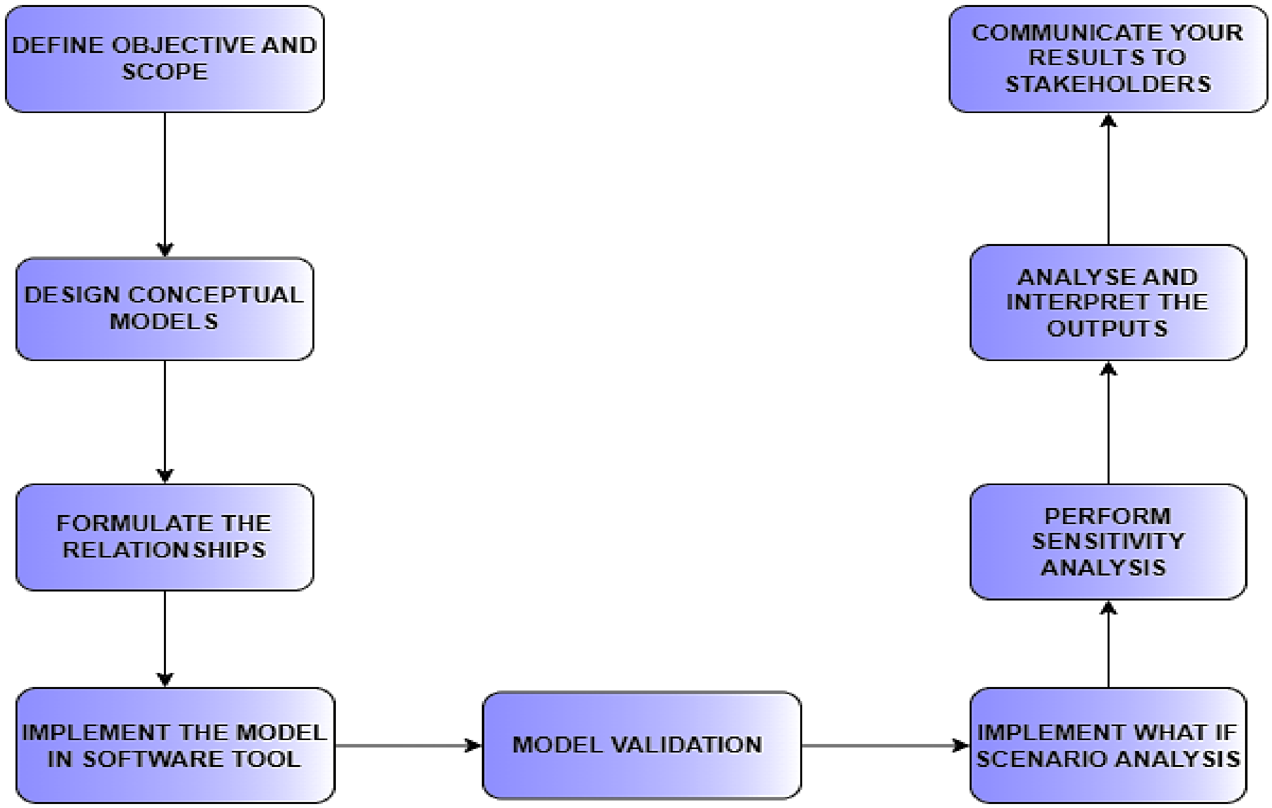

Figure 18 Process of simulation

3.6 DEFINING OBJECTIVE AND SCOPE

The objective is to explore how different modes of transportation and vehicle technologies like EV vehicles, biofuel vehicles, hydrogen vehicles, gasoline vehicles, public buses and bikes interact with the key factors like government initiatives, customer awareness, infrastructure developments and price of fuel and vehicle that influence their growth and observe how greenhouse gas emissions decrease over time to meet net zero goal.

The scope of this simulation is to find system boundaries. The temporal boundary of this simulation is 25 years. We are trying to perform what if scenario for the years 2024-2050. The geographical boundary of this simulation is Canada. Our technological boundaries for this simulation include three types of alternative fuel-based vehicles that have gotten popular in recent times that is electric vehicle, biofuel-based vehicles, hydrogen fuel-based vehicles. Since our objective is to also reduce emissions, we have included gasoline fuel-based vehicles which are extensively being used and efforts are being made to reduce these vehicles on roads to help curb pollution levels. We have also included two modes of transportation which is public bus and, in our simulation, has been taken as hybrid public buses due to data constraints and bikes that have also gained popularity in recent times and are proven to have zero emissions.

Key variables that drive the increase in vehicles and different mode of transportation include

1. Customer awareness

It include knowledge about the technology, for example the various methods of charging a vehicle in the case of electric vehicles or different blends used in biofuels, understanding the rebates and incentives that are being provided, understanding the importance of switching to alternative fuels to help reduce emissions, learning about the risks and benefits of the technology, understanding the importance of public transportation and biking on the benefits of health and environment, knowledge on where to look for more information about these vehicles.

2. Government Initiatives

It includes incentives while purchasing the vehicles to reduce upfront costs, reduced registration fees compared to the traditional gasoline vehicles, more tax credits for using alternative fuel-based vehicles, more incentives for developing infrastructure facilities, mandates for automakers, stricter emissions regulation for gasoline vehicles, creating promotional advertisements and programs to motivate the people and teach them the benefits of sustainable transportation, more funding and research and development in improving the infrastructure and technology.

3. Fuel Price

It includes lower electricity prices compared to gasoline prices for EV adoption, the price difference of biofuels compared to gasoline, the cost of blending biofuels with traditional fuels impacts the overall fuel price, cost of hydrogen fuel for hydrogen vehicle adoption.

4. Cost of vehicle

It includes cost of EV vehicles, the cost of battery, different models of the vehicle, cost of biofuel vehicles, cost of engine modification expenses if needed, cost of hydrogen fuel-based vehicles, cost of bikes, higher end models, electric bikes that are more expensive, reduced cost of public bus fares.

5. Infrastructure

It includes expansion of public charging networks in highways, cities and in workplaces, installation of home charging infrastructure, upgrading existing fuel distribution networks to accommodate biofuels, improving grid to handle increased electricity demand from EVs, ensuring compatibility of fuel pumps and storage tanks with various biofuel blends, investing in infrastructure for the production of green hydrogen from renewable energy sources, building a network of hydrogen refueling stations strategically located along major transportation corridors, construction of dedicated bike lanes and paths , installation of bike parking facilities and repair stations, expanding and improving bike-sharing systems, expansion of bus routes and increased frequency of service, improvements to bus stops and terminals, increase accessibility and convenience.

3.7 DESIGNING CONCEPTUAL MODELS

Creating your conceptual models in Step 2 is essential as it provides a visual and structural illustration of the interactions among different components of your system. This foundation guarantees that as you proceed to develop mathematical relationships and construct the simulation, you possess a comprehensive overview of the essential dynamics, feedback loops, and dependencies. This clarity helps model validation and gives stakeholders a clear understanding of how different components contribute to achieving the objective.

3.7.1 CAUSAL LOOP DIAGRAM OF THE MODEL

Causal loop diagrams, also known as CLDs, are an effective tool for visualizing the interdependencies and feedback processes that are present inside a system. Using a CLD, one can identify the cause-and-effect links that exist between various system variables, thereby drawing attention to feedback loops that have an effect on the behavior of the system over time. Through the utilization of a causal loop diagram, the objective of this study is to conduct an analysis of how various factors like government initiatives, customer awareness, cost of various fuels and vehicles, infrastructure development and greenhouse gases interact with different entities of sustainable transportation solutions like using public buses, biking and reducing the use of gasoline vehicles.

3.7.1.1 LIST OF VARIABLES USED IN THE CAUSAL LOOP MODEL

Name	Description
Bikes	Personal bikes
Biofuel adoption	Increase in biofuel vehicles
Charging infrastructure of EV	Charging stations, maintenance facilities, home charging station.
Clean grids for EV	Improvement in grid technology for EV charging
Customer Awareness	User behaviour for adopting these technologies and other modes of transportation.
Cost of bikes	Average cost of a bike
Cost of fuel and vehicle	Cost of fuel for alternative vehicles, cost of electricity prices for charging EV vehicles
EV adoption	Increase in EV vehicles
Fare price public bus	Cost of a ticket in public buses
Gasoline vehicles	Vehicles that run on gasoline
GHG emissions	GHG emissions of the system
Government initiatives	Initiatives led by the government to help consumers, businesses and people to help in better adoption of alternative fuel technology, bikes and public buses, penalties and higher taxes for using gasoline vehicles.
Hydrogen fuel adoption	Adopting hydrogen fuel-based vehicles
Infrastructure bikes	Bike paths, parking stations and maintenance repair stations for bikes
Infrastructure for alternative fuel	Infrastructure for transport and storage of fuels, production of fuels, improving and setting up more fuel stations
Public buses	Public buses that help in sustainable transportation

Table 1 List of variables used in causal loop diagram.

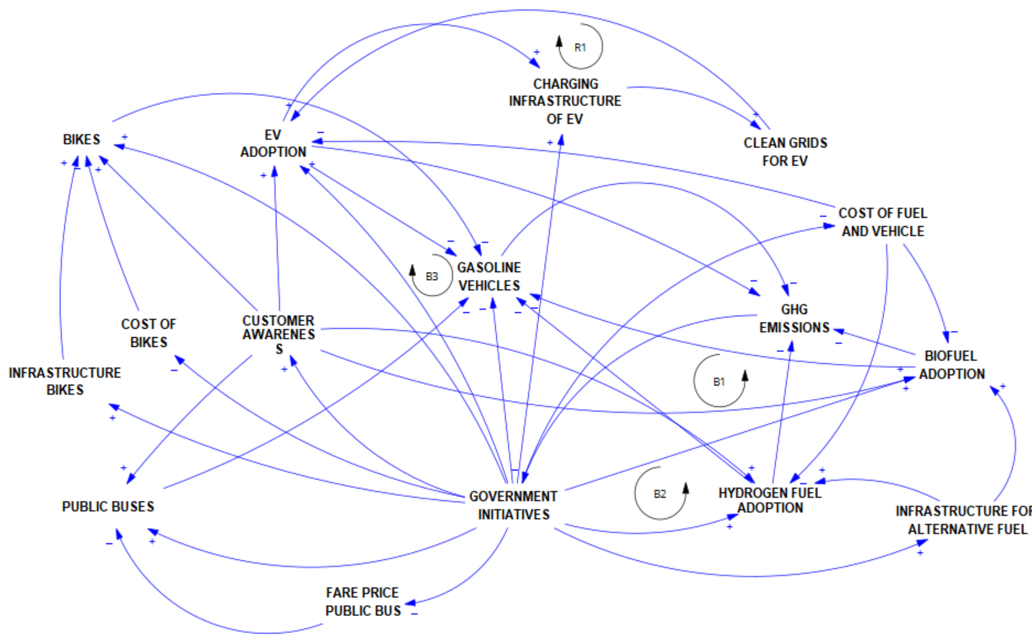

Figure 19 Causal loop diagram

3.7.1.2 RELATIONSHIP BETWEEN THE VARIABLES

Figure 20 shows the relationship between the variables. This matrix shows which elements for example cost, infrastructure, customer awareness has an impact on various modes of transportation or energy adoption (bikes, biofuel, electric vehicles, public buses). Every check mark shows how directly one variable affects another stressing the interdependence of variables. The table shows generally that several factors like government initiatives, infrastructure availability can collectively influence adoption patterns which underlines the need of an integrated approach to transportation planning and reduce emissions. Detailed relationship between the variables for all modes of transportation are discussed further through causal loop diagram.

Variables of interest	Variable(s) that are effected by the variable(s) of interest															
	BIKES	BIOFUEL ADOPTION	CHARGING INFRASTRUCTURE OF EV	CLEAN GRIDS FOR EV	COST OF BIKES	COST OF FUEL AND VEHICLE	CUSTOMER AWARENESS	EV ADOPTION	FARE PRICE PUBLIC BUS	GASOLINE VEHICLES	GHG EMISSIONS	GOVERNMENT INITIATIVES	HYDROGEN FUEL ADOPTION	INFRASTRUCTURE BIKES	INFRASTRUCTURE FOR ALTERNATIVE FUEL	PUBLIC BUSES
BIKES										✓						
BIOFUEL ADOPTION										✓	✓					
CHARGING INFRASTRUCTURE OF EV				✓												
CLEAN GRIDS FOR EV								✓								
COST OF BIKES	✓															
COST OF FUEL AND VEHICLE		✓						✓					✓			
CUSTOMER AWARENESS	✓	✓						✓					✓			✓
EV ADOPTION			✓							✓	✓					
FARE PRICE PUBLIC BUS																✓
GASOLINE VEHICLES											✓					
GHG EMISSIONS												✓				
GOVERNMENT INITIATIVES	✓	✓	✓		✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
HYDROGEN FUEL ADOPTION										✓	✓					
INFRASTRUCTURE BIKES	✓															
INFRASTRUCTURE FOR ALTERNATIVE FUEL		✓											✓			
PUBLIC BUSES										✓						

Figure 20 Effects between variables.

3.7.1.3 CAUSAL LOOP MODEL OF BIKES AND PUBLIC BUSES

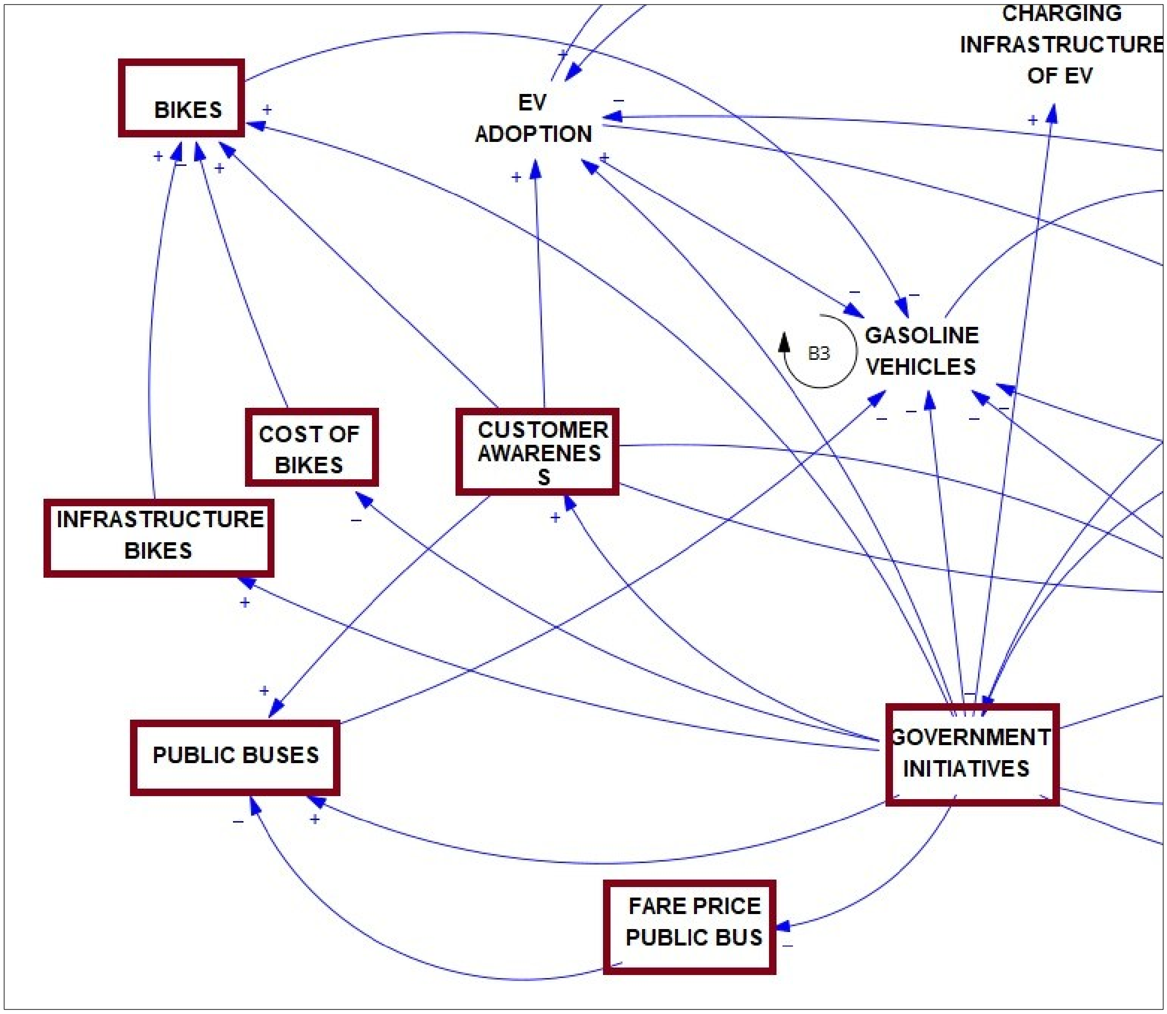

Figure 21 Highlighted part of bikes and public buses of the main diagram.

Here, from figure 21 we can observe variables consumer behaviour, cost of bikes, government initiatives, infrastructure of bikes have an effect on the variable bikes. When government initiatives increase then bikes also increase over time. By providing tax rebates and incentives, this will drive the customers into adopting biking culture. So, they are represented with a (+) arrow. When consumer behaviour increases, the bikes also increase over time because the customers are more aware of the importance and usefulness of bikes. Hence it is represented with a (+) arrow. If the cost of bikes decreases, then the number of bikes would increase over time. Since the bikes have become cheaper, it will drive many customers to purchase. Hence it is represented with (-) arrow. If the variable infrastructure bikes increase, then eventually bikes also increase. Due to developing and increasing bike paths and maintenance centers for bikes, the adoption of biking also increases. For public buses, if government initiatives increase then public buses increase. Government initiatives to build infrastructure, create more bus routes, invest in technology to improve the public bus system, increase in frequency of buses, help create awareness among the people to use more public transportation leads to growth in public buses. Hence it is represented with (+) arrow. If customer awareness increases, growth in public buses also increase. If more customers are aware of the benefits of using sustainable transportation, then the demand increases the number of public buses. Hence it is represented by (+) arrow. If cost of a fare of a public bus increase, then number of consumers decrease which eventually reduces the growth in public buses. Hence it is represented by (-) arrow.

3.7.1.4 CAUSAL LOOP MODEL OF EV ADOPTION

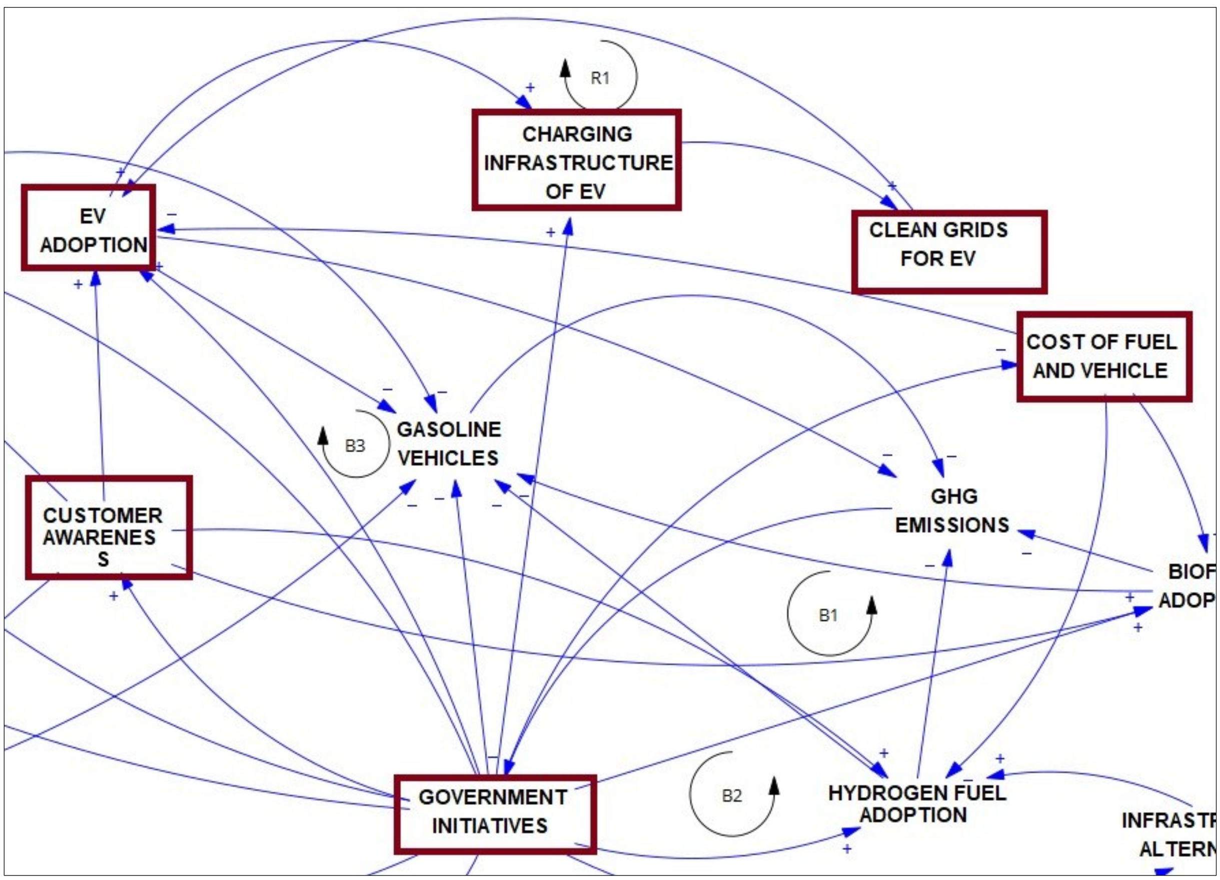

Figure 22 Highlighted part of EV adoption from the main diagram.

From figure 22 for EV adoption variable, the variables affecting it are consumer awareness, government initiatives, cost of fuel and vehicle, clean grids for EV, charging infrastructure of EV. If customer awareness increases then EV adoption increases. If customers are more aware of the technology and are willing to switch to EV's and they understand the benefits of using alternative fuel vehicles then the growth of EV adoption increases. Hence represented by (+) arrow. If government initiatives increase over time, then EV adoption also increases. For example, if the government initiates a program, mandates, incentives, rebates for helping the consumer switch to these alternative energy-based vehicles and also support the stakeholders interested in investing in improving this technology, then EV adoption increases. Hence represented by (+) arrow. If the cost of fuel and vehicle is lowered, then EV adoption increases. If we reduce the cost of vehicles and fuels by rebates, tax incentives while purchasing the car, reduced-price in-home charging station, reduced electricity prices then EV adoption increases. Hence represented by (-) arrow. Clean grids of EV increases, EV adoption also increases. If grid technology is improved and electricity generated from renewable sources, then a greater number of people will choose to adopt to EV vehicles. Hence represented by (+) arrow. If charging infrastructure for EV improves, then EV adoption also increases. By increasing the number of charging stations, improving the infrastructure, and installations of home and building charging stations, the adoption of EV vehicles increases. Hence represented by (+) arrow.

3.7.1.5 CAUSAL LOOP MODEL OF BIOFUEL ADOPTION AND HYDROGEN ADOPTION

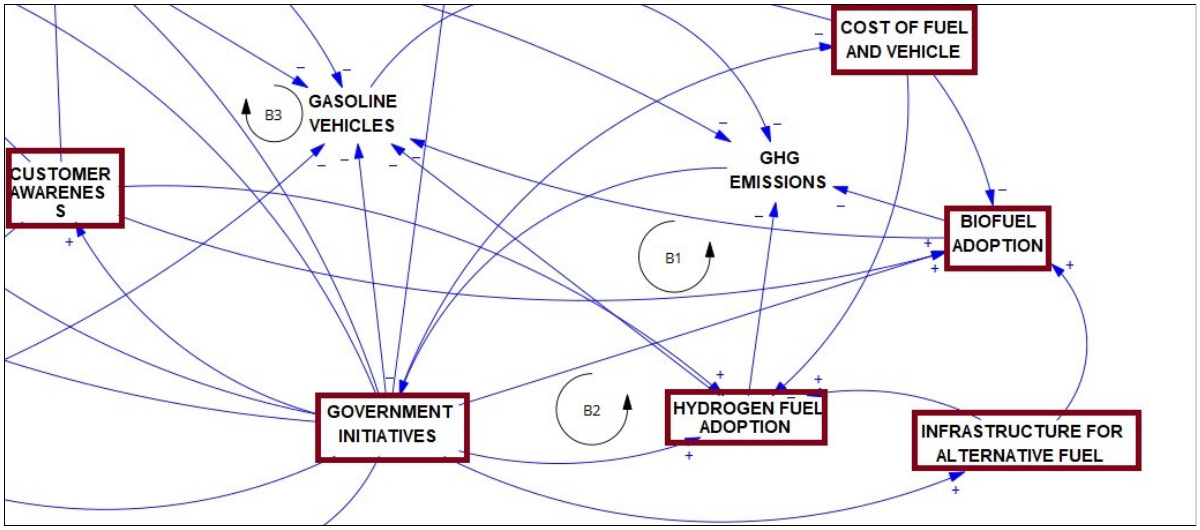

Figure 23 Highlighted part of biofuel adoption and hydrogen fuel adoption from the main diagram.

From figure 23 for biofuel adoption variable, the variables affecting it are customer awareness, government initiatives, cost of fuel and vehicle, infrastructure of alternative fuel. If customer awareness increases then biofuel adoption increases. If customers are more aware of the technology and are willing to switch to biofuels and they understand the benefits of using alternative fuel vehicles then the growth of biofuel adoption increases. Hence represented by (+) arrow. If government initiatives increase over time, then biofuel adoption also increases. For example, if the government initiates a program, mandates, incentives, rebates for helping the consumer switch to these alternative energy-based vehicles and also support the stakeholders interested in investing in improving this technology, then biofuel adoption increases. Hence represented by (+) arrow. If the cost of fuel and vehicle is lowered, then biofuel adoption increases. If we reduce the cost of vehicles and fuels by rebates, tax incentives while purchasing the car, fuel blends, reduced fuel prices. Hence represented by (-) arrow. If infrastructure for biofuel vehicle improves, then biofuel adoption also increases. By increasing the number of fuel stations, better storage and transportation of this fuel, increasing manufacturing of these fuels, the adoption of biofuel vehicles increases. Hence represented by (+) arrow. From figure for hydrogen fuel adoption variable, the variables affecting it are consumer awareness, government initiatives, cost of fuel and vehicle, infrastructure of alternative fuel. If consumer awareness increases then hydrogen fuel adoption increases. If customers are more aware of the technology and are willing to switch to hydrogen fuel and they understand the benefits of using alternative fuel vehicles then the growth of hydrogen fuel adoption increases. Hence represented by (+) arrow. If government initiatives increase over time, then hydrogen fuel adoption also increases. For example, if the government initiates a program, mandates, incentives, rebates for helping the consumer switch to these alternative energy-based vehicles and also support the stakeholders interested in investing in improving this technology, then hydrogen fuel adoption increases. Hence represented by (+) arrow. If the cost of fuel and vehicle is lowered, then hydrogen fuel adoption increases. If we reduce the cost of vehicles and fuels by rebates, tax incentives while purchasing the car, fuel types, reduced fuel prices. Hence represented by (-) arrow. If infrastructure for hydrogen fuel vehicle improves, then hydrogen fuel adoption also increases. By increasing the number of fuel stations, better storage and transportation of this fuel, increasing manufacturing of these fuels, the adoption of hydrogen fuel vehicles increases. Hence represented by (+) arrow.

3.7.1.6 CAUSAL LOOP MODEL OF GASOLINE VEHICLES

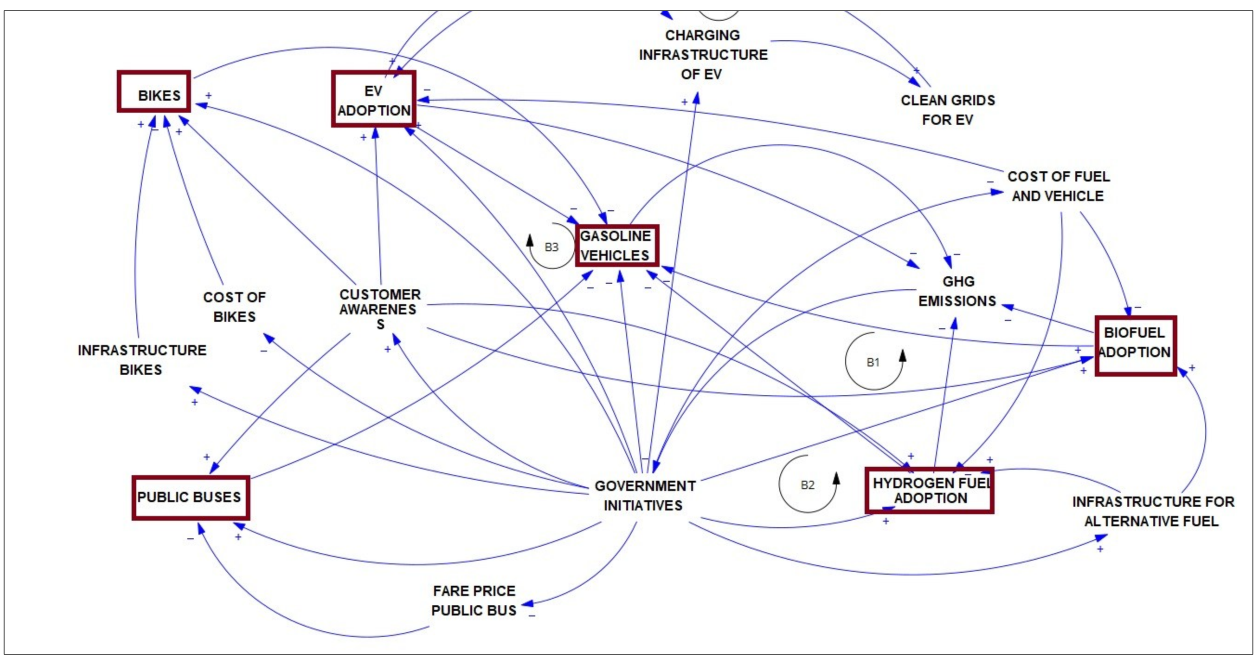

Figure 24 Highlighted part of the causal loop diagram that shows gasoline vehicles relationship with other variables.

If EV adoption increases, then eventually gasoline vehicles will be replaced and it reduces over time. Hence, it is represented with (-) arrow. Similarly, if more public buses are being used and more consumers start using bikes for short distance travel, then number of gasoline vehicles reduces over time. Hence, it is represented with (-) arrow. For hydrogen fuel adoption and biofuel adoption, if more consumers switch or adopt to these alternative fuel-based technology, then it will slowly replace the heavy carbon emitter vehicles like gasoline vehicles. So, it will decrease over time. Hence, it is represented with (-) arrow.

3.7.1.7 R1 REINFORCEMENT LOOP

R1 loop talks about variables clean grids for EV, charging infrastructure for EV and EV adoption. Below is the part of R1 loop in the causal loop diagram.

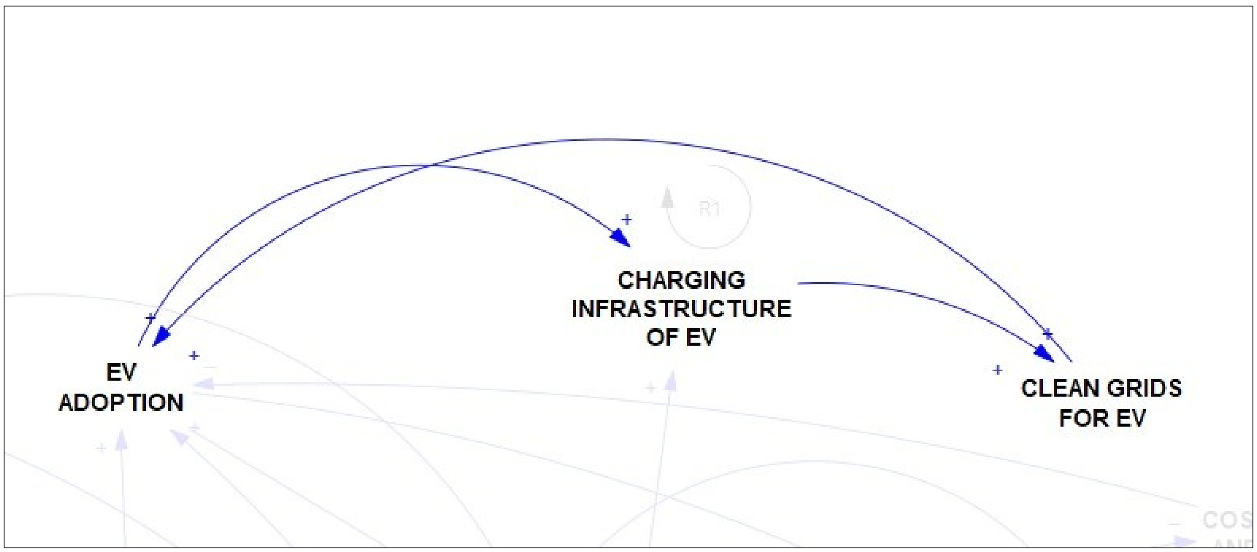

Figure 25 R1 loop of the causal loop diagram

The positive reinforcement loop between charging infrastructure of EV, clean grids for EV, and EV adoption is vital to sustainable transportation. This loop shows how EV adoption can start a chain of events that boost EV adoption. EV adoption shows the readiness to accept cleaner EV mobility alternatives. Environmental and sustainability concerns, enhanced vehicle performance, economic and government initiatives boost adoption. Creating a strong charging infrastructure for EV drivers refuel their vehicles reliably and conveniently with a well-distributed charging station network, boosting customer confidence in the technology. Expanding the charging network draws investment and technological innovation, which improves infrastructure. This makes charging station availability improve due to EV adoption.

Clean grids for EV are a part of technological and infrastructural advancements. Clean grids use renewable or low-carbon electricity to increase EVs' environmental benefits. Charging EVs using clean electricity reduces transportation's carbon footprint. Clean energy improves customer confidence in EV adoption.

EV adoption, charging infrastructure of EV, and clean grids for EV form a loop that boosts their benefits. EV adoption initially increases charging infrastructure of EV investment. More advanced and accessible charging networks boost EV demand. The increase in electricity demand from EVs adoption improves renewable energy investments, and the grid's ability to be used by more vehicles. The positive feedback loop creates a self-sustaining system where advances in one area accelerate progress in others, quickening the route to net zero emissions.

3.7.1.8 B1 BALANCING LOOP

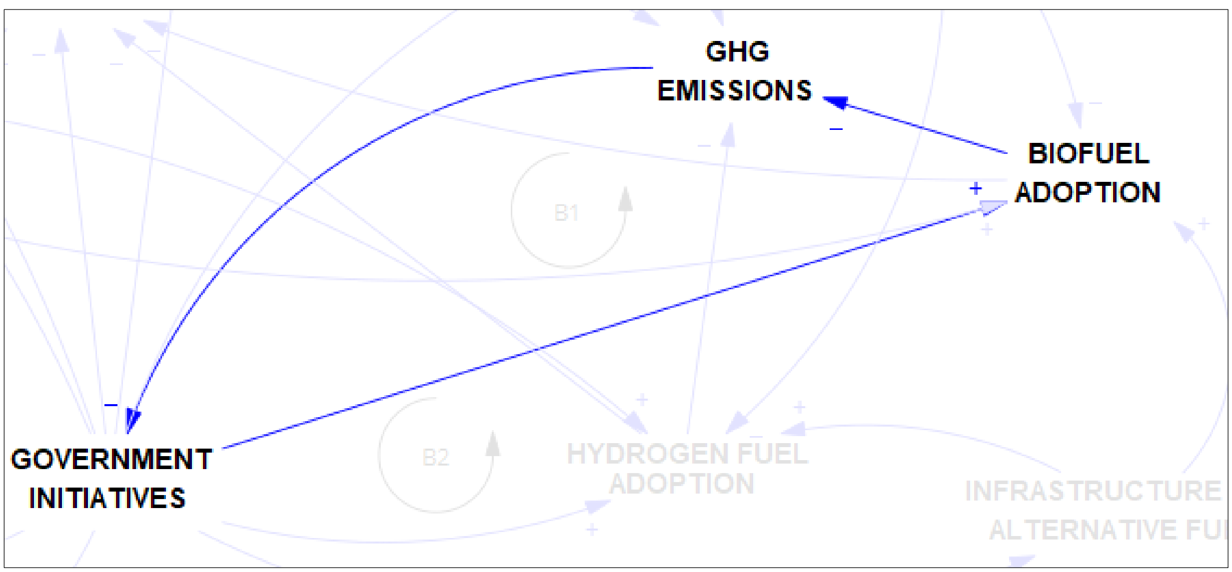

Figure 26 Balancing loop B1

Balancing Loop B1 illustrates the government initiatives increasing the biofuel adoption to reduce greenhouse gas (GHG) emissions in sustainable energy systems. Government subsidies, regulatory mandates, and public research funding are used to promote biofuel technology development. These initiatives stimulate biofuel usage with the goal of reducing GHG emissions.

GHG emissions decrease as biofuel replaces carbon-intensive energy sources. Biofuel, especially when produced through low-carbon or renewable technologies, can significantly reduce energy and emissions. As positive results are observed and GHG emissions fall, the urgency that motivated for policy initiatives slowly fades. Reduced emissions over time can alert policymakers that environmental goals are being met, prompting a reassessment of government initiatives. Balancing loops revolve around recalibration after a while. Reduced GHG emissions reduce the perceived need for significant government interventions, reducing biofuel adoption incentives. Thus, as the system meets its emissions reduction goals, the loop's feedback mechanism slows intervenes. This negative feedback prevents over-investment and over-regulation.

3.7.1.9 B2 BALANCING LOOP

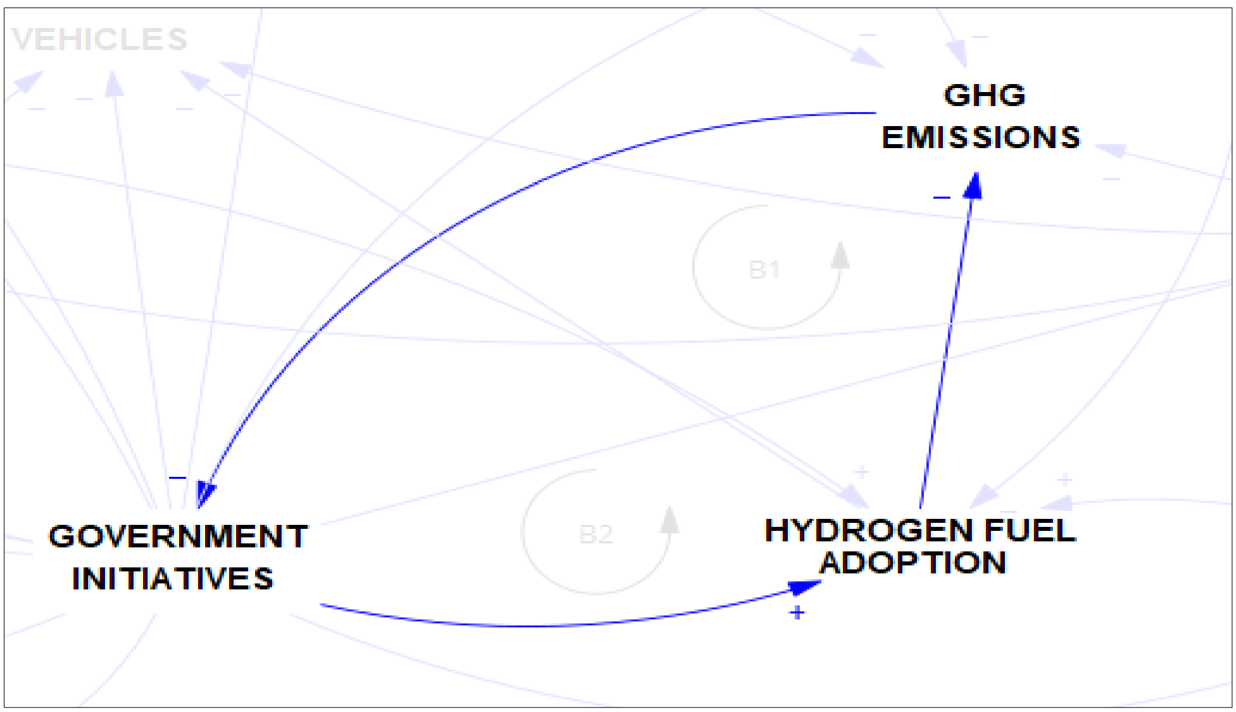

Figure 27 Balancing loop B2.

Balancing Loop B2 illustrates the government initiatives increasing the hydrogen fuel adoption to reduce greenhouse gas (GHG) emissions in sustainable energy systems. Government subsidies, regulatory mandates, and public research funding are used to promote hydrogen fuel technology development. These initiatives stimulate hydrogen fuel usage with the goal of reducing GHG emissions.

GHG emissions decrease as hydrogen fuel replaces carbon-intensive energy sources. Hydrogen, especially when produced through low-carbon or renewable technologies, can significantly reduce energy and emissions. As positive results are observed and GHG emissions fall, the urgency that motivated for policy initiatives slowly fades. Reduced emissions over time can alert policymakers that environmental goals are being met, prompting a reassessment of government initiatives. Balancing loops revolve around recalibration after a while. Reduced GHG emissions reduce the perceived need for significant government interventions, reducing hydrogen fuel adoption. Thus, as the system meets its emissions reduction goals, the loop's feedback mechanism slows intervenes. This negative feedback prevents over-investment and over-regulation.

3.7.1.10 B3 BALANCING LOOP

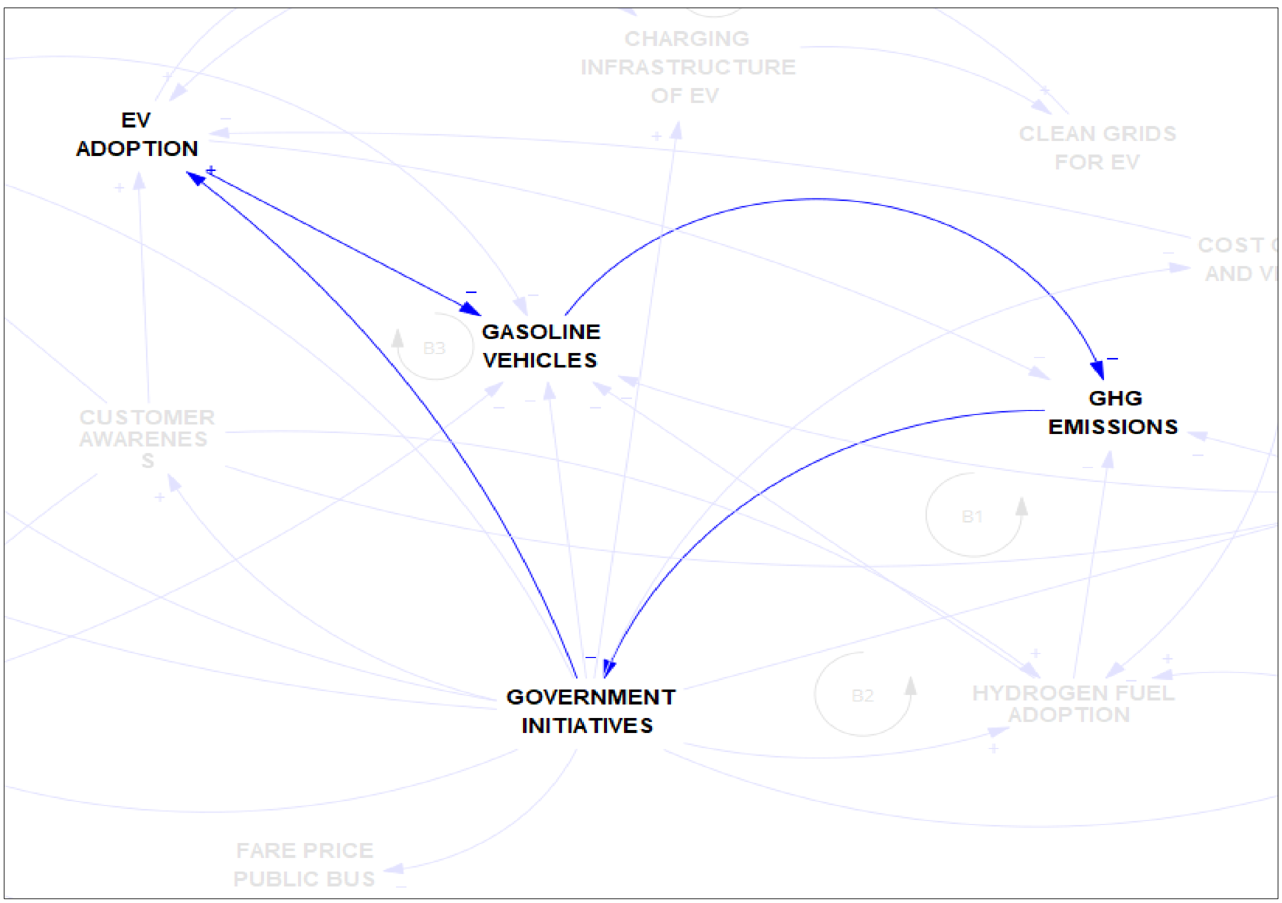

Figure 28 Balancing loop B3.

Balancing Loop B3 illustrates the government initiatives increasing the EV adoption and this also reduces the gasoline vehicles over time to reduce greenhouse gas (GHG) emissions in sustainable energy systems. Government subsidies, regulatory mandates, and public research funding are used to promote EV technology. These initiatives stimulate EV usage with the goal of reducing gasoline vehicles and GHG emissions. GHG emissions decrease as EV replaces carbon-intensive gasoline vehicles. EV can significantly reduce energy and emissions. As positive results are observed and GHG emissions fall, the urgency that motivated for policy initiatives slowly fades. Reduced emissions over time can alert policymakers that environmental goals are being met, prompting a reassessment of government initiatives. Balancing loops revolve around recalibration after a while. Reduced GHG emissions reduce the need for significant government interventions, reducing EV adoption incentives. Thus, as the system meets its emissions reduction goals, the loop's feedback mechanism slows intervenes. This negative feedback prevents over-investment and over-regulation.

3.7.2 STOCK FLOW DIAGRAM

In this stock and flow model created in Insightmaker, the first step is to identify the stocks, variables, and converters. Then subsequently, we find and establish relationships and interactions between the entities. Modelers build relationships and interactions between various entities. The links between stocks and flows are then turned into mathematical formulations, which usually are achieved via the use of equations. These formulas serve as a base for simulation.

3.7.2.1 LIST OF STOCKS, FLOWS AND VARIABLES

Name	Type	Description
EV vehicles	Stock	Number of EV vehicles
Increment_EV	Flow	Increase in EV
Eol_EV	Flow	End of life of EV decrement in EV
Fuelprice_EV	Converter	Cost of electricity to charge EV
Cost_EV	Converter	Cost of EV vehicle
Charging_Infrastructure_EV	Converter	Investments and research on EV charging public and private

Government_Initiatives_EV	Converter	Government helping in investments and spreading awareness
Customer_Awareness_EV	Converter	Knowledge about EV's and its benefits and drawbacks.
GHG_EV	Converter	Grid emissions
EV_Emission	Variable	Total EV emissions emitted through all the vehicles
Biofuel vehicles	Stock	Vehicles that run on biofuels
Increment_BV	Flow	Increase in biofuel vehicles
Eol_BV	Flow	End of life of a biofuel vehicle,
Fuelprice_BV	Converter	Price of biofuel blends with gasoline
Cost_BV	Converter	Cost of a vehicle that can run on biofuels
Infrastructure_BV	Converter	Biofuel production, biofuel transport, improved biofuel stations
Government_Initiatives_BV	Converter	Government helping in investments and spreading awareness
Customer_Awareness_BV	Converter	Knowledge about biofuel and its benefits and drawbacks.
GHG_BV	Converter	Emissions produced by a biofuel vehicle
Biofuel_Vehicle_Emission	Variable	Total emissions generated by all the biofuel vehicles
Bikes	Stock	Personal bikes
Increment_Bike	Flow	Increase in bikes
Eol_Bike	Flow	End of life of bikes or decrease in bikes
Cost_Bike	Converter	Price of a bike
Infrastructure_Expansion_Bike	Converter	Improving bike lanes and paths, repair stores, parking

Government_Initiatives_Bike	Converter	Government helping in investments and spreading awareness
Customer_Awareness_Bike	Converter	Knowledge about bikes and its benefits on health and environment
Annual_Mileage_Bike	Variable	Total distance a bike can be ridden in a year on an average
GHG_Bike	Variable	Emissions from a bike
Bike_Emission	Variable	Emissions from total number of bikes
Public Buses	Stock	Total number of public buses
Increment_PB	Flow	Increase in public buses
Eol_PB	Flow	End of life of a public bus or decrement in buses
Fare_public_bus	Converter	Cost of a ticket for a trip in public bus
Expansion_Infrastructure_public_bus	Converter	Improving bus stops, more bus routes, faster frequency
Government_Initiatives_public_bus	Converter	Government helping in investments and spreading awareness
Customer_Awareness_public_bus	Converter	Knowledge about public buses and its benefits on environment
GHG_PB	Converter	Emissions from a public bus
Public_Buses_Emission	Variable	Emissions from all public buses
Annual_Mileage_PB	Variable	Total distance a public bus runs in a year on an average
Hydrogen vehicles	Stock	Vehicles that run on hydrogen fuel
Increment_Hydrogen	Flow	Increase in hydrogen vehicles
Eol_Hydrogen	Flow	End of life of hydrogen vehicle or decrement in hydrogen vehicles
Fuelprice_Hydrogen_Vehicle	Converter	Cost of hydrogen fuel

Cost_Hydrogen_Vehicle	Converter	Cost of vehicle that runs on hydrogen fuel
Infrastructure_Hydrogen_Vehicle	Converter	Hydrogen fuel production, hydrogen fuel transport, improved hydrogen fuel stations
Government_Initiatives_Hydrogen_Vehicle	Converter	Government helping in investments and spreading awareness
Customer_Awareness_Hydrogen_Vehicle	Converter	Knowledge about biofuel and its benefits and drawbacks.
GHG_Hydrogen_Vehicle	Variable	Emission from a hydrogen vehicle
Hydrogen_Vehicle_Emission	Variable	Emissions from total number of hydrogen vehicles
Gasoline Vehicles	Stock	Vehicles that use gasoline fuel
Increment_GV	Flow	Increase in gasoline vehicles
Eol_GV	Flow	End of life of a gasoline vehicle or decrement of vehicle
Fuelprice_GV	Converter	Price of gasoline fuel
Cost_GV	Converter	Cost of a vehicle thar runs of gasoline
Government_Initiatives_GV	Converter	Government helping in investments and spreading awareness
Customer_Awareness_GV	Converter	Knowledge about biofuel and its benefits and drawbacks.
GV_lifespan	Variable	An average lifespan of a gasoline vehicle.
GHG_GV	Converter	Emission from a gasoline vehicle
Gasoline_Vehicle_Emission	Variable	Emissions from total gasoline vehicles
Annual_Mileage_Vehicles	Variable	Total distance a vehicle runs over a year on an average
Total GHG Emissions	Stock	Total GHG emissions from transportation
Increment_Total_GHG	Flow	Increase in GHG emissions

Decrement_Natural_Process	Flow	Decrease in emissions from carbon sequestration by planting trees

Table 2 List of all stocks, flows and variables used in the model.

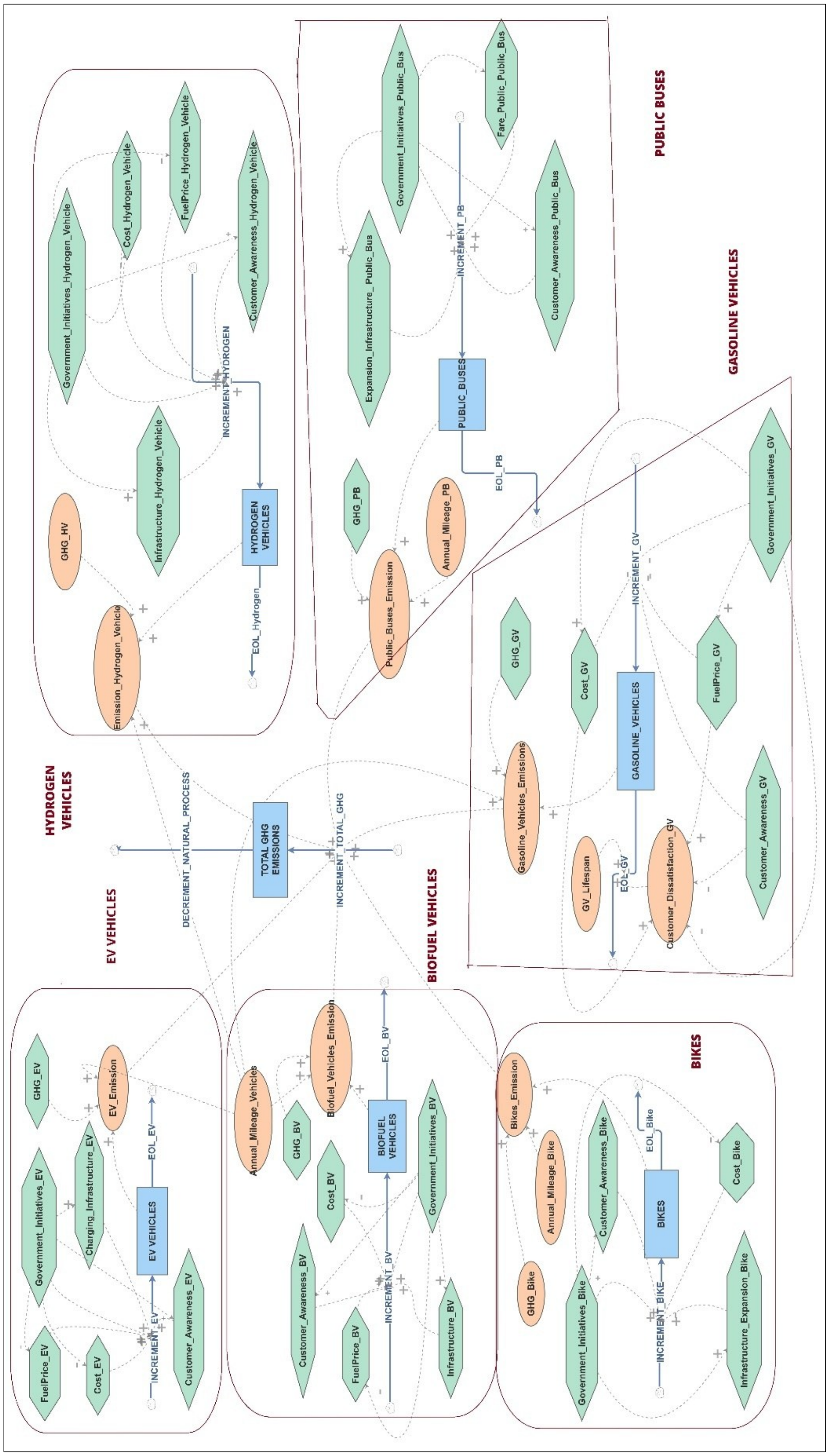

Figure 29 Stock flow diagram of the model

3.7.2.2 EV VEHICLES STOCK

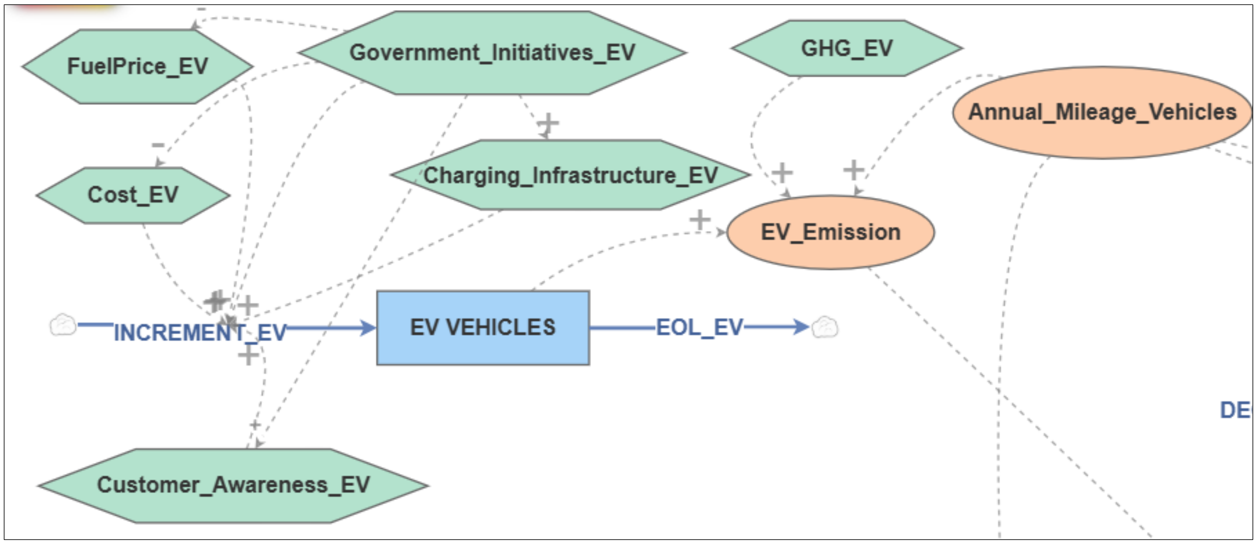

Figure 30 EV stock and its variables affecting it.

In this part of the model, we talk about EV vehicles. EV vehicles are created as a stock because the number vehicles increase over time. Here we take a sample input of cumulative total number of vehicles for a particular period of time. Since the temporal boundary of our model is 25 years, we take it as at time t=0 for 1999, the total number of vehicles was 0 due to lack of EV vehicles available commercially in Canada and the popularity of EV vehicles started increasing from 2011. And at time t=25 for the year 2024, the cumulative total number of vehicles is taken as 1978449. We have derived the value of stock at 2024 through cumulative sales of vehicles during this period due to lack of yearly based data. We have Increment_EV which is the increase in flow of EV's. And we have EOL_EV which is end of life of EV or the time it takes for an EV vehicle to retire. It is 15 years for an EV vehicle to be decommissioned.

The factors that drive the EV stock are represented by green hexagons. They are called converters. In InsightMaker, converters are not set values; they may shift over time in response to changing real-world conditions. A converter might assume several values at different times, like to a time series or a lookup table, rather than being an individual constant number. This enables the model to detect changes in factors such as Government_Initiatives_EV, FuelPrice_EV, Cost_EV, Charging_Infrastructure_EV, Customer_Awareness_EV as they progress throughout the simulation. This makes the results of the simulation more realistic.

By decreasing the fuel price of EV over time, which is to reduce the electricity prices for the users to charge. The number of users interested to switch to EV vehicles would increase. Hence, the inflow of EV vehicles increases and the number of EV's grows over time. Similarly, by reducing cost of EV vehicle, this creates a positive outlook for customers to adopt EV's as they are cheaper and hence the adoption of EV increases. This drives the increment inflow of EV vehicles and increases the EV vehicles over time positively.

For Government_Initiatives_EV, by increasing more incentives, rebates, tax-saving options, better funding for development of charging infrastructures and production, investing in improving the technology, it motivates the users to adopt EV more and eventually EV vehicles increase due to positive increment in the flow of EV vehicles.

For Charging_Infrastructure_EV, if there are more charging stations in highways, this reassures the customers that they would not have to worry about charging their vehicles and reduces anxiety among people. Faster charging, improved technology, rebates for home charging stations helps increase more users to adopt to EV vehicle technology. Hence this increases the increment flow of EV vehicles and drives the growth of EV vehicles over time.

For Customer_Awareness_EV if more people are educated about the benefits of using EV, debunking the myths about this technology, guiding people on how to use EV's and where to look for information, workshops and events sharing knowledge and awareness among people, eventually this creates a positive outlook to purchasing more EV's and this will increase the inflow increment of EV and drives the growth of EV vehicles.

From understanding articles, reports, surveys, newsletters, government of Canada websites, and blogs we have taken estimation of qualitative data. We have taken input values for Government_Initiatives_EV, Charging_Infrastructure_EV and Customer_Awareness_EV, on a scale from 0-1. The meaning of converter value inputs on a 0–3 scale is like assigning a relative strength or influence to these factors where 0 represents no effect, 1 represents a national average, 2 represents a moderate effect and 3 represents the maximum effect. This normalized scale makes it easier to compare different factors and understand their influence on the model's behavior.

Converter	Input	Units

Government_Initiatives_EV	0.1 (t=0), 0.7 (t=25)	No units
Charging_Infrastructure_EV	0 (t=0), 1 (t=25)	No units
Customer_Awareness_EV	0 (t=0), 0.7 (t=25)	No units
FuelPrice_EV	0. 18 (t=0), 0.19 (t=25)	$/KWH
Cost_EV	112934 (t=0), 53990 (t=25)	$

Table 3 Input values of factors affecting EV [34].

With improvements in grid technology and better optimization, we can reduce the emissions produced by electric grids. Hence, we take GHG_EV also as a converter. The input value we assume it as the same for 25 years since it's a relatively new technology which is 1236 kgco2. Annual_Mileage_Vehicles is taken as 1500 km per year. EV_Emission is a variable and it represents the total emissions produced by the stock of EV vehicles.

Table 4 shows the equation used for EV stock.

NAME	FORMULA	DESCRIPTION
INCREMENT_EV	(1/[Cost_EV])*(1/[FuelPrice_EV])*[Customer_Awareness_EV]*[Government_Initiatives_EV])*[Charging_Infrastructure_EV]	Since cost and fuel price are inversely proportional and customer awareness, government initiatives and charging infrastructure are directly proportional
EOL_EV	EOL_EV= [EV VEHICLES]/ (15)	Because it takes 15 years on an average for a vehicle to be decommissioned.
EV_EMISSION	EV_Emission=[EV VEHICLES] * [Annual_Mileage_Vehicles] *[GHG_EV]	Function of GHG of each EV vehicle and annual mileage and total number of EV vehicles

Table 4 Equations for EV stock

3.7.2.3 BIOFUEL VEHICLES STOCK

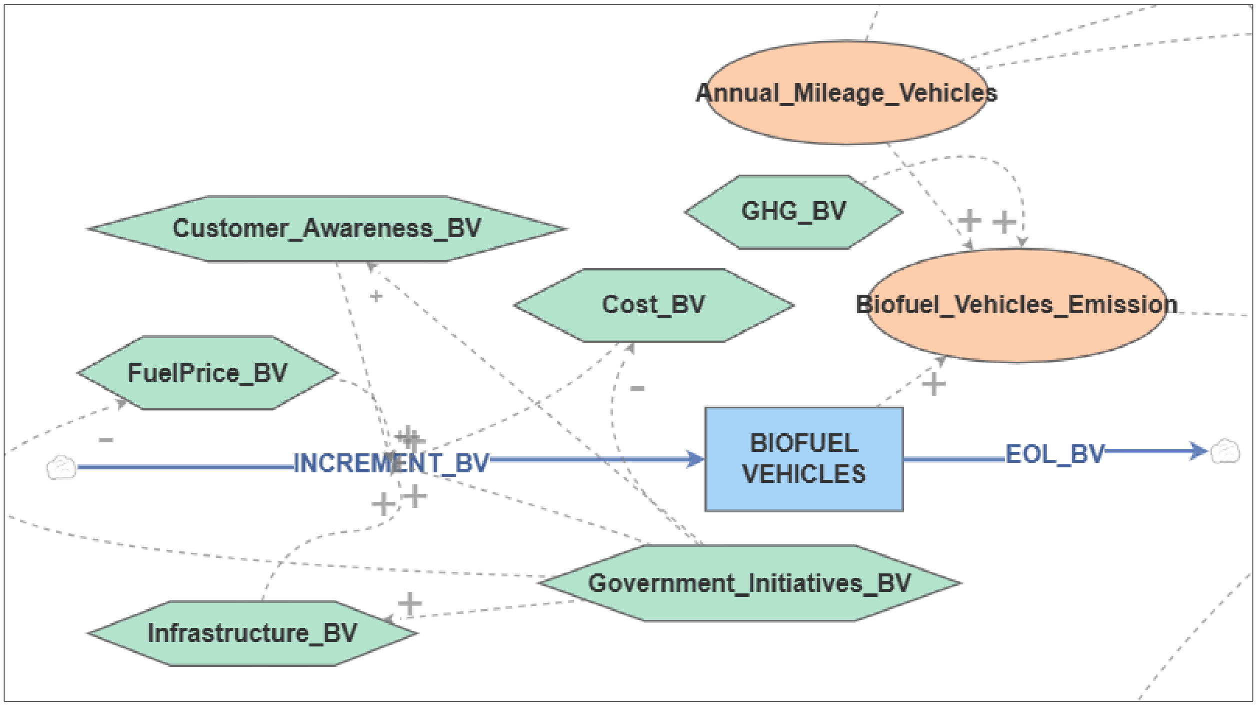

Figure 31 Biofuel stock and its variables affecting it.

In this section of the model, we talk about biofuel vehicles. Biofuel vehicles are created as a stock because the number vehicles increase over time. Here we take a sample input of cumulative total number of vehicles for a particular period of time. Since the temporal boundary of our model is 25 years, we take it as at time t=0 for 1999, the total number of vehicles was 0 due to lack of biofuel vehicles available commercially in Canada and the popularity of these vehicles started increasing later. And at time t=25 for the year 2024, the cumulative total number of vehicles is taken as 908100. We have derived the value of stock at 2024 through cumulative sales of vehicles during this period due to lack of yearly based data. We have inflow and outflow to the stock. Increment_BV which is the increase in flow of biofuel vehicles. And we have EOL_BV which is end of life of a biofuel vehicle or the time it takes for a vehicle to retire. It is 15 years for biofuel vehicle to be decommissioned.

The factors that drive the biofuel vehicles stock are represented by green hexagons. They are called converters. In InsightMaker, converters are not set values; they may shift over time in response to changing real-world conditions. A converter might assume several values at different times, like to a time series or a lookup table, rather than being an individual constant number. This enables the model to detect changes in factors such as Government_Initiatives_BV, FuelPrice_BV, Cost_BV, Infrastructure_BV, Customer_Awareness_BV as they progress throughout the simulation. This makes the results of the simulation more realistic.

By decreasing the fuel price for a biofuel vehicle over time, by decreasing the cost of biofuel blends, customers would be motivated to use biofuels. Hence vehicles using biofuels would increase. And this will increase the increment of vehicles inflow over time and hence drives the growth of vehicles.

Similarly, by reducing cost of biofuel vehicle, which is by designing vehicles that can run on higher blends and are cheaper to purchase, customers would likely be interested in investing in such vehicles and this improves the adoption of biofuel vehicles. This increases the increment flow of vehicles over time and increases the number of biofuel vehicles.

If Government_Initiatives_BV increases, for example if incentives, rebates, funding to develop and research about these technologies, invest in creating awareness among users increases, then eventually people wanting to adopt to biofuel vehicles also increase. Hence, this drives the growth of flow of increment.

If Customer_Awareness_BV increases, for example if customers are more aware of the types of biofuels, its blend, the technology used, the benefits of using biofuel for environment, educating people on how to use this new technology will make customers more gravitate towards these vehicles. And this will drive the growth of adoption of biofuel vehicles and it will increase the number of vehicles over time.

So, from understanding articles, reports, surveys, newsletters, government of Canada websites, and blogs we have taken estimation of qualitative data. We have taken input values for Government_Initiatives_BV, Infrastructure_BV and Customer_Awareness_BV, on a scale from 0-3. The meaning of converter value inputs on a 0–3 scale is like assigning a relative strength or influence to these factors where 0 represents no effect and 1 represents a national average, 2 represents a moderate effect and 3 represents the maximum effect. This normalized scale makes it easier to compare different factors and understand their influence on the model's behavior.

Converter	Input	Units
Government_Initiatives_BV	0 (t=0), 0.3 (t=25)	No units
Infrastructure_BV	0 (t=0), 0.5 (t=25)	No units
Customer_Awareness_BV	0 (t=0), 0.5 (t=25)	No units
FuelPrice_BV	2.00 (t=0), 0.99 (t=25)	$/L
Cost_BV	34,407 (t=0), 22900 (t=25)	$

Table 5 Input values of factors affecting Biofuel Vehicles [34].

With improvements in blending technology and use of renewable sources to produce biofuels, we can reduce the emissions produced by the vehicles. Hence, we take GHG_BV also as a converter. The input value we assume it as the same for 25 years since it's a relatively new technology which is 1680 kgco2. Annual_Mileage_Vehicles is taken as 1500 km per year. Biofuel_Vehicle_Emission is a variable and it represents the total emissions produced by the stock of biofuel vehicles.

Table 6 shows equations used for biofuel vehicles.

NAME	FORMULA	DESCRIPTION
INCREMENT_BV	INCREMENT_BV=(1/[Cost_BV])*(1/[FuelPrice_BV])*[Customer_Awareness_BV]*[Government_Initiatives_BV])*[Infrastructure_BV]	Since cost and fuel price are inversely proportional and customer awareness, government initiatives and infrastructure are directly proportional
EOL_BV	EOL_BV=[BIOFUEL VEHICLES]/ (15)	Because it takes 15 years on an average for a vehicle to be decommissioned.
BIOFUEL_VEHICLES_EMISSION	Biofuel_Vehicles_Emission= [BIOFUELVEHICLES]*[Annual_Mileage_Vehicles]*[GHG_BV]	Function of GHG of each biofuel vehicle and annual mileage and total number of biofuel vehicles

Table 6 Equations for Biofuel Vehicle stock.

3.7.2.4 HYDROGEN VEHICLES STOCK

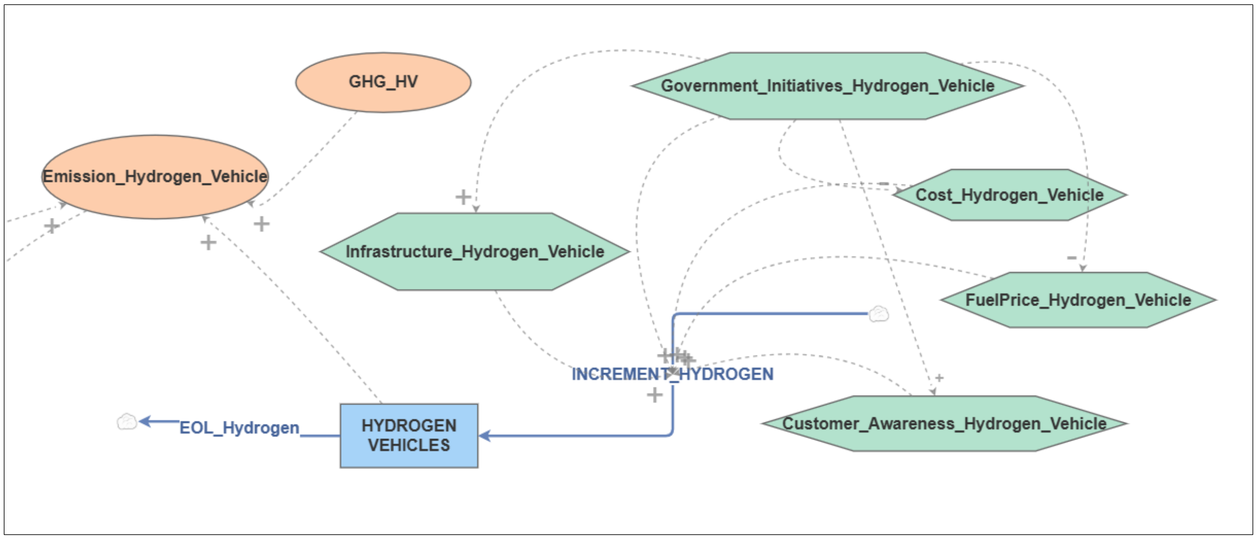

Figure 32 Hydrogen vehicle stock and its variables effecting it.

In this part of the model, we talk about hydrogen vehicles. Hydrogen vehicles are created as a stock because the number vehicles increase over time. Here we take a sample input of cumulative total number of vehicles for a particular period of time. Since the temporal boundary of our model is 25 years, we take it as at time t=0 for 1999, the total number of vehicles was 0 due to lack of biofuel vehicles available commercially in Canada and the popularity of these vehicles started increasing later in 2014. And at time t=25 for the year 2024, the cumulative total number of vehicles is taken as 1040. We have derived the value of stock at 2024 through cumulative sales of vehicles during this period due to lack of yearly based data. We have taken an inflow and outflow to the stock. Inflow of the stock is Increment_hydrogen which is the growth in flow of hydrogen vehicles. And we have EOL_Hydrogen which is end of life of a hydrogen vehicle or the time it takes for a vehicle to retire or decommissioned which is usually 15 years.

The factors that drive the hydrogen vehicles stock are represented by green hexagons. They are called converters. In InsightMaker, converters are not set values; they may shift over time in response to changing real-world conditions. A converter might assume several values at different times, like to a time series or a lookup table, rather than being an individual constant number. This enables the model to detect changes in factors such as Government_Initiatives_Hydrogen_Vehicle, FuelPrice_Hydrogen_Vehicle, Cost_BV, Infrastructure_Hydrogen_Vehicle, Customer_Awareness_Hydrogen_Vehicle as they progress throughout the simulation. This makes the results of the simulation more realistic.

By decreasing the fuel price for a biofuel vehicle over time, by decreasing the cost of production of hydrogen fuel and improving the technology, the customer would be more willing to adopt hydrogen vehicles. This will increase the increment flow of hydrogen vehicles and will drive the growth of the vehicles.

For cost of the vehicle, since the technology is relatively new if the cost of purchasing the vehicle reduces with more rebates, incentives from government and automakers, more people would be interested in buying the vehicle. This will increase the increment flow of hydrogen vehicles over time. And this drives the growth of hydrogen vehicles.

For Government_Initiatives_Hydrogen_Vehicle, if government decides to rapidly scale the growth in hydrogen fuel production plants, setting up more hydrogen fuel stations, better incentives, rebates and funds for research and development. Eventually customers would be more interested to adopt to this new technology and this will increase the increment of vehicles and improve the growth of hydrogen vehicles.

For Infrastructure_Hydrogen_Vehicle, if more fuel stations are built, better maintenance centers, improved transport of fuel to the pump stations, setting up more hydrogen fuel production plants for faster transport of fuels, the users develop interest in wanting to adopt to hydrogen vehicles. And hence it increases the increment flow of hydrogen vehicles. And this drives the growth in hydrogen vehicles.

For Customer_Awareness_Hydrogen_Vehicle, through media, advertisements, workshops if people are more educated on the subject of hydrogen vehicles and its benefits, guiding them on special incentive programs and using of such fuel technology improves the customer satisfaction and shifts the perception towards the fuel and vehicle. This improves the growth of such vehicles over time and increases the increment flow of the vehicle.

Through articles, reports, surveys, newsletters, government of Canada websites, and blogs we have taken estimation of qualitative data. We have taken input values for Government_Initiatives_Hydrogen_Vehicle, Infrastructure_Hydrogen_Vehicle and

Customer_Awareness_Hydrogen_Vehicle, on a scale from 0-3. The meaning of converter value inputs on a 0–3 scale is like assigning a relative strength or influence to these factors where 0 represents no effect and 1 represents a national average, 2 represents a moderate effect and 3 represents the maximum effect. This normalized scale makes it easier to compare different factors and understand their influence on the model's behavior.

Converter	Input	Units
Government_Initiatives_Hydrogen_Vehicle	0.1 (t=0), 0.3 (t=25)	No units
Infrastructure_Hydrogen_Vehicle	0 (t=0), 1 (t=25)	No units
Customer_Awareness_Hydrogen_Vehicle	0.1 (t=0), 1 (t=25)	No units
FuelPrice_Hydrogen_Vehicle	28.28 (t=0), 5.7 (t=25)	$/L
Cost_Hydrogen_Vehicle	100,000 (t=0), 54350 (t=25)	$

Table 7 Input values of factors affecting Hydrogen Vehicles [34].

Hydrogen fuel cells that are used in vehicles, are considered a zero-emission technology. Hence, we take GHG_Hydrogen_Vehicle as a variable. The input value we take it as 0 kgco2. Annual_Mileage_Vehicles is taken as 1500 km per year. Hydrogen_Vehicle_Emission is a variable and it represents the total emissions produced by the stock of hydrogen vehicles.

Table 8 shows equations used for Hydrogen vehicles.

NAME	FORMULA	DESCRIPTION
INCREMENT_HYDROGEN	INCREMENT_HYDROGEN=(1/[Cost_Hydrogen_Vehicle])*(1/[FuelPrice_Hydrogen_Vehicle])*[Customer_Awareness_Hydrogen_Vehicle]*[Government_Initiatives_Hydrogen_Vehicle]*[Infrastructure_Hydrogen_Vehicle]	Since cost and fuel price are inversely proportional and customer awareness, government initiatives and infrastructure are directly proportional.
EOL_HYDROGEN	EOL_HYDROGEN=[HYDROGEN VEHICLES]/ (15)	Because it takes 15 years on an average for a vehicle to be decommissioned.
EMISSION_HYDROGEN_VEHICLE	Emission_Hydrogen_Vehicle=[HYDROGEN VEHICLES] *[Annual_Mileage_Vehicles]*[GHG_HV]	Function of GHG of each hydrogen vehicle and annual mileage and total number of vehicles.

Table 8 Equations for Hydrogen Vehicle stock.

3.7.2.5 BIKES STOCK

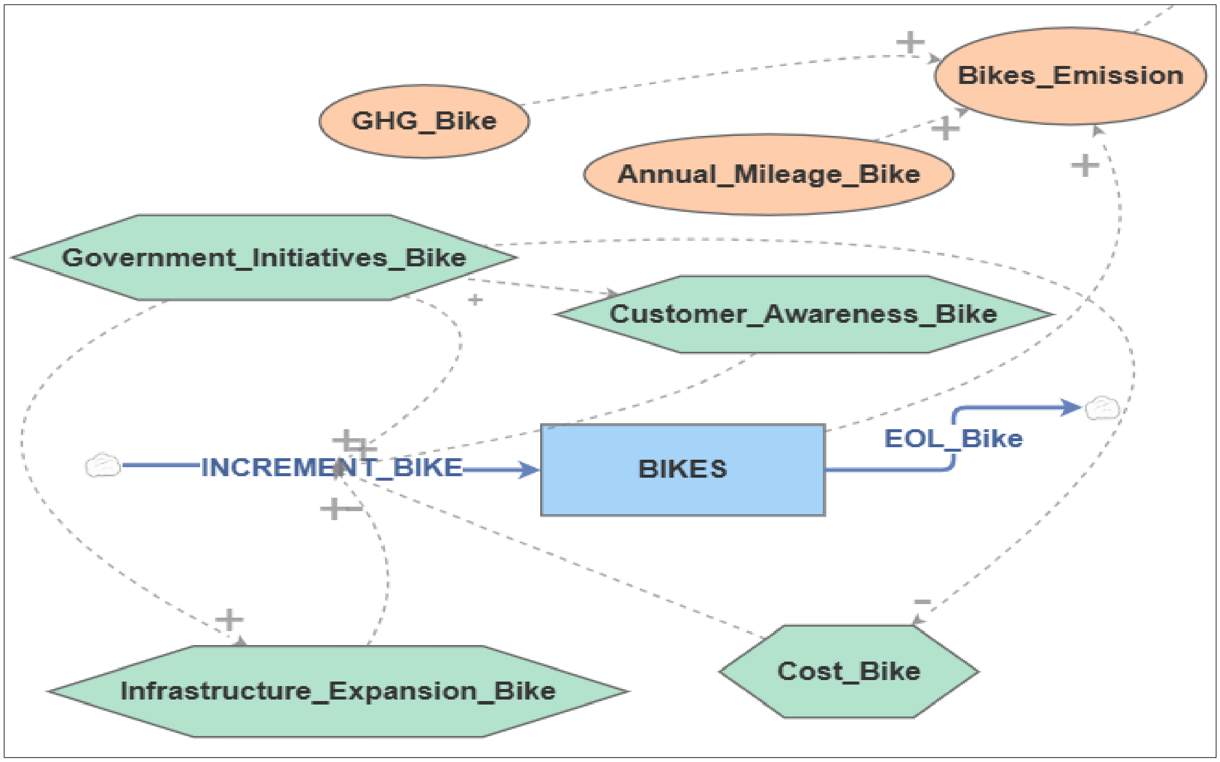

Figure 33 Bikes stock and its variables effecting it.

Subsequently we discuss about Bikes. Bikes are created as a stock because the number bikes increase over time. Here we take a sample input of cumulative total number of bikes for a particular period of time. Since the temporal boundary of our model is 25 years, we take it as at time t=0 for 1999, the total number of bikes was 388000. And at time t=25 for the year 2024, the cumulative total number of bikes is taken as 811000.

The factors that drive the bikes stock are represented by green hexagons. They are called converters. In InsightMaker, converters are not set values; they may shift over time in response to changing real-world conditions. A converter might assume several values at different times, like to a time series or a lookup table, rather than being an individual constant number. This enables the model to detect changes in factors such as Government_Initiatives_Bike, Cost_Bike, Infrastructure_Expansion_Bike, Customer_Awareness_Bike as they progress throughout the simulation. This makes the results of the simulation more realistic.

By decreasing the cost of bikes, more customers would be interested in purchasing and adopting this culture. Hence, the bike adoption increases. And eventually number of bikes also increase. So it affects the increment flow of bikes.

If Government_Initiatives_Bike increases by creating more awareness through media and news, decreasing the cost of bikes by rebates and tax incentives, improving the funds for the infrastructure with bike lanes and paths, improved bike stands and repair stores. Then eventually, more users would be willing to experience this in a positive way. This increases the bikes overall and it affects positively with the increment flow of bikes.

If Infrastructure_Expansion_Bike improves by creating more bike paths, bike lanes and better infrastructure for bikes. Improved services and maintenance centers for bikes. This creates a positive outlook for customers to adopt more biking. Eventually number of bikes increase. This factor increases the increment inflow of bikes.

Customer_Awareness_Bike increases by educating the people on benefits of bikes for environment and health, creating better navigation systems for them to understand the routes, educating them on where to purchase bikes and for repairs. Creating awareness through ads, workshops, news etc. This reassures the customers in a positive way to adopt more biking. Eventually people will start using more bikes and it increases the increment flow of bikes over time.

So, from articles, reports, surveys, newsletters, government of Canada websites, and blogs we have taken estimation of qualitative data. We have taken input values for Government_Initiatives_Bike, Infrastructure_Bike and Customer_Awareness_Bike, on a scale from 0-3. The meaning of converter value inputs on a 0–3 scale is like assigning a relative strength or influence to these factors where 0 represents no effect, 1 represents a national average, 2 represents a moderate effect and 3 represents the maximum effect. This normalized scale makes it easier to compare different factors and understand their influence on the model's behavior.

Converter	Input	Units
Government_Initiatives_Bike	1 (t=0), 1 (t=25)	No units
Infrastructure_Expansion_Bike	0.3 (t=0), 0.6 (t=25)	No units
Customer_Awareness_Bike	1 (t=0), 1 (t=25)	No units

Cost_Bike	360 (t=0), 1000 (t=25)	$

Table 9 Input values of factors affecting Bikes [34].

GHG_Bike is zero because bikes are a part of zero-emission sustainable transportation. We also have Bikes_Emissions which is emissions due to all the bikes. Annual mileage of a bike is taken as an average distance a biker travels a year which in Canada is 3000 km/year.

Table 10 shows equations used for Bikes stock.

NAME	FORMULA	DESCRIPTION
INCREMENT_BIKE	INCREMENT_BIKE=(1/[Cost_Bike])*[Customer_Awareness_Bike]*[Government_Initiatives_Bike]*[Infrastructure_Expansion_Bike]	Since cost of bike is inversely proportional and customer awareness, government initiatives and infrastructure expansion are directly proportional
EOL_BIKE	EOL_BIKE=[BIKES]/(15)	Because it takes 15 years on an average for a bike to be decommissioned.
BIKES_EMISSION	Bikes_Emission=[BIKES]*[Annual_Mileage_Bike] *[GHG_Bike]	Function of GHG of each bike and annual mileage of a bike and total number of bikes.

Table 10 Equations for Bikes stock

3.7.2.6 GASOLINE VEHICLES STOCK

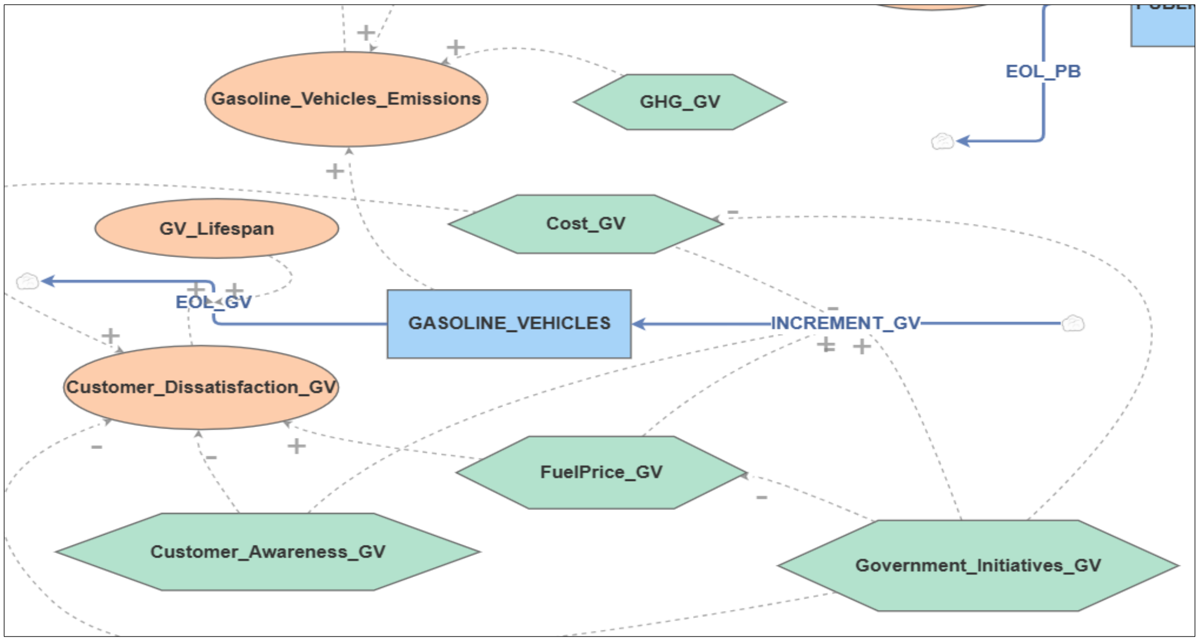

Figure 34 Gasoline stock and its variables effecting it.

In this section of the model, we analyse gasoline vehicles. Gasoline vehicles are created as a stock because the number vehicles increase over time. Here we take a sample input of cumulative total number of vehicles for a particular period of time. Since the temporal boundary of our model is 25 years, we take it as at time t=0 for 1999, the total number of vehicles was 37751000. And at time t=25 for the year 2024, the cumulative total number of vehicles is taken as 634000000. We have derived the value of stock at 2024 through cumulative sales of vehicles during this period due to lack of yearly based data. Increment_GV is the inflow that drives the gasoline vehicles and EOL_GV is the outflow called end of life of gasoline vehicles which reduces the vehicles over time through decommissioning. GV_lifespan is an average life of a gasoline vehicle which is 15 years.

The factors that drive the gasoline vehicles stock are represented by green hexagons. They are called converters. In InsightMaker, converters are not set values; they may shift over time in response to changing real-world conditions. A converter might assume several values at different times, like to a time series or a lookup table, rather than being an individual constant number. This helps the model to detect changes in factors such as Government_Initiatives_GV FuelPrice_GV, Cost_GV, Infrastructure_GV, Customer_Awareness_GV as they progress throughout the simulation. This makes the results of the simulation more realistic.

By decreasing the fuel price for a gasoline vehicle over time, we can expect the number of gasoline vehicle users increasing. Hence the adoption of gasoline vehicles increases over time. So, they are represented with a negative relationship with the Increment_GV. Similarly, by reducing cost of gasoline vehicle, more customers would be keen on purchasing these types of vehicles. So, the adoption of gasoline vehicles increases and hence they have a negative relationship with the increment.

For Government_Initiatives_GV, if government decides to provide better incentives, rebates, discounts, help in the overall development of infrastructure and technology through research funding, more customers would be willing to adopt gasoline vehicles. Hence, gasoline vehicles increase over time. So, it has a positive relationship with the increment flow.

If Customer_Awareness_GV increases by more positive perception among the people for using gasoline vehicles, understanding the benefits and drawbacks, this improves the adoption of gasoline vehicles over time. Hence this increases the number of gasoline vehicles. So, they have a positive relationship with the increment flow.

If government puts increasing effort in reducing the price of fuel and cost of vehicle and rapidly scales up on the investments and research required in improving the infrastructure and customer adoption, hence the relationship between the cost of vehicle and fuel price is negative, and with infrastructure developments and customer awareness, the relationship is positive.

Customer_Dissatisfaction of gasoline is taken as an additional variable for gasoline vehicle stock. By government deciding not to spend on customer awareness, to create positive impact about these vehicles through news and media, educating the people. This eventually reduces the customer awareness and interest over time, and increases the dissatisfaction among customers. If government deciding to not reduce the cost of fuel and vehicles, this brings a shift in customers wanting to choose gasoline vehicles. Hence the customer dissatisfaction of gasoline increases.

From understanding articles, reports, surveys, newsletters, government of Canada websites, and blogs we have taken estimation of qualitative data. We have taken input values for

Government_Initiatives_GV and Customer_Awareness_GV, on a scale from 0-3. The meaning of converter value inputs on a 0–3 scale is like assigning a relative strength or influence to these factors where 0 represents no effect, 1 represents a national average, 2 represents a moderate effect and 3 represents the maximum effect. This normalized scale makes it easier to compare different factors and understand their influence on the model's behavior.

Converter	Input	Units
Government_Initiatives_GV	1 (t=0), 1 (t=25)	No units
Customer_Awareness_GV	1 (t=0), 1(t=25)	No units
FuelPrice_GV	1.52 (t=0), 3.25 (t=25)	$/L
Cost_GV	15000 (t=0), 67000 (t=25)	$

Table 11 Input values of factors affecting Gasoline Vehicles [34].

GHG_GV is the emission produced by a single gasoline vehicle. It is taken as a converter due to the technological improvements in engines and fuel to reduce the emissions in the future. Here between 1999-2024, it is taken as 26 MTCO2. Gasoline_Vehicles_Emissions is the total emissions from all the gasoline vehicles over time. The more gasoline vehicles, the emissions produced will also be higher. The annual mileage of a car in Canada is 15,000 km/year.

Table 12 shows equations used for Gasoline Vehicles stock.

NAME	FORMULA	DESCRIPTION
INCREMENT_GV	INCREMENT_GV=(1/[Cost_GV]) *(1/[FuelPrice_GV]) *[Customer_Awareness_GV] *[Government_Initiatives_GV]	Since cost and fuel price are inversely proportional and customer awareness, government initiatives are directly proportional
EOL_GV	INCREMENT_GV=(1/[Cost_GV])*(1/[FuelPrice_GV])*[Customer_Awareness_GV]*[Government_Initiatives_GV]	Because it takes 15 years on an average for a vehicle to be decommissioned.
CUSTOMER_DISSATISFACTION_GV	Customer_Dissatisfaction_GV=(1/[Customer_Awareness_GV])*([FuelPrice_GV])*([Cost_GV])*(1/[Government_Initiatives_GV])	Dissatisfaction of a customer is indirectly proportional to government initiatives and customer awareness and its directly proportional to fuel price and cost of vehicle.
GASOLINE_VEHICLES_EMISSIONS	Gasoline_Vehicles_Emissions=[GASOLINE VEHICLES]*[Annual_Mileage_Vehicles]*[GHG_GV]	Function of GHG of each gasoline vehicle and annual mileage and total number of gasoline vehicles.

Table 12 Equations for Gasoline Vehicles stock.

3.7.2.7 PUBLIC BUSES STOCK

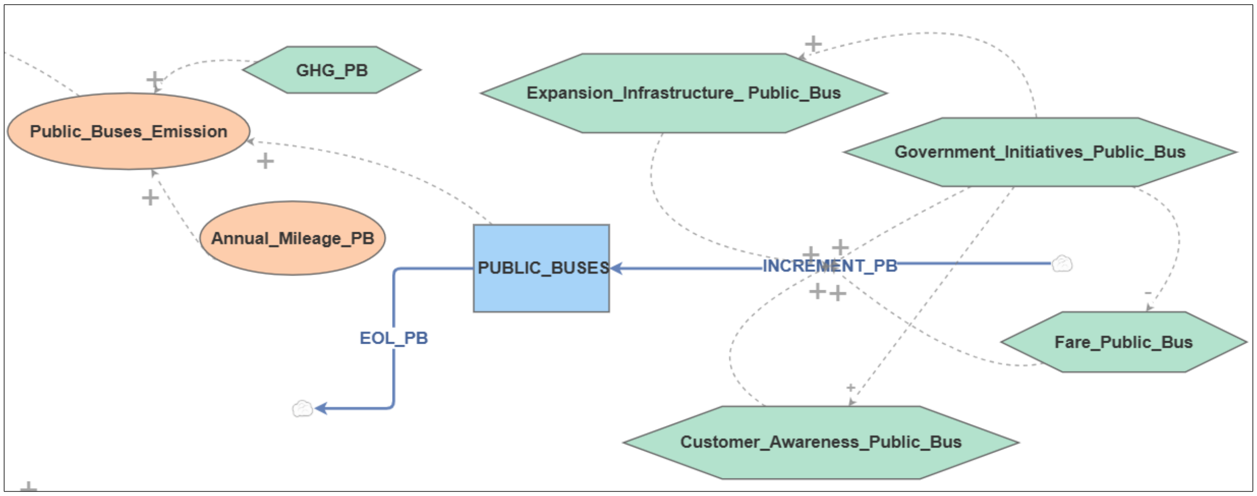

Figure 35 Public_Buses stock and its variables effecting it.

In this portion of the model, we discuss about public buses stock. The public buses are taken as a stock because the number public buses increase over time. Here we take a sample input of cumulative total number of buses for a specific period of time. Since the temporal boundary of our model is 25 years, we take it as at time t=0 for 1999, the total number of public buses was found to be 73174. And at time t=25 for the year 2024, the cumulative total number of vehicles is taken as 84199. We have derived the value of stock at 2024 through cumulative sales of public buses during this period due to lack of yearly based data. There are two types of flows that interact with the stock, one is Increment_PB which is in the increase in adoption of public buses. This increases the value of stock. We have EOL_PB which is end of life of public bus or decommissioning of a public bus. It takes 20 years for a public bus to retire. This outflow decreases the value of stock over time.

The main factors that increase the growth of public buses are represented by green hexagons. They are called converters. In InsightMaker, converters are not set values; they may shift over time in response to changing real-world conditions. A converter might assume several values at different times, like to a time series or a lookup table, rather than being an individual constant number. This enables the model to detect changes in factors such as Government_Initiatives_Public_Bus, Fare_Public_Bus, Expansion_Infrastructure_Public_Bus, Customer_Awareness_Public_Bus as they progress throughout the simulation. This makes the results of the simulation more realistic.

By decreasing the cost of a ticket for public bus, we can expect the number of people willing to use public buses increase over time. So, the public buses will also increase.

If Government_Initiatives_Public_Bus increases, for example if government initiatives, funding to develop, expand and research about the development of public transportation and buses, invest in creating awareness among users to adopt to traveling in public buses, then eventually more customers will be willing to switch to public transportation so Fare_Public_Bus decreases.

And, if Expansion_Infrastructure_Public_Bus, Customer_Awareness_Public_Bus increases over time due to improving the bus routes, increasing the frequency of buses, improving infrastructure of bus stops and navigation, a shift in public perception towards sustainable transportation, benefits of using public transportation and buses for reducing the emissions. This increases the adoption of public buses and hence increases the number of public buses over time.

We have taken input values for Government_Iniiatives_Public_Bus, Expansion_Public_Bus and Customer_Awareness_Public_Bus, on a scale from 0-3. Through analysing articles, reports, surveys, newsletters, government of Canada websites, and blogs we have taken estimation of qualitative data. The meaning of converter value inputs on a 0–3 scale is like assigning a relative strength or influence to these factors where 0 represents no effect, 1 represents a national average, 2 represents a moderate effect and 3 represents maximum effect. This normalized scale makes it easier to compare different factors and understand their influence on the model's behavior.

Converter	Input	Units
Government_Initiatives_Public_Bus	0.1 (t=0), 0.7 (t=25)	No units
Expansion_Infrastructure_Public_Bus	0.1 (t=0), 0.7 (t=25)	No units
Customer_Awareness_ Public_Bus	0.1 (t=0), 0.7 (t=25)	No units
Fare_Public_Bus	6 (t=0), 4 (t=25)	$

Table 13 Input values of factors affecting public buses [34].

GHG_PB which is emission of a public bus is taken as converter because with technological improvements in fuel and engines, it can reduce over time. For the period between 1999-2024, it is taken as 2 MTCO2. Annual_Mileage_PB is average distance a public bus travels in a year, which is taken as 61,049.71 km/year. Public_Buses_Emissions is taken as a variable and this represents the overall emissions of all the public buses. If GHG of a public bus increase, then Public_Buses_Emissions also increase.

Table 14 shows equations used for public buses stock.

NAME	FORMULA	DESCRIPTION
INCREMENT_PB	INCREMENT_PB=(1/[Fare_Public_Bus])*[Customer_Awareness_Public_Bus]*[Government_Initiatives_Public_Bus]) *[Infrastructure_Expansion_Public_Bus]	Since cost of ticket is inversely proportional and customer awareness, government initiatives and infrastructure expansion are directly proportional.
EOL_PB	EOL_PB= [PUBLIC BUSES]/(20)	Because it takes 20 years on an average for a public bus to be decommissioned.
PUBLIC_BUSES_EMISSION	Public_Buses_Emission = [PUBLIC BUSES]*[Annual_Mileage_PB]*[GHG_PB]	Function of GHG of each public bus and annual mileage of a bus and total number of public buses.

Table 14 Equations for Public Buses stock

3.7.2.8 TOTAL GHG EMISSIONS STOCK

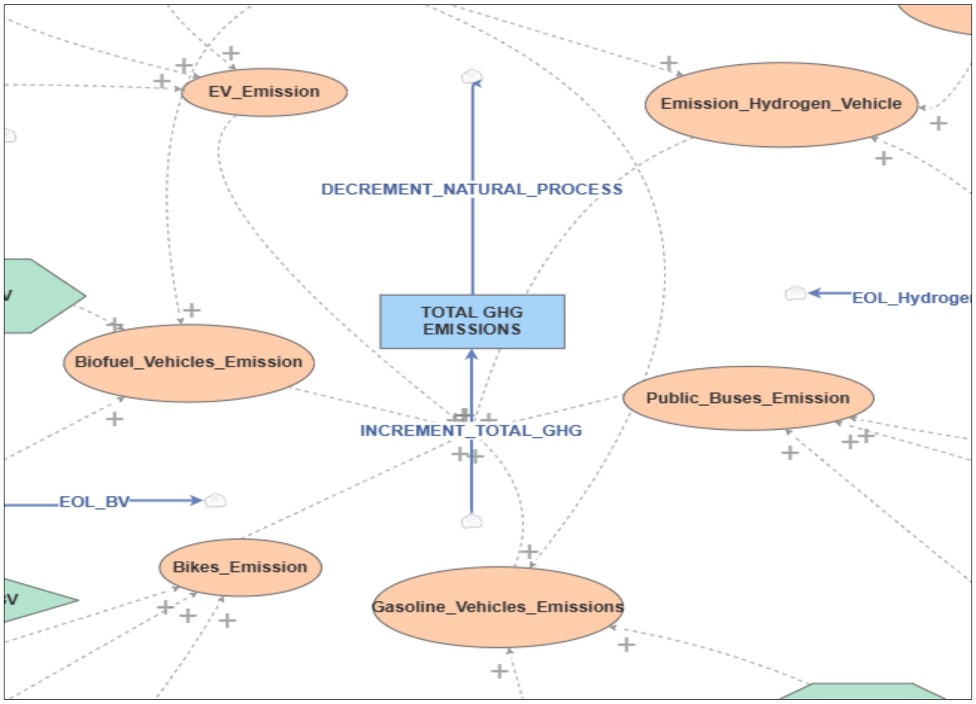

Figure 36 Total GHG Emissions stock.

The total GHG Emissions of this model is the total of all the emissions produced by all the vehicles. Inflow is the increment or increase in GHG emissions and the outflow here is the decrease in GHG emissions due to carbon sequestration.

The inflow of the stock is INCREMENT_TOTAL_GHG= [Emission_Hydrogen_Vehicles] +[Bio-fuel_Vehicles_Emission] +[Bikes_Emission] +[EV_Emission] +[Gasoline_Vehicles_Emissions] +[Public_Buses_Emission]

And the outflow of the stock is DECREMENT_NATURAL_PROCESS = [TOTAL GHG EMIS SIONS]/40. Through carbon sequestration method, it takes 40 years for tree to absorb carbon.

CHAPTER 4

NUMERICAL APPLICATION OF THE MODEL

4.1 MODEL VALIDATION

From Figure 18 we know the next step after formulation of the model is to validate the created model. Model validation in simulation is the procedure of verifying that a simulation model accurately reflects the real-world system it aims to replicate. This procedure is essential for establishing credibility in the model's predictions and its relevance for decision-making. Validation is comparing simulation results with real-world information or recognized benchmarks to evaluate the model's authenticity.

The input data is collected from various sources like open-source government of Canada websites, vehicle inventory websites, blogs, polls, articles and various fuel price websites (DataSourceThesis, 2025.). Due to limitations of yearly based data, the cumulative inputs for the parameters in the model are taken for 1999 and 2024. Due to some parameters representing qualitative data, a calculated estimate has been taken from surveys and articles online. From a scale of 0-3, where 0 being no effect, 1 being average effect, 2 having moderate effect and 3 having the highest effect. Some input parameters have been taken as assumptions due to lack of data.

The temporal boundary of this model is 25 years. We will run the simulation from 1999-2024 to verify the outputs generated by the model. The results of the simulation are compared with the historical data found to verify the model. The outputs of the model are the stocks EV Vehicles, biofuel vehicles, hydrogen vehicles, gasoline vehicles, public buses, bikes and total GHG emission.

There was no record of commercial EV vehicles sold in Canada in 1999. The prices of electricity to power the electric grid for charging EV was found to be 0.19 $/kwh and 0.18 $/kwh for the year 1999 and 2024. The cost of an EV from conceptual vehicles and experimental technologies was found to be $112934 in 1999 and is currently $53,990 in 2024. All the costs are adjusted to inflation. Since Charging_infrastructure_EV, Government_initiatives_EV, Customer_awareness_EV are a type of qualitative data, a value between 0-3 has been taken. The GHG_EV signifies emissions produced by the electric grid to charge vehicles. Although EV vehicles do not have tailpipe emissions, the electric grid releases a certain amount of GHG and it is found to be 1236 kgco2. Average distance a car travels in Canada is approximately 15000 km/year and this has been taken as input for Annual_Mileage_Vehicle. Table 15 shows the input data taken for EV vehicles to perform validation.

Name	Input	Unit
EV Vehicles	0 (1999)	Units
FuelPrice_EV	0.19 (1999), 0.18(2024)	$/KWH
Cost_EV	112934(1999), 53,990(2024)	$
Charging_Infrastructure_EV	0 (1999), 1 (2024)	No units
Government_Initiatives_EV	0.1 (1999), 0.7 (2024)	No units
Customer_Awareness_EV	0 (1999), 0.7 (2024)	No units
GHG_EV	1236 (1999)	KgCo2
Annual_Mileage_Vehicles	15000	Km/year

Table 15 EV Vehicles input data for validation. [34]

Since, there was no record of biofuel used in commercial vehicles in Canada during 1999. The cost of production of biofuels which are essentially blends that are used with gasoline was found to be $2 and $0.99 for the year 1999 and 2024. The cost of a conceptual vehicles and initial release models that can run on biofuels was found to be $34407 in 1999 and is $22900 in 2024. All the costs are adjusted to inflation. Since Infrastructure_BV, Government_initiatives_BV, Customer_awareness_BV are a type of qualitative data, a value between 0-3 has been taken as an estimate. The GHG_BV signifies emissions that are produced by a vehicle that uses biofuel which was found to be 1680 kgco2. On an average in Canada, a vehicle travels a distance of approximately 15000 km/year and this has been taken as input for Annual_Mileage_Vehicle. Table 16 shows the input data taken for biofuel vehicles to perform validation.

Name	Input	Units
Biofuel Vehicles	0 (1999)	Units

Government_Initiatives_BV	0 (1999), 0.3 (2024)	No units
Infrastructure_BV	0 (1999), 0.5 (2024)	No units
Customer_Awareness_BV	0 (1999), 0.5 (2024)	No units
FuelPrice_BV	2.00 (1999), 0.99 (2024)	$/L
Cost_BV	34,407 (1999), 22900 (2024)	$
GHG_BV	1680 (1999)	KgCo2
Annual_Mileage_Vehicles	15000	Km/year

Table 16 Biofuel Vehicles input data used for validation. [34]

For hydrogen vehicles, there was no record of commercial vehicle sold in Canada in 1999 so the input is taken as 0. The cost of hydrogen fuel produced for vehicles was found to be 28.28$/L in 1999 and it decreased to 5.7$/L in 2024. Since these vehicles were not mainstream back in 1999, the cost of hydrogen vehicle was expensive approximatey $100,000 and is $54350 in 2024. All the costs are adjusted to inflation. Since, Infrastructure_Hydrogen_Vehicle, Government_Initiatives_Hydrogen_Vehicle, Customer_Awareness_Hydrogen_Vehicle are qualitative data, a value between 0-3 has been assumed. The GHG_HV signifies emissions produced by hydrogen vehicles. Since they do not produce any emissions, it is taken as 0 kgco2. Average distance a car travels in Canada is approximately 15000 km/year and this has been taken as input for Annual_Mileage_Vehicle. Table 17 shows the input data taken for hydrogen vehicles to perform validation.

Name	Input	Units
Hydrogen Vehicles	0 (1999)	Units
Government_Initiatives_Hydrogen_Vehicle	0.1 (1999), 0.3 (2024)	No units
Infrastructure_Hydrogen_Vehicle	0 (1999), 1 (2024)	No units
Customer_Awareness_Hydrogen_Vehicle	0.1 (1999), 1 (2024)	No units
FuelPrice_Hydrogen_Vehicle	28.28 (1999), 5.7 (2024)	$/L
Cost_Hydrogen_Vehicle	100,000(1999), 54350 (2024)	$
GHG_HV	0	KgC02
Annual_Mileage_Vehicles	15000	Km/year

Table 17 Hydrogen Vehicles input data for validation. [34]

Table 18 offers input data of bikes for model validation. The table show that there were recorded 388,000 bikes overall in 1999, so providing a baseline for bicycle existence. Given Infrastructure_Expansion_Bike, Government_initiatives_Bike, Customer_awareness_ Bike are qualitative data; hence, a value between 0-3 has been estimated. On the other hand, the cost associated with bikes, represented by Cost_Bike, shows a clear rise from $360 in 1999 to $1000 in 2024, maybe due to changes in market and inflationary. Furthermore, GHG_Bikes stays at 0 KgCO2, and it has positive environmental impact and zero-emission nature of transportation. Additionally specified in the table is an annual mileage of 3000 kilometers per bike which is average distance a biker covers in a year.

Name	Input	Units
Bikes	388000 (1999)	Units
Government_Initiatives_Bike	1 (1999), 1 (2024)	No units
Infrastructure_Expansion_Bike	0.3 (1999), 0.6 (2024)	No units
Customer_Awareness_Bike	1 (1999), 1 (2024)	No units
Cost_Bike	360 (1999), 1000 (2024)	$
GHG_Bikes	0	KgC02
Annual_Mileage_Bike	3000	Km/year

Table 18 Bikes input data for validation. [34]

Table 19 offers a complete picture of the data used for validation of the model for public buses. It starts by stating the initial size of the bus fleet was 73,174 units in 1999. As Expansion_Infrastructure_Public_Bus, Government_Initiatives_Public_Bus, Customer_awareness_Public_Bus are qualitative data, a value between 0-3 has been assumed. The Fare for Public Bus services was observed to be $6 in 1999 and reduced to $4 in 2024, a change that is maybe due increase in ridership. Furthermore, the table also offers GHG_PB, which is calculated at 2 MTCo2 and denotes the greenhouse gas emissions connected to the public bus network. At 61,049.71km/year, the Annual Mileage for Public Buses is finally noted.

Name	Input	Units
Public Buses	73174 (1999)	Units

Government_Initiatives_Public_Bus	0.1 (1999), 0.7 (2024)	No units
Expansion_Infrastructure_Public_Bus	0.1 (1999), 0.7 (2024)	No units
Customer_Awareness_ Public_Bus	0.1 (1999), 0.7 (2024)	No units
Fare_Public_Bus	6 (1999), 4 (2024)	$
GHG_PB	2	MTCo2
Annual_Mileage_PB	61,049.71	km/yr

Table 19 Public buses input data for validation. [34]

Table 20 offers a quantitative and qualitative data of gasoline vehicles used for model validation. In 1999 there were 37,751,000 gasoline vehicles establishing a baseline for vehicle usage. Fuel price for gasoline vehicles rises from $1.52 per liter in 1999 to $3.25 per liter in 2024. Simultaneously, the cost of gasoline vehicles rises from $15,000 in 1999 to $67,000 in 2024, maybe due to a change in market conditions. Since Government_initiatives_GV, Customer_awareness_BV are a type of qualitative data, a value between 0-3 has been taken as an estimate. The greenhouse gas emissions which are found to be 26 MTCO2 and the gasoline vehicle lifespan is set at 15 years, providing information on longevity of the vehicles. Assuming an annual mileage of 15,000 kilometers per vehicle in Canada.

Name	Input	Units
Gasoline Vehicles	37751000 (1999)	Units
Government_Initiatives_GV	1 (1999), 1 (2024)	No units
Customer_Awareness_GV	1 (1999), 1(2024)	No units
FuelPrice_GV	1.52 (1999), 3.25 (2024)	$/L
Cost_GV	15000 (1999), 67000 (2024)	$
GHG_GV	26	MTCo2
Annual_Mileage_Vehicles	15000	Km/year
GV_Lifespan	15	Years

Table 20 Gasoline Vehicles input data for validation [34].

Table 21 presents a key metric used for environmental impact; it was found that total greenhouse gas emission for the year 1999 was 6572 Co2MT.

Name	Input	Units
Total GHG Emission	6572 (1999)	Co2MT

Table 21 Total GHG Emissions input data for validation. [34]

After taking the input values for all the parameters from the above data we run the simulation for a time of 25 years and timestep 0.1 for better accuracy. Next, we generated the output for the stocks EV vehicles, gasoline vehicles, hydrogen vehicles, biofuel vehicles, public buses, bikes and Total GHG Emissions and time series graphs were plotted.

Figure 37 shows the change in total GHG emissions from 1999 to 2024. It is shown to gradually increase from 6572 CO2MT to approximately 25000 CO2MT by the end of 2024.

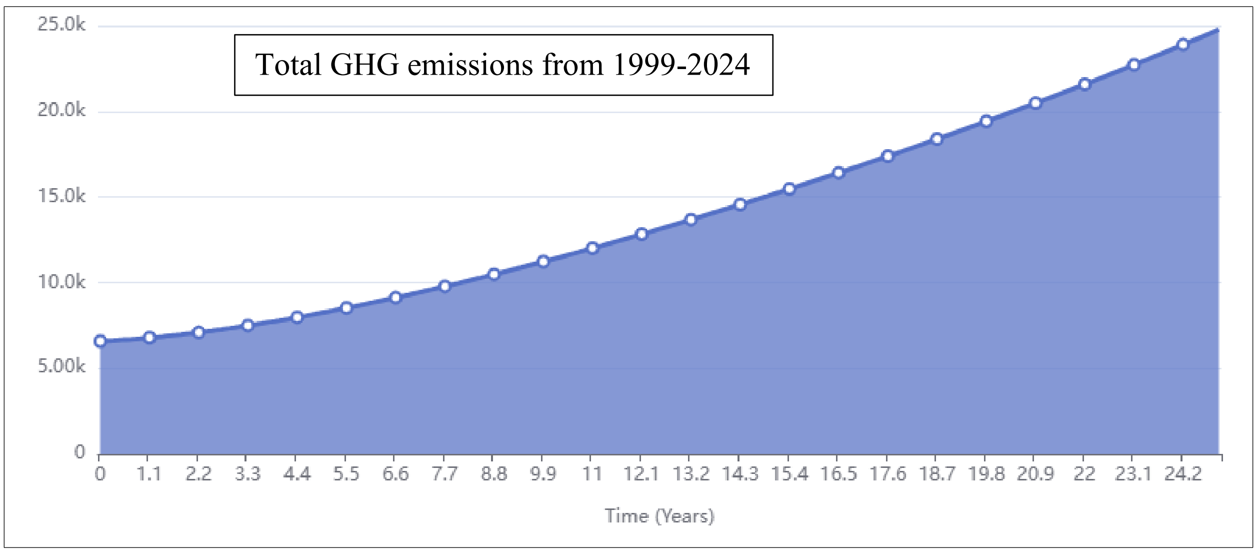

Figure 37 Time series graph of the stock Total GHG Emission from 1999 to 2024 in validated model

The following graph in Figure 38 shows the time series analysis of EV Vehicles, public buses, bikes, biofuel vehicles, hydrogen vehicles change from 1999 to 2025. It is shown to increase steadily with EV vehicles having the highest growth by the end of 2024 and hydrogen vehicles having the least growth.

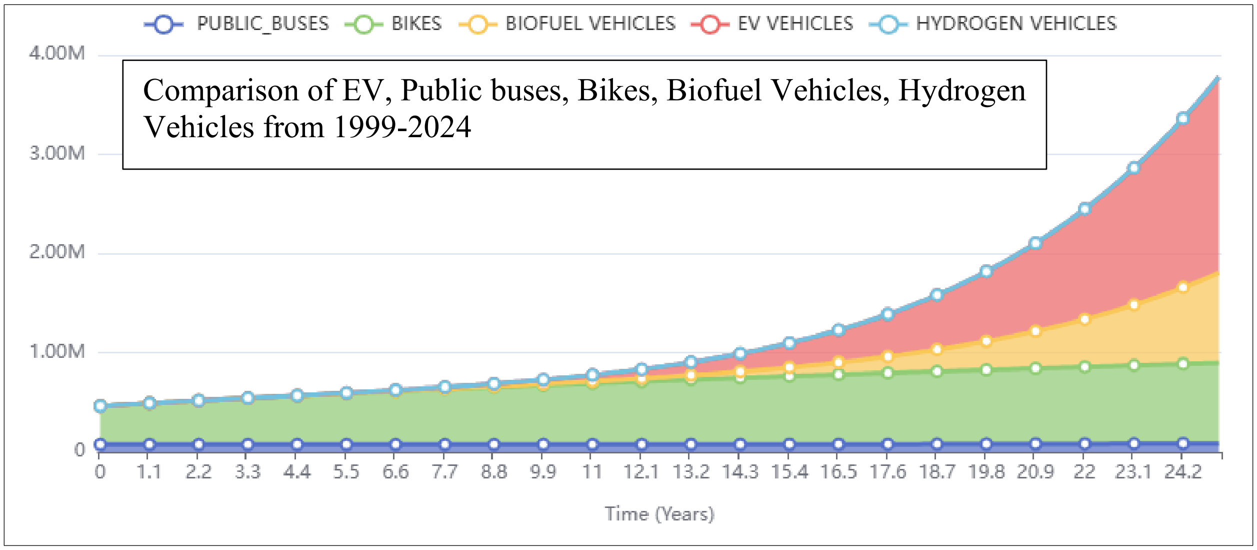

Figure 38 Time series graph of different sustainable transportation options used in the validated model from 1999-2024

The following graph in Figure 39 shows the growth of gasoline vehicles from 1999 to 2024. The vehicles have increased steadily from 37751000 vehicles in 1999 initially to a nearly 646 million vehicles by the end of 2024 due to increase in popularity and demand.

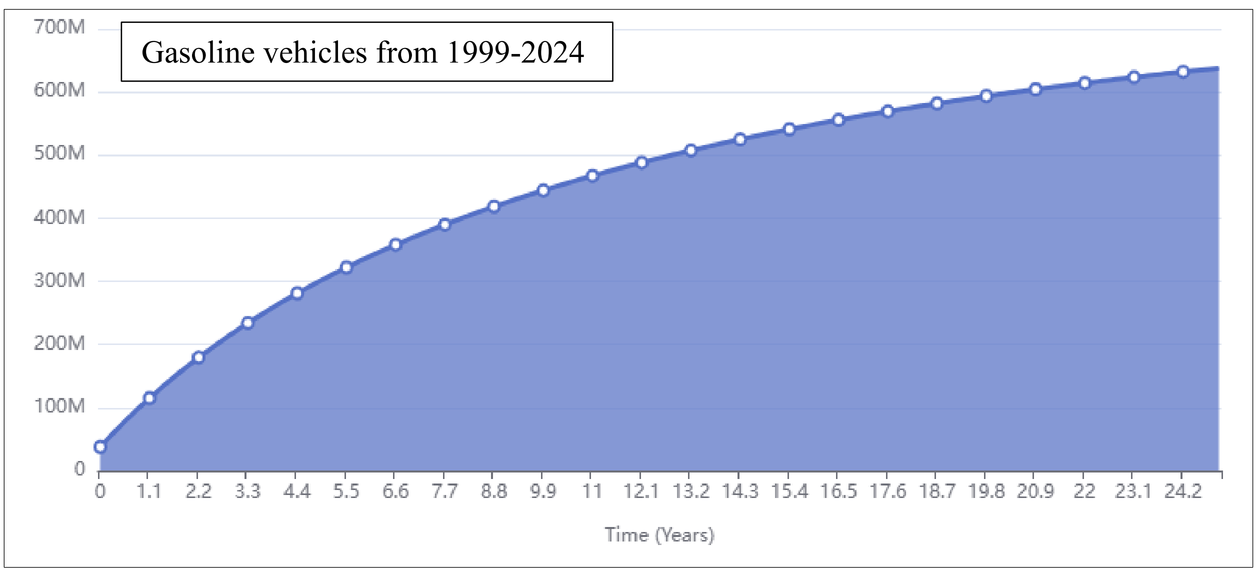

Figure 39 Time series graph of gasoline vehicles from 1999-2024 for validated model

Figure 40 shows the output table generated in Insightmaker software that was benefitial to understand the precise numbers of the vehicles and total GHG emission by 2025.

VEHICLES GASOLINE | ALTERNATIVE VEHICLES | TOTAL EMISSIONS | NEW DISPLAY

Time	PUBLIC_BUSES	GASOLINE_VEHICLES	EV VEHICLES	HYDROGEN VEHICLES	BIOFUEL VEHICLES	BIKES	TOTAL GHG EMISSIONS
23.4	81,883.4659	625,690,123	1,461,608.52	743.851702	650,607.848	793,018.236	23,032.5902
23.5	82,023.706	626,480,301	1,489,951.39	759.442752	664,592.849	794,219.787	23,139.1083
23.6	82,165.7532	627,265,158	1,518,759.24	775.398904	678,837.75	795,418.377	23,245.9901
23.7	82,309.6256	628,044,730	1,548,038.79	791.731234	693,346.876	796,614.018	23,353.2394
23.8	82,455.3415	628,819,054	1,577,796.83	808.451271	708,124.625	797,806.719	23,460.8602
23.9	82,602.9195	629,588,168	1,608,040.27	825.571025	723,175.466	798,996.493	23,568.8564
24	82,752.3781	630,352,108	1,638,776.11	843.103016	738,503.941	800,183.35	23,677.2323
24.1	82,903.7361	631,110,910	1,670,011.47	861.060297	754,114.666	801,367.301	23,785.9918
24.2	83,057.0125	631,864,609	1,701,753.53	879.456487	770,012.333	802,548.357	23,895.1394
24.3	83,212.2264	632,613,240	1,734,009.63	898.305804	786,201.712	803,726.528	24,004.6793
24.4	83,369.397	633,356,838	1,766,787.17	917.623097	802,687.65	804,901.826	24,114.6159
24.5	83,528.5436	634,095,438	1,800,093.68	937.423886	819,475.076	806,074.261	24,224.9539
24.6	83,689.6859	634,829,073	1,833,936.81	957.7244	836,568.997	807,243.843	24,335.6978
24.7	83,852.8436	635,557,777	1,868,324.29	978.541621	853,974.507	808,410.583	24,446.8523
24.8	84,018.0364	636,281,584	1,903,264	999.893328	871,696.782	809,574.491	24,558.4222
24.9	84,185.2845	637,000,525	1,938,763.92	1,021.79815	889,741.084	810,735.578	24,670.4124
25	84,354.6081	637,714,633	1,974,832.14	1,044.27561	908,112.764	811,893.854	24,782.8278

Figure 40 Table in Insightmaker tool for the output of model validation.

Name	Historical Data Output (2024)	Model Output (2024)	Error %	Unit
Gasoline Vehicles	634000000	637714633	0.59%	Units
EV Vehicles	1978449	1974832	0.18%	Units
Biofuel Vehicles	908100	908112	0.0013%	Units
Hydrogen Vehicles	1040	1044	0.38%	Units
Bikes	811000	811893	0.11%	Units
Public Buses	84199	84354	0.18%	Units
Total GHG Emission	24982	24782	0.80%	MTCO2

Table 22 Comparison of Historical data to model output for validation [34].

The output generated by the model was then compared to the historical data according to Table 22. After calculating the error margin in percentage, it was found to be less than 1% which is negligible. Therefore, the model created is successfully validated.

4.2 WHAT-IF SCENARIO ANALYSIS

From figure 18 of the process of simulation, the next step after model validation is to implement scenario analysis. In the setting of a stock-flow model, what-if scenario analysis requires systematic adjustments of key parameters or assumptions in order to explore the ways in which various conditions influence the behavior of the system over time. This strategy is useful for gaining an awareness of uncertainty and determining the degree to which your model's predictions provide precise outcomes.

The steps to perform a scenario analysis include creating a baseline scenario. This baseline serves as the reference point for all subsequent comparisons. Subsequently, we create two futuristic scenarios where in first scenario EV's and biofuel vehicles are projected to grow and in second scenario hydrogen vehicles continue to grow and compare the results.

4.2.1 BASELINE SCENARIO

Baseline scenario is also called business as usual scenario where the future predictions would follow as per the historical data (Roberts et al., 2018). The values for the baseline scenario between 2024–2050 were selected based on historical data trends and projections.

Table 23 shows the inputs taken that can be used to predict the EV Vehicles by the end of 2050. By comparing the trends in the previous historic data, we assume a projected 2% drop in fuel price from $0.18 per kWh in 2024 to $0.11 per kWh in 2050 and a corresponding 2% decrease in vehicle cost from $53,990 to $32,581by 2050. EV vehicles for the year 2024 is taken as 1,978,449 units. While Government_Initiatives_EV and Customer_Awareness_EV are expected to rise from 0.7 to 1.15 which is a 2% growth from the previous trends, and Charging_Infrastructure_EV is assumed to expand by 2% growth annually, from 1 to 1.6. With an annual mileage of 15,000 km per vehicle assumed and recorded greenhouse gas emissions linked with EVs at 1236 $KgCO_2$, by assuming that the energy efficiency of electric grids have not improved significantly.

Name	Input	Unit
EV Vehicles	1978449 (2024)	Units
FuelPrice_EV	0.18 (2024), 0.11 (2050)	$/KWH
Cost_EV	53990 (2024), 32581(2050)	$
Charging_Infrastructure_EV	1 (2024), 1.6 (2050)	No units

Government_Initiatives_EV	0.7 (2024), 1.15(2050)	No units
Customer_Awareness_EV	0.7 (2024), 1.15(2050)	No units
GHG_EV	1236 (2024)	KgCo2
Annual_Mileage_Vehicles	15000	Km/year

Table 23 Input data of EV vehicles parameters for baseline scenario [34].

Table 24 summarizes input variables of the Biofuel vehicles for baseline scenario for the years 2024 and 2050. By following previous historical data trends, Government_Initiatives_BV are expected to increase from 0.3 to 0.5 by 2% growth annually, and both Infrastructure_BV and Customer_Awareness_BV are projected to improve from 0.5 to 0.8 by a 2% growth annually as well. FuelPrice_BV is set to reduce from $0.99 per liter in 2024 to $0.60 in 2050, while the Cost_BV is expected to reduce from $22,900 to $13819 over the same period. Both are decreased by a 2% annual growth from previous projections in the market. Additionally, the greenhouse gas emissions associated with BV which is GHG_BV are assumed to be 1680 KgCO_2 for 2024 and assumed to be unchanged, and the model uses a constant annual mileage of 15,000 Km per vehicle.

Name	Input	Units
Biofuel Vehicles	908100 (2024)	Units
Government_Initiatives_BV	0.3 (2024),0.5 (2050)	No units
Infrastructure_BV	0.5 (2024), 0.8 (2050)	No units
Customer_Awareness_BV	0.5 (2024), 0.8 (2050)	No units
FuelPrice_BV	0.99 (2024), 0.60 (2050)	$/L
Cost_BV	22900 (2024), 13819(2050)	$
GHG_BV	1680 (2024)	KgCo2
Annual_Mileage_Vehicles	15000	Km/year

Table 24 Input data of Biofuel Vehicles parameters for baseline scenario [34].

Table 25 illustrates the input related to hydrogen vehicles, comparing projected values for 2024 and 2050. Government_Initiatives_Hydrogen_Vehicle increase from 0.3 to 0.49 with a growth of 2% annually, while both the Infrastructure_Hydrogen_Vehicle and

Customer_Awareness_Hydrogen_Vehicle have been assumed to grow from 1 to 1.64 with a similar 2% increase annually according to the trends from previous historic data. Fuel prices are expected to decline from $5.7 per liter to $3.44 per liter, and the cost of hydrogen vehicles decreases from $54,350 to $32,798, with the same assumption of 2 % annual decrease. The greenhouse gas emissions GHG_HV of hydrogen vehicles are listed as 0 $KgCO_2$, and the annual mileage per vehicle is taken as 15,000 km.

Name	Input	Units
Hydrogen Vehicles	1040 (2024)	Units
Government_Initiatives_Hydrogen_Vehicle	0.3 (2024), 0.49(2050)	No units
Infrastructure_Hydrogen_Vehicle	1 (2024),1.64 (2050)	No units
Customer_Awareness_Hydrogen_Vehicle	1 (2024), 1.64(2050)	No units
FuelPrice_Hydrogen_Vehicle	5.7 (2024),3.44 (2050)	$/L
Cost_Hydrogen_Vehicle	54350 (2024), 32798(2050)	$
GHG_HV	0	KgC02
Annual_Mileage_Vehicles	15000	Km/year

Table 25 Input data of Hydrogen Vehicles parameters for baseline scenario [34].

Table 26 presents key inputs related to bikes. For Government_Initiatives_Bike, Infrastructure_Expansion_Bike, and Customer_Awareness_Bike from 2024 to 2050 values rise from 1 to 1.64 and from 0.6 to 0.98, respectively due to 2% annual growth previous trends. At the same time, the cost of bikes is assumed to decrease from $1000 in 2024 to $600 in 2050, with a consistent 2% decrease in growth annually. The greenhouse gas emissions, GHG_Bikes remain the same at 0 $KgCO_2$, while the Annual_Mileage_Bike is at 3000 Km/year.

Name	Input	Units
Bikes	811000 (2024)	Units
Government_Initiatives_Bike	1 (2024), 1.64 (2050)	No units
Infrastructure_Expansion_Bike	0.6 (2024), 0.98 (2050)	No units
Customer_Awareness_Bike	1 (2024), 1.64 (2050)	No units
Cost_Bike	1000 (2024), 600(2050)	$

GHG_Bikes	0	KgC02
Annual_Mileage_Bike	3000	Km/year

Table 26 Input data of Bikes parameters for baseline scenario [34].

Table 27 outlines inputs to the baseline scenario for public buses from 2024 to 2050. From 0.7 to 1.15 Government_Initiatives_Public_Bus, Expansion_Infrastructure_Public_Bus and Customer_Awareness_ Public_Bus all show a progressive increase by 2% growth annually from past trends. Simultaneously, public bus fares assume to drop from $4 in 2024 to $2.42 in 2050, a decrease in 2% annually. A consistent greenhouse gas emission level GHG_PB of 2 $MTCO_2$ is assumed and an annual mileage Annual_Mileage_PB of 61,049.71km/year per bus.

Name	Input	Units
Public Buses	84199 (2024)	Units
Government_Initiatives_Public_Bus	0.7 (2024), 1.15 (2050)	No units
Expansion_Infrastructure_Public_Bus	0.7 (2024), 1.15 (2050)	No units
Customer_Awareness_ Public_Bus	0.7 (2024), 1.15 (2050)	No units
Fare_Public_Bus	4 (2024), 2.42 (2050)	$
GHG_PB	2	MTCo2
Annual_Mileage_PB	61,049.71	km/yr

Table 27 Input data of public buses parameters for baseline scenario [34].

Table 28 illustrates the parameters for gasoline vehicles. In 2024, there are 634 million gasoline vehicles, and both Government_Initiatives_GV and Customer_Awareness_GV are assumed at a constant level of 1 from 2024 through 2050 from previous trends. FuelPrice_GV are assumed to decrease from $3.25 per liter in 2024 to $1.96 per liter by 2050, while the purchase cost of gasoline vehicles Cost_GV is assumed to reduce from $67,000 in 2024 to $40,432 in 2050. Both have a 2% annual decrease in growth. The table also shows greenhouse gas emissions GHG_GV at 26 MTCo2 and is maintained the same throughout till 2050. It is also assumed an annual mileage of 15,000 kilometers and a vehicle lifespan of 15 years till 2050.

Name	Input	Units

Gasoline Vehicles	634000000 (2024)	Units
Government_Initiatives_GV	1 (2024), 1 (2050)	No units
Customer_Awareness_GV	1 (2024), 1 (2050)	No units
FuelPrice_GV	3.25 (2024), 1.96 (2050)	$/L
Cost_GV	67000 (2024), 40432 (2050)	$
GHG_GV	26	MTCo2
Annual_Mileage_Vehicles	15000	Km/year
GV_Lifespan	15	Years

Table 28 Input data of Gasoline Vehicles parameters for baseline scenario [34].

For Total GHG emission, the input data for baseline scenario is taken as the current 2024 emissions.

Name	Input	Units
Total GHG Emission	24982 (2024)	Co2MT

Table 29 Input data of Total GHG emission parameters for baseline scenario [34].

We run this model for a timeline of 25 years from 2024-2050 to analyse how the model behaves over time and what would be the future for transportation in Canada without significantly improving and integrating alternative fuels and sustainable transportation into the current system. We simulate and find the output for alternative fuel-based vehicles, gasoline vehicles, public buses and bikes change over time. And we also find the Total GHG emissions by the year 2050.

4.2.2 SCENARIO 1 (EV'S HIGHEST BY 2050)

The values of the inputs for the EV vehicles are set for 2024 and assumed for 2050. In Scenario 1, EV Vehicles are emphasized to grow due to their present degree of maturity and supporting infrastructure and popularity. Biofuel vehicles use renewable fuels in current engines, offering an instantaneous and practical approach towards cleaner transportation. EV's are shown to reduce GHG reductions with expansion of current charging infrastructure. Hence, the parameters are scaled rapidly for EV's and Biofuel vehicles. Given their high emissions and not aligning with decarbonization goals, gasoline vehicles are almost completely phased out in this scenario. While the cost of EVs is assumed to fall from $53,990 to $15,000 over the same period, which reflects a 4.81% annual decrease, fuel price for EVs is assumed to drop from $0.18/kWh to $0.05/kWh, corresponding to an approximately annual decrease of 4.81%. By contrast, charging infrastructure for EV's is assumed to grow annually by roughly 4.32% from 1 to 3 units by 2050. Customer awareness for EV's is predicted to rise from 0.7 to 2, or roughly 4.12% annually and government initiatives for EV's are assumed to rise from 0.7 to 3, an annual increase of roughly 5.75%. While annual vehicle mileage stays the same at 15,000 km/year, GHG emissions for EVs are expected to drop drastically from 1,260 kg CO_2 to 50 kg CO_2, assuming rapid technological developments in making the electric grids used for charging the vehicle greener, so that equates to an annual decrease of almost 11.6%. Table 30 shows the inputs taken for performing this scenario.

Name	Input	Unit
EV Vehicles	1978449 (2024)	Units
FuelPrice_EV	0.18 (2024), 0.05 (2050)	$/KWH
Cost_EV	53,990 (2024), 15000 (2050)	$
Charging_Infrastructure_EV	1 (2024), 3 (2050)	No units
Government_Initiatives_EV	0.7 (2024), 3 (2050)	No units
Customer_Awareness_EV	0.7 (2024), 2 (2050)	No units
GHG_EV	1236 (2024), 50 (2050)	KgCo2
Annual_Mileage_Vehicles	15000	Km/year

Table 30 Input data of EV vehicles parameters for Scenario 1 [34].

For biofuel vehicles, the input for 2024 is 908,101 units. It is assumed to rise from 0.3 to 2 between 2024 and 2050, government initiatives for biofuel vehicles match an annual growth rate of roughly 7.6%. While customer awareness factor is expected to double from 0.5 to 1 (about 2.7% annually), infrastructure developments and investment for biofuel is assumed to rise from 0.5 to 2 (about 5.5% annual). Fuel prices are assumed to drop from $0.99/L to $0.30/L, reflecting an annual decline of roughly 4.5%; the cost per vehicle is projected to drop from $22,900 to $10,000, a change of roughly 3.1% annually from 2024 to 2050. While annual mileage remains constant at 15,000 km/year, by assuming improvements in biofuel blending technology and the production of higher quality blends that can reduce greenhouse gas emissions it is anticipated to drop from 1,680 kg

CO_2 to 300 kg CO_2, corresponding with an annual drop of roughly 6.4%. Table 31 summarizes the input data taken for this scenario.

Name	Input	Units
Biofuel Vehicles	908100 (2024)	Units
Government_Initiatives_BV	0.3 (2024), 2 (2050)	No units
Infrastructure_BV	0.5 (2024), 2 (2050)	No units
Customer_Awareness_BV	0.5 (2024), 1 (2050)	No units
FuelPrice_BV	0.99 (2024), 0.30 (2050)	$/L
Cost_BV	22900 (2024), 10000 (2050)	$
GHG_BV	1680 (2024), 300 (2050)	KgCo2
Annual_Mileage_Vehicles	15000	Km/year

Table 31 Input data of Biofuel Vehicles parameters for Scenario 1 [34].

In this scenario, hydrogen vehicles are 1,040 units in 2024. Reflecting an average annual growth rate of 7.6%, government initiatives for hydrogen vehicles are assumed to rise from 0.3 to 2 between 2024 and 2050. Infrastructure developments for hydrogen vehicles are expected to rise from 1 to 3 over the same period which is an annual increase of roughly 4.3%. Customer awareness is assumed to be 1. From $5.70 to $1 per liter, fuel prices are assumed to drop roughly 6.5% annually; the cost per hydrogen vehicle is expected to decrease from $54,000 to $25,000, a 2.9% annual drop. Greenhouse gas emissions remain zero because of hydrogen fuel known to produce no emission, and annual mileage is set at 15,000 km/year. Table 32 summarizes the input data of hydrogen vehicles.

Name	Input	Units
Hydrogen Vehicles	1040 (2024)	Units
Government_Initiatives_Hydrogen_Vehicle	0.3 (2024), 2 (2050)	No units
Infrastructure_Hydrogen_Vehicle	1 (2024), 3 (2050)	No units
Customer_Awareness_Hydrogen_Vehicle	1 (2024), 1 (2050)	No units
FuelPrice_Hydrogen_Vehicle	5.7 (2024), 1 (2050)	$/L

Cost_Hydrogen_Vehicle	54000(2024), 25000 (2050)	$
GHG_HV	0	KgC02
Annual_Mileage_Vehicles	15000	Km/year

Table 32 Input data of Hydrogen Vehicles parameters for Scenario 1 [34].

Under this scenario, bikes in 2024 are 811,000 units. It is assumed to double from 1 to 2 by 2050, government initiatives reflect an annual growth rate of almost 2.67%. Over the same period, infrastructure development is expected to rise from 0.6 to 2, corresponding to an annual increase of roughly 4.74%. Customer awareness is also assumed to double between 1 and 2, suggesting a similar annual rise of almost 2.67%. But in contrast, the cost per bike is assumed to drop from $1,000 in 2024 to $400 in 2050, which results in an average annual drop of almost 3.5%. The annual mileage is constant at 3,000 km/year while greenhouse gas emissions stay zero. These trends point to the possibility of higher bike adoption rates over the long run depending on more government support, better infrastructure, and more customer awareness together with declining costs. Table 33 shows the input data taken for bikes.

Name	Input	Units
Bikes	811000 (2024)	Units
Government_Initiatives_Bike	1 (2024), 2 (2050)	No units
Infrastructure_Expansion_Bike	0.6 (2024), 2 (2050)	No units
Customer_Awareness_Bike	1 (2024), 2 (2050)	No units
Cost_Bike	1000 (2024), 400 (2050)	$
GHG_Bikes	0	KgC02
Annual_Mileage_Bike	3000	Km/year

Table 33 Input data of Bikes parameters for Scenario 1 [34].

Public buses are taken 84,199 units in 2024. Government initiatives, infrastructure development, and customer awareness each assume to rise from 0.7 to 2, reflecting an estimated annual growth rate of 4.1%, between 2024 and 2050. For public buses, the fare drops from $4 to $1, or roughly 5.2%, annually. Meanwhile, annual mileage per bus is kept at 61,049.71km/year and greenhouse gas emissions at 2 $MTCO_2$ remain constant. Table 34 shows the input data taken for public buses.

Name	Input	Units
Public Buses	84199 (2024)	Units
Government_Initiatives_Public_Bus	0.7 (2024), 2 (2050)	No units
Expansion_Infrastructure_Public_Bus	0.7 (2024), 2 (2050)	No units
Customer_Awareness_ Public_Bus	0.7 (2024), 2 (2050)	No units
Fare_Public_Bus	4 (2024), 1 (2050)	$
GHG_PB	2	MTCo2
Annual_Mileage_PB	61,049.71	km/yr

Table 34 Input data of public buses parameters for Scenario 1 [34].

The gasoline vehicles in 2024 are 634 million units. While customer awareness assumes to fall from 1 to 0.0003 an annual drop of roughly 26.8%, government initiatives is expected to drop from a normalized value of 1 to 0.002 an approximate annual decrease of 21.2%. Meanwhile, vehicle prices rise from $67,000 to $185,000 and fuel prices go from $3.25 per liter to $9 per liter, both of which reflect an annual growth rate of about 4%. Greenhouse gas emissions (26 MTCo2), annual mileage (15,000km/year), and vehicle lifespan (15 years) remain constant throughout. Table 35 shows the input data taken for gasoline vehicles.

Name	Input	Units
Gasoline Vehicles	634000000 (2024)	Units
Government_Initiatives_GV	1 (2024), 0.002 (2050)	No units
Customer_Awareness_GV	1 (2024), 0.0003 (2050)	No units
FuelPrice_GV	3.25 (2024), 9 (2050)	$/L
Cost_GV	67000 (2024), 185000 (2050)	$
GHG_GV	26	MTCo2
Annual_Mileage_Vehicles	15000	Km/year
GV_Lifespan	15	Years

Table 35 Input data of Gasoline Vehicles parameters for Scenario 1 [34].

For Total GHG emission, the input data for baseline scenario is taken as the current 2024 emissions.

Name	Input	Units
Total GHG Emission	24982 (2024)	Co2MT

Table 36 Input data of Total GHG emission parameters for Scenario 1 [34].

4.2.3 SCENARIO 2 (HYDROGEN VEHICLES HIGHEST BY 2050)

In Scenario 2, strategic emphasis is on zero tailpipe emissions of hydrogen vehicles and bikes. Given their ability to provide really clean energy as well as advantages like faster refueling and longer range which are essential. Bikes enhance this goal by providing an ultra-low emission choice meant to reduce urban congestion and pollution. Gasoline vehicles are assumed to almost phase out due to high greenhouse gas emissions.

While the cost of EVs is expected to drop from $53,990 to $20,000, corresponding with an annual reduction of roughly 3.75%, fuel prices for EVs are assumed to drop from $0.18/kWh to $0.10/kWh, an annual decrease of about 2.2%. Projected to double over the period, charging infrastructure reflects an annual increase rate of about 2.7%. Furthermore, government programs and consumer awareness are expected to rise from 0.7 to 2, with an annual increase of roughly 4.1% each that could greatly influence acceptance. Especially, GHG emissions per EV are expected to drop from 1236 kgCO_2 to 50 kgCO_2 an annual decline almost 11.6% indicating environmental performance improvement. For these estimates, annual mileage stays constant at 15,000 km/year. Table 37 shows the input data taken for EV's.

Name	Input	Unit
EV Vehicles	1978449 (2024)	Units
FuelPrice_EV	0.18 (2024), 0.10 (2050)	$/KWH
Cost_EV	53,990 (2024), 20000 (2050)	$
Charging_Infrastructure_EV	1 (2024), 2 (2050)	No units
Government_Initiatives_EV	0.7 (2024), 2 (2050)	No units
Customer_Awareness_EV	0.7 (2024), 2 (2050)	No units
GHG_EV	1236 (2024), 50 (2050)	KgCo2

Annual_Mileage_Vehicles	15000	Km/year

Table 37 Input data of EV vehicles parameters for Scenario 2 [34].

For biofuel vehicles, while infrastructure improvements are expected to rise from 0.5 to 2 a growth rate of roughly 5.5% annually, government initiatives are expected to grow from 0.3 to 1, corresponding with an annual increase of roughly 4.7%. Reflecting an annual increase to nearly 4.3%, customer awareness is expected to rise from 0.5 to 1.5. Fuel prices are expected to drop from $0.99 to $0.50 per liter, an approximate annual drop of 2.6%, and the cost of biofuel vehicles is assumed to drop from $22,900 to $12,000, so reducing roughly 2.5% annually. While the annual mileage per vehicle stays constant at 15,000 km/year, greenhouse gas emissions are expected to drop drastically from 1,680 $kgCO_2$ to 300 $kgCO_2$, so reflecting an annual decrease of roughly 6.4%. Table 38 shows the input data taken for biofuel vehicles.

Name	Input	Units
Biofuel Vehicles	908100 (2024)	Units
Government_Initiatives_BV	0.3 (2024), 1 (2050)	No units
Infrastructure_BV	0.5 (2024), 2 (2050)	No units
Customer_Awareness_BV	0.5 (2024), 1.5 (2050)	No units
FuelPrice_BV	0.99 (2024), 0.50 (2050)	$/L
Cost_BV	22900 (2024), 12000 (2050)	$
GHG_BV	1680 (2024), 300 (2050)	KgCo2
Annual_Mileage_Vehicles	15000	Km/year

Table 38 Input data of Biofuel Vehicles parameters for Scenario 2 [34].

The number of hydrogen vehicles in 2024 is 1,040. While both infrastructure and customer awareness indices are assumed to rise from 1 to 3, equating to roughly a 4.3% annual growth, government initiatives are projected to grow from 0.3 to 3, reflecting an approximate annual increase of 9.3%. Fuel prices are expected to drop from $5.70 per liter to $0.50 per liter, so representing an annual decrease of roughly 8.9%; the cost of hydrogen vehicles is assumed to drop from $54,000 to $10,000, so corresponding to an annual reduction of roughly 6.3%. At 15,000 km/year, the annual mileage per vehicle stays the same; greenhouse gas emissions are kept at 0 kgCO2. Table 39 shows the input data taken for hydrogen vehicles.

Name	Input	Units
Hydrogen Vehicles	1040 (2024)	Units
Government_Initiatives_Hydrogen_Vehicle	0.3 (2024), 3 (2050)	No units
Infrastructure_Hydrogen_Vehicle	1 (2024), 3 (2050)	No units
Customer_Awareness_Hydrogen_Vehicle	1 (2024), 3 (2050)	No units
FuelPrice_Hydrogen_Vehicle	5.7 (2024), 0.5 (2050)	$/L
Cost_Hydrogen_Vehicle	54000(2024), 10000 (2050)	$
GHG_HV	0	KgC02
Annual_Mileage_Vehicles	15000	Km/year

Table 39 Input data of Hydrogen Vehicles parameters for Scenario 2 [34].

For bikes, government programs are expected to rise from a value of 1 to 3, reflecting an approximate annual growth rate of 4.3%; customer awareness with a similar annual increase. From 0.6 to 3, infrastructure expansion shows a clearer increase corresponding to an expected annual growth rate of roughly 6.4%. Meanwhile, the cost per bike is assumed to drop from $1000 to $250, so saving almost 5.2% annually. Annual mileage is consistent at 3000 km per year while greenhouse gas emissions remain constant at 0 kg CO_2. Table 40 shows the input data taken for bikes.

Name	Input	Units
Bikes	811000 (2024)	Units
Government_Initiatives_Bike	1 (2024), 3 (2050)	No units
Infrastructure_Expansion_Bike	0.6 (2024), 3 (2050)	No units
Customer_Awareness_Bike	1 (2024), 3 (2050)	No units
Cost_Bike	1000 (2024), 250 (2050)	$
GHG_Bikes	0	KgC02
Annual_Mileage_Bike	3000	Km/year

Table 40 Input data of Bikes parameters for Scenario 2 [34].

The public bus data for scenario 2 shows government initiatives and expansion of infrastructure that are expected to rise from 0.7 to 3, with an average annual growth rate of 5.8%. Customer awareness is assumed to rise from 0.7 to 2, or roughly a 4.1% annual rise as well. By contrast, the Fare for public buses is expected to drop dramatically from $4 to $0.4, reflecting an approximate annual drop of 8.5%. Over this time, GHG emissions (2 $MTCO_2$), and Annual Mileage (61,049.71km/yr) remain constant. Table 41 shows the input data taken for public buses.

Name	Input	Units
Public Buses	84199 (2024)	Units
Government_Initiatives_Public_Bus	0.7 (2024), 3 (2050)	No units
Expansion_Infrastructure_Public_Bus	0.7 (2024), 3 (2050)	No units
Customer_Awareness_ Public_Bus	0.7 (2024), 2 (2050)	No units
Fare_Public_Bus	4 (2024), 0.4 (2050)	$
GHG_PB	2	MTCo2
Annual_Mileage_PB	61,049.71	km/yr

Table 41 Input data of public buses parameters for Scenario 2 [34].

In Gasoline vehicles the parameters like customer awareness falls from 1 to 0.0003 (a drop of roughly 99.8%), while government initiatives drop from 1 to 0.002 (a decrease of roughly 99.8%). While the cost of gasoline vehicles expected to rise from $67,000 to $185,000 nearly a 176% increase and fuel prices are expected to rise from $3.25 to $9 per liter an increase of roughly 177%. Annual mileage (15,000 km/year), vehicle lifespan (15 years), and greenhouse gas emissions (26 $MTCO_2$) are kept constant. Table 42 shows the input data taken for gasoline vehicles.

Name	Input	Units
Gasoline Vehicles	634000000 (2024)	Units
Government_Initiatives_GV	1 (2024), 0.002 (2050)	No units
Customer_Awareness_GV	1 (2024), 0.0003 (2050)	No units
FuelPrice_GV	3.25 (2024), 9 (2050)	$/L
Cost_GV	67000 (2024), 185000 (2050)	$
GHG_GV	26	MTCo2

Annual_Mileage_Vehicles	15000	Km/year
GV_Lifespan	15	Years

Table 42 Input data of Gasoline Vehicles parameters for Scenario 2 [34].

For Total GHG emission, the input data for baseline scenario is taken as the current 2024 emissions.

Name	Input	Units
Total GHG Emission	24982 (2024)	Co2MT

Table 43 Input data of Total GHG emission parameters for Scenario 2 [34].

4.3 IDENTIFICATION OF THE MOST INFLUENTIAL PARAMETER: A SENSITIVITY ANALYSIS APPROACH

In system dynamics simulations, sensitivity analysis is an analytical approach used to evaluate how change in input parameters affects the output behavior of a model. In the overall picture of dynamic systems, it verifies the robustness of the simulation and the most significant factors for the performance of the system. We have used the one-at-a-time (OAT) sensitivity analysis method which modifies one parameter at a time while keeping all other parameters unchanged (Reinhard et al., 2021). This method classifies the impact of each parameter on the result so allowing us to determine the minor effect of one parameter on the model output. It helps us find the crucial factors that show the most notable changes.

Sensitivity analysis is performed in Insightmaker tool, for timeline of 25 years. The number of runs is taken 50 and the graphs are analysed for 95% confidence interval region. The 95% confidence range is commonly used in statistics and sensitivity analysis because of its precise and robust results (Hespanhol et al., 2018). The Upper bound, lower bound and the median values are generated by the output graph. The difference in the upper and the lower bound for 95% confidence are compared with all the parameters to conclude the most impactful factor. 95% confidence range intervals give us the best results because of its stability and better accuracy. We assume the initial data of the model, the same used for model validation. A minimum and a maximum value is taken for each parameter separately. The sensitivity analysis of EV Vehicles, Public Buses, Bikes and

Gasoline Vehicles are analysed. Due to EV Vehicles, Biofuel Vehicles, and Hydrogen Vehicles having the same parameters affecting the growth of vehicles, only EV vehicles are considered for convenience.

4.3.1 SENSITIVITY ANALYSIS FOR ALTERNATIVE-FUEL VEHICLE

Sensitivity analysis for all the parameters like Cost_EV, Fuelcost_EV, Government_Initiatives_EV, Customer_Awareness_EV and Charging_Infrastructure_EV are assessed and compared. In this section.

COST_EV PARAMETER

Figure 41 shows the outcomes of a 95% confidence interval sensitivity analysis with a focus toward changes in cost of EV that affect the output of the model. At time 0, the changes in cost have little to no impact. But starting about time 2 and forward, the model output starts to climb, reflecting a growing effect of EV cost on the system. One important characteristic is the widening difference between the 95% Lower and Upper bounds as time goes on, which highlights increasing model output uncertainty when the parameter cost changes. At time =10 and by time= 25 the variation in the lower and upper bounds widens, this suggests system sensitivity to cost parameter since it implies that minor changes in EV cost assumptions can produce a different result.

The Median is located between the 95% Lower and Upper bounds in the graph, trajectory shows constant increase over the time. This suggests that the model still shows a notable rise in EV adoption. We have assumed the maximum and the minimum value for the cost of EV vehicle to be 200000 and 10000 respectively for calculating sensitivity analysis.

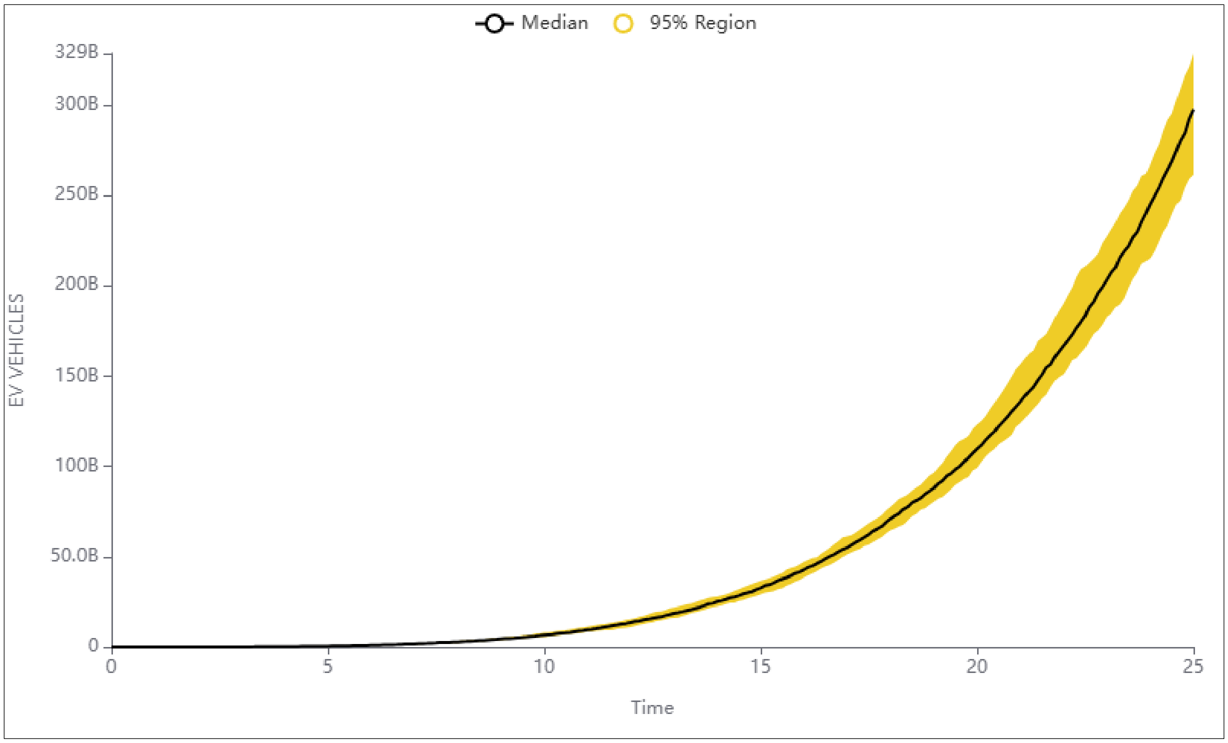

Figure 41 Sensitivity Analysis graph of Cost_EV parameter affecting the EV stock.

Table 44 shows the outputs of EV Vehicles at upperbound and lowerbound at time t=25 for Cost_EV.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
261464393000	328519521000	200000-10000	67055128000

Table 44 Output of sensitivity analysis of 95% confidence range for time t=25 for Cost_EV.

FUELPRICE_EV PARAMETER

The output of the model is analysed over time 0 to 25 while the fuel cost for electric vehicles (EVs) is changed within a designated range in this sensitivity study.

Every time step reports three values: the median, the 95% lower bound, and the 95% upper bound. The confidence interval is first quite small and stays close to zero until time 0.2, so indicating little short-term influence. But with time, the lower and upper limits grow fast. This widening interval points to higher sensitivity of the model's output to fluctuations in fuel cost and also increasing uncertainty of the output. The difference between the lower and upper bounds becomes more wider by time 10 to 15 indicating that even smaller changes in fuel cost can generate different results. Under the median trajectory it always rises over the time. Figure 42 shows the sensitivity analysis and the confidence level and median of cost of fuel for EV affecting EV vehicles.

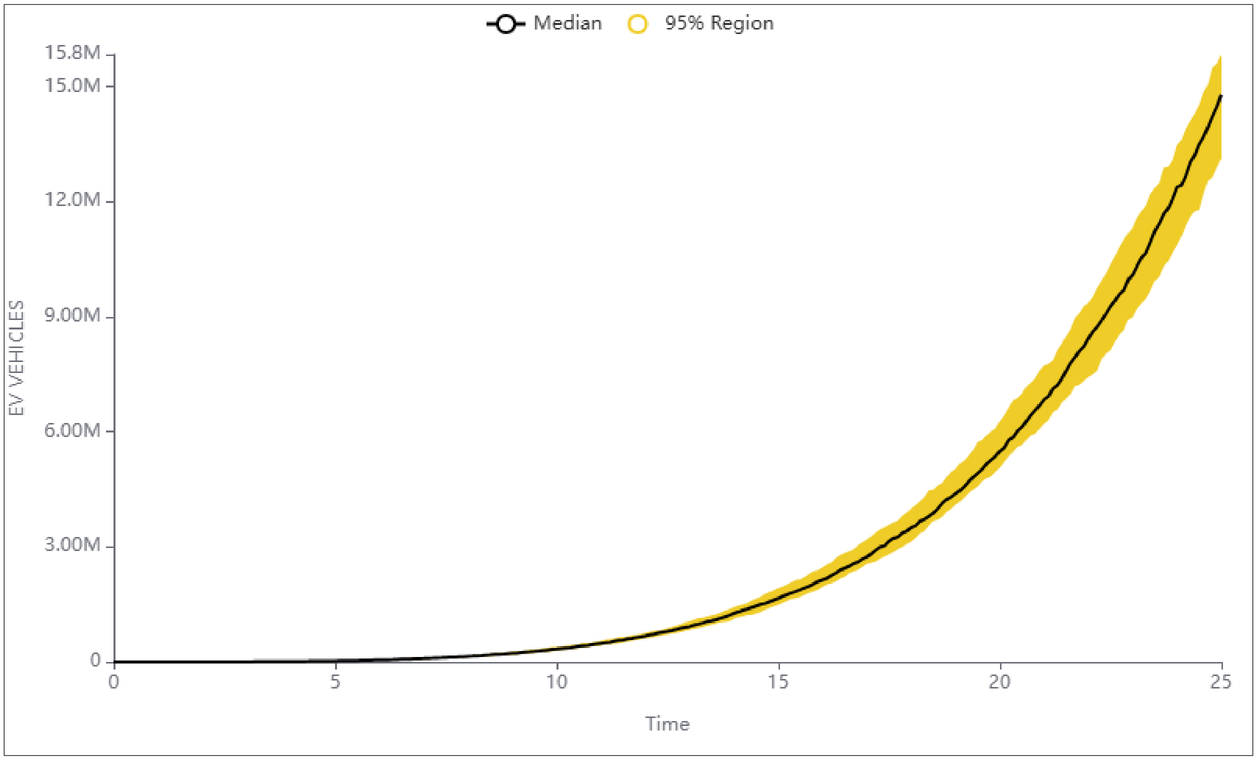

Figure 42 Sensitivity Analysis graph of FuelPrice_EV parameter affecting the EV stock.

Table 45 shows the outputs of EV Vehicles at upperbound and lowerbound at time t=25 for fuelcost_EV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
13122779.7	15837171.1	0.5-10	2,714,391.4

Table 45 Output of sensitivity analysis of 95% confidence range for time t=25 for FuelPrice_EV.

CUSTOMER_AWARENESS_EV PARAMETER

Figure 43, at time 0 to 25, the Customer_Awareness_EV value shows a fast 95% widening confidence interval. Both the lower and upper bounds remain close to zero in the early time steps at time 0 to 0.2, suggesting little effect on the system. But by time 1, the limits change drastically, implying that differences in consumer awareness might cause progressively different EV vehicles.

At time 25, the median values rise from almost zero to over four million vehicles; the upper bound exceeds four million and the lower bound is three-million. This significant spread suggests that the output of the model is influenced by uncertainty in customer awareness.

These findings highlight the larger sensitivity of the system to the Customer_Awareness_EV value. The projections of the model outputs can be much changed by even slight changes in customer opinion.

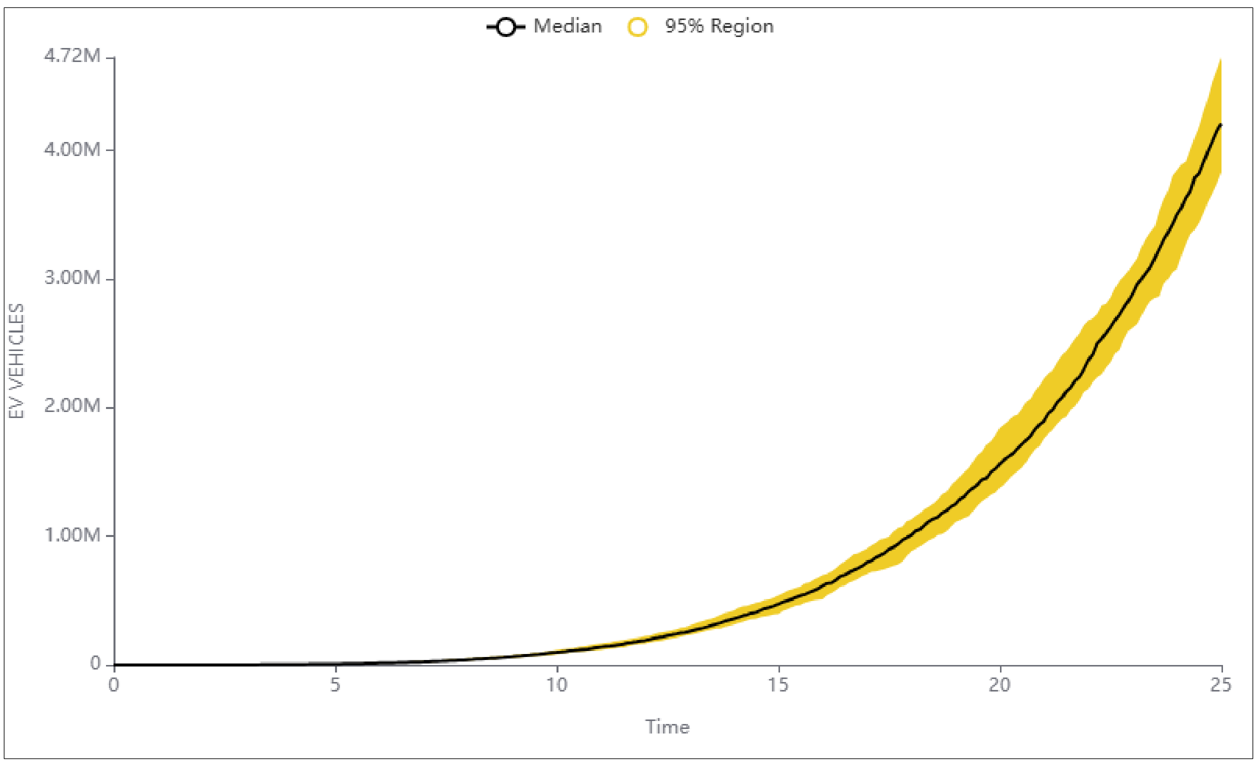

Figure 43 Sensitivity Analysis graph of CUSTOMER_AWARENESS_EV parameter affecting the EV stock.

Table 46 shows the outputs of EV Vehicles at upperbound and lowerbound at time t=25 for CUSTOMER_AWARENESS_EV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
3829070.86	4720443.39	0-3	891372.53

Table 46 Output of sensitivity analysis of 95% confidence range for time t=25 for CUSTOMER_AWARENESS_EV

GOVERNMENT_INITIATIATIVES_EV PARAMETER

Figure 44 shows the lower bound, upper bound, and median outputs over time that offer insight on how changes in government initiatives might greatly influence outcome of the model which is EV Vehicles. From time 0 to 25, the median output increases significantly from almost zero to more than four million, suggesting the increasing impact of the factor on simulation runs. At time 0–1, the small intervals show almost no sensitivity. The 95% intervals widens greatly when the model enters around time t=15. This widening implies that variations in the parameter government initiatives gives different EV vehicle values. The increasing confidence intervals suggest that the system is quite sensitive to the parameter. By the end of the simulation period, even little changes in government initiatives for EV vehicles can cause significant variations in EV adoption.

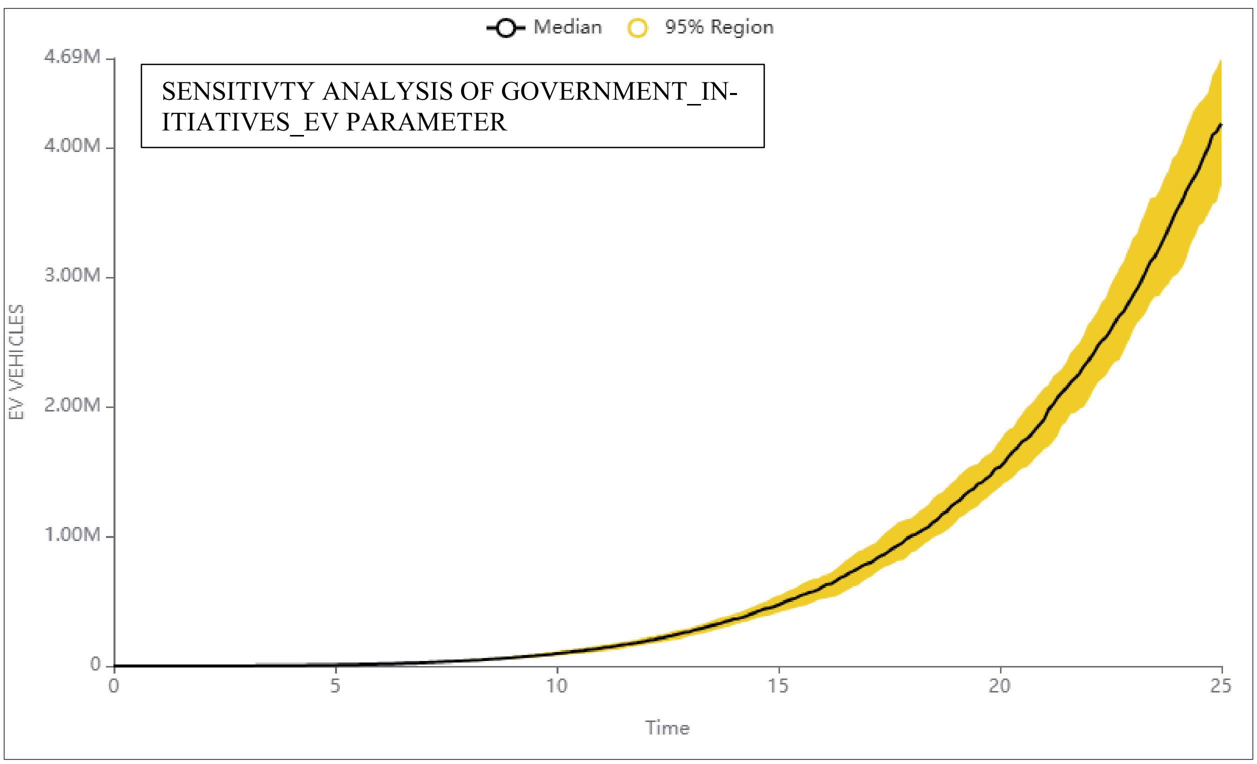

Figure 44 Sensitivity Analysis of Government_Initiatives_EV parameter affecting the EV stock.

Table 47 shows the outputs of EV Vehicles at upperbound and lowerbound at time t=25 for Government_Initiatives_EV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
3711817.28	4689486.18	0-3	977668.9

Table 47 Output of sensitivity analysis of 95% confidence range for time t=25 for Government_Initiatives_EV.

CHARGING_INFRASTRUCTURE_EV PARAMETER

Figure 45 displays the outcomes of a 95% confidence interval sensitivity analysis. The output shows a clear upward projection in its Median values over time, if the charging infrastructure parameter changes, the model's projected outcome then total EV stock increases significantly. The increase in difference between the 95% Lower and 95% Upper bounds emphasizes increasing uncertainty over time. The model output difference between the lower and upper bounds becomes clear at mid and later time period. This shows that minor changes in charging infrastructure assumptions can result in different EV adoption outcomes. Based on both the growing median and the increase in wide confidence intervals in later time periods, charging infrastructure are probably going to have a significant impact on accelerating EV vehicles.

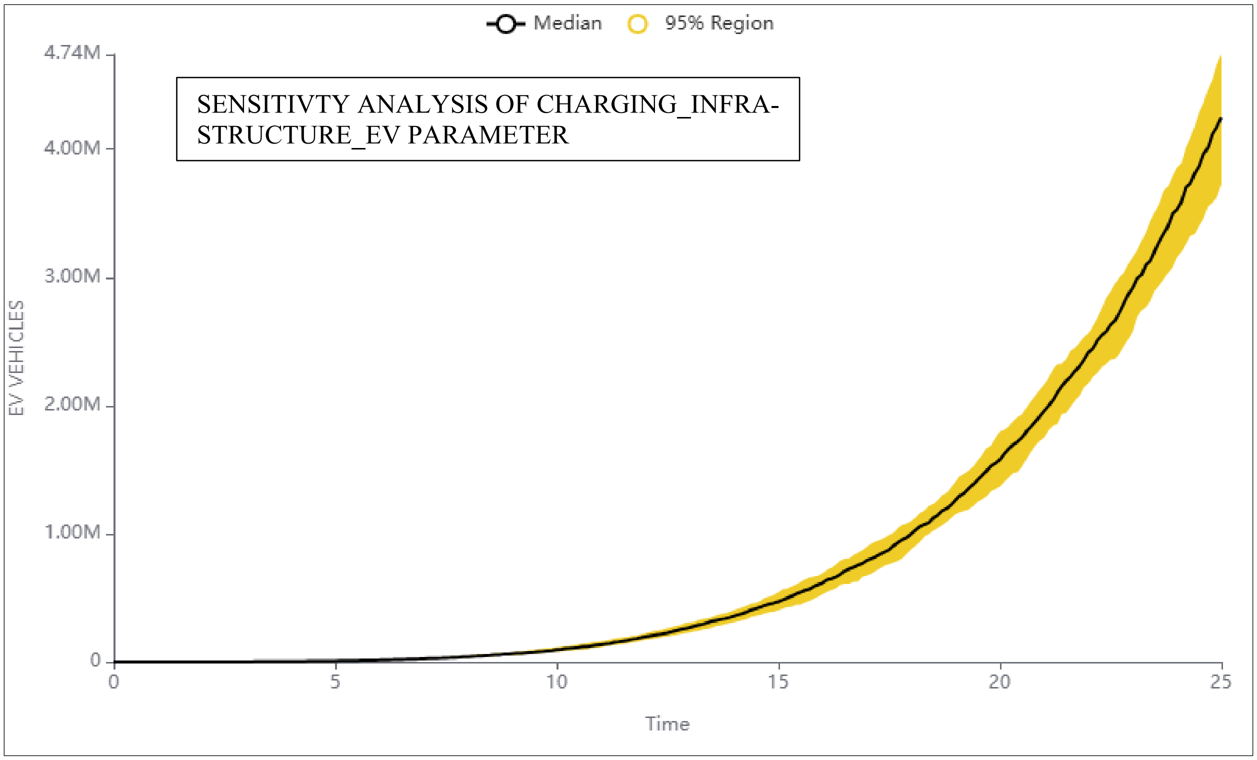

Figure 45 Sensitivity Analysis of Charging_Infrastructure_EV parameter affecting the EV stock.

Table 48 shows the outputs of EV Vehicles at upperbound and lowerbound at time t=25 for Charging_Infrastructure_EV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
3724279.44	4740091.97	0-3	1015812.53

Table 48 Output of sensitivity analysis of 95% confidence range for time t=25 for Charging_Infrastructure_EV.

COMPARISON OF EV PARAMETERS

The sensitivity analysis for EV Vehicles parameters reveals that the Cost_EV parameter exhibits the widest confidence interval, indicating a high sensitivity to input variations and a significant impact on EV adoption. Hence, Cost_EV is the most influential factor driving the highest number of EV vehicles. Based on these findings, the factors can be ranked in descending order of importance as follows: Cost_EV, FuelPrice_EV, Charging_Infrastructure_EV, Government_Initiatives_EV, and Customer_awareness_EV.

4.3.2 SENSITIVITY ANALYSIS FOR BIKES

Sensitivity analysis for all the parameters like Cost_Bike, Government_Initiatives_Bike, Customer_Awareness_Bike and Infrastructure_Expansion_EV are assessed and compared in this section.

GOVERNMENT_INITIATIATIVES_BIKE PARAMETER

With the 95% confidence interval the results show a consistent upward trend in the output of the model which is increasing from roughly 388,000 at the time 0 to over one million by time 25. Though the upper and lower bounds differ, the difference is not very significant when compared to the median, so the changes in the GOVERNMENT_INITIATIVE_BIKE parameter do not have a huge effect on the number of bikes. The system exhibits a consistent growth pattern with only moderate uncertainty and the model stays constant and is not highly sensitive to changes in parameters. Figure 46 shows the graph of output of sensitivity analysis for parameter Government_Initiative_Bike.

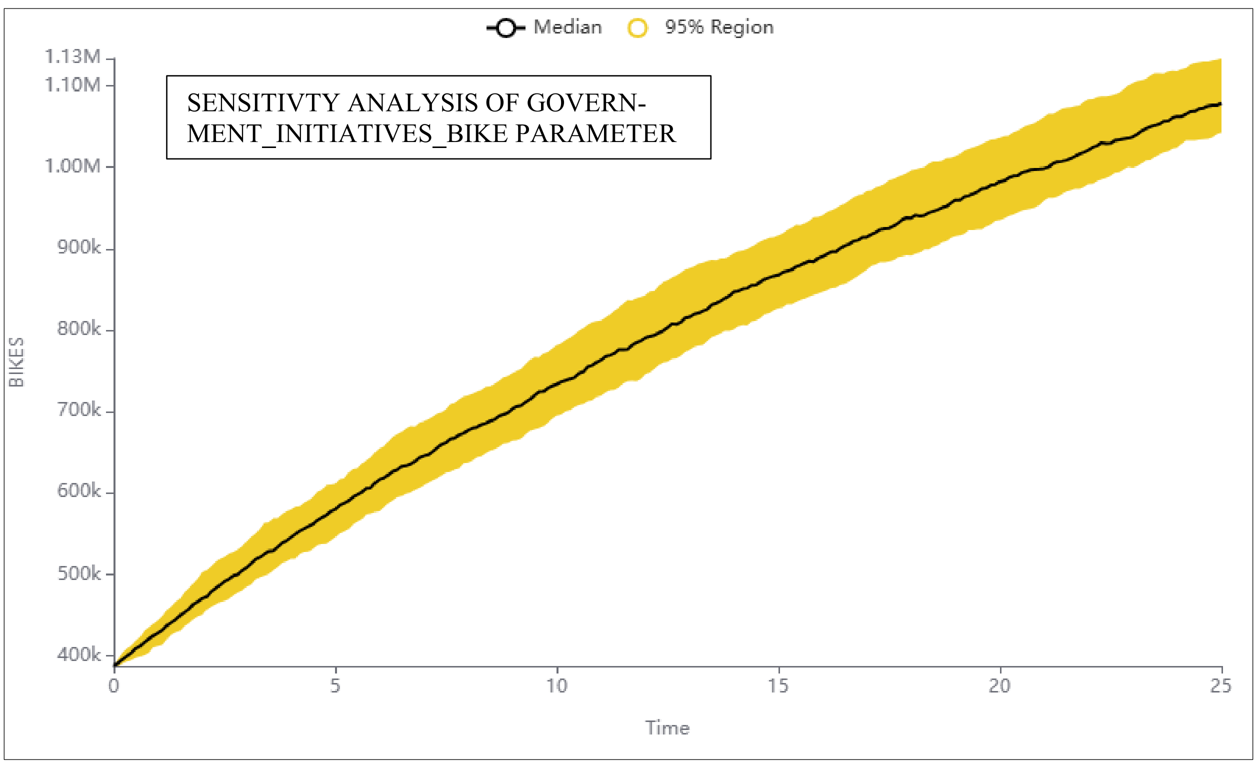

Figure 46 Sensitivity Analysis of Government_Initiatives_Bike parameter affecting the Bikes stock.

Table 49 shows the outputs of bikes at upperbound and lowerbound at time t=25 for GOVERNMENT_INITIATIVES_BIKE parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
1042728.99	1133705.68	0-3	90976.69

Table 49 Output of sensitivity analysis of 95% confidence range for time t=25 for GOVERNMENT_INITIATIVES_BIKE

CUSTOMER_AWARENESS_BIKE PARAMETER

Starting at about 388,000, the median outcome for the CUSTOMER_AWARENESS_BIKE parameter increases over time till the end of the simulation period at t =25 it exceeds one million. The 95% confidence intervals widen somewhat as the model advances. Still, the difference between the lower and upper bounds is smaller, implying that it does not cause great influence in the stock. Figure 47 shows the graph of output of sensitivity analysis for parameter CUSTOMER_AWARENESS_BIKE.

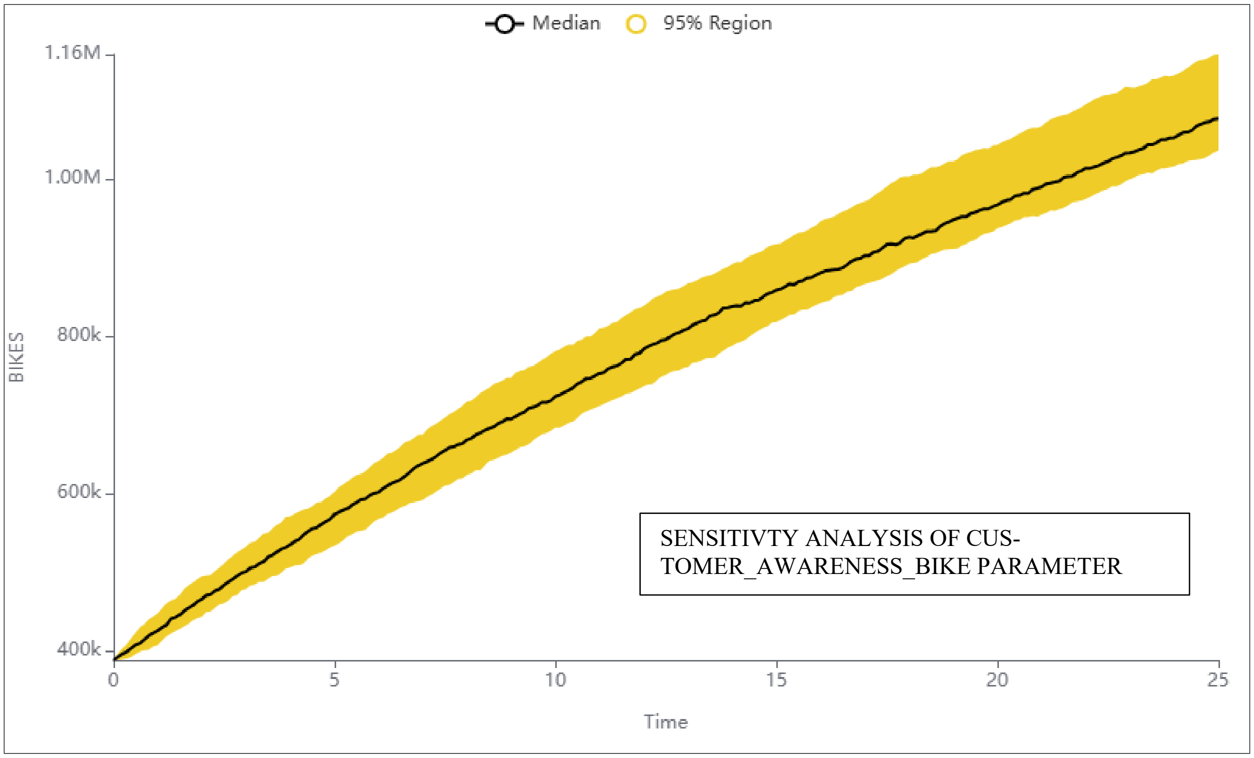

Figure 47 Sensitivity Analysis of Customer_Awareness_Bike parameter affecting the Bikes stock.

Table 50 shows the outputs of bikes at upperbound and lowerbound at time t=25 for Customer_Awareness_Bike parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
1029295.46	1157632.95	0-3	128337.49

Table 50 Output of sensitivity analysis of 95% confidence range for time t=25 for Customer_Awareness_Bike.

INFRASTRUCTURE_EXPANSION_BIKE PARAMETER

The results show that while the INFRASTRUCTURE_EXPANSION_BIKE parameter does have an influence in the model's output and the median increases from approximately 388,000 at time 0 to 1.07 million by time 25. The 95% confidence bounds remain relatively narrow throughout the simulation. This indicates that variations in the parameter are impactful but do not lead to extreme outcomes of bikes compared to parameters with wider confidence intervals. The relatively narrow gap between the lower and upper bounds suggests a small degree of uncertainty. Figure 48 shows the graph of output of sensitivity analysis for parameter INFRASTRUCTURE_EXPANSION_BIKE PARAMETER.

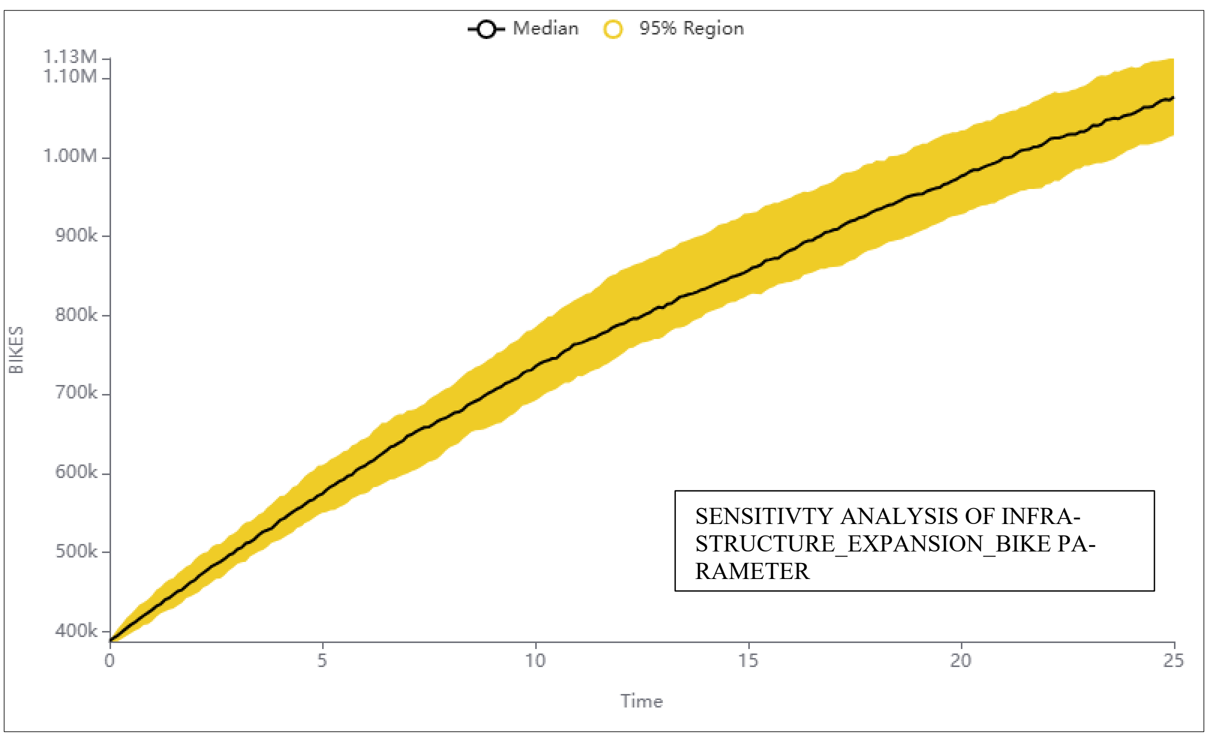

Figure 48 Sensitivity Analysis of Infrastructure_Expansion_Bike parameter affecting the Bikes stock.

Table 51 shows the outputs of bikes at upperbound and lowerbound at time t=25 for Infrastructure_Expansion_Bike parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
1028013.91	1125028.1	0-3	97014.19

Table 51 Output of sensitivity analysis of 95% confidence range for time t=25 for Infrastructure_Expansion_Bike.

COST_BIKE PARAMETER

With the 95% confidence intervals widening as time progresses, the model output shows a clear upward trend in response to changes in the Cost_Bike parameter over the simulation horizon. The output is fixed at a single value 388,000 bikes first at time 0, but by 0.1 the lower and upper bounds already vary greatly from about 1.96 million to 15.61 million, so reflecting increased sensitivity even in early stages. While the difference between the lower and upper limits also widens, the median keeps increasing steadily and will reach over one billion at the end of the period. Figure 49 shows the graph of output of sensitivity analysis for parameter Cost_Bike parameter.

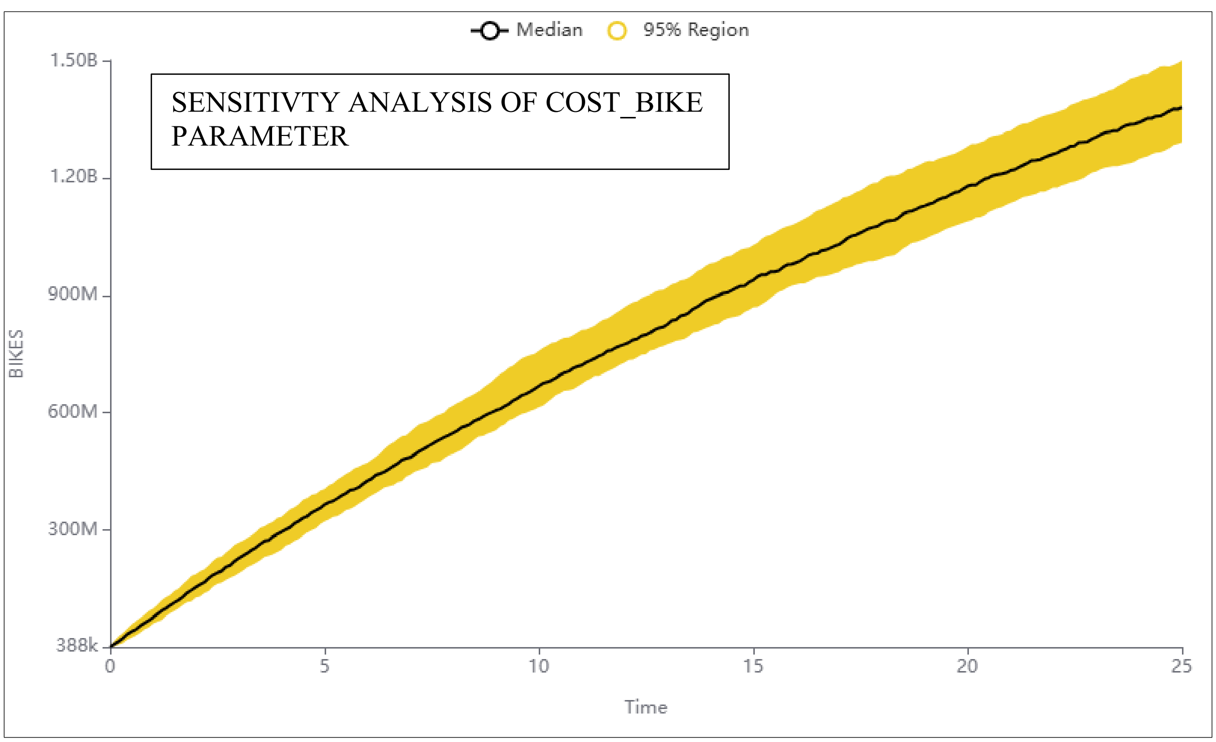

Figure 49 Sensitivity Analysis of Cost_Bike parameter affecting the Bikes stock.

Table 52 shows the outputs of bikes at upperbound and lowerbound at time t=25 for Cost_Bike parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
1291665870	1501832660	200,5000	210166790

Table 52 Output of sensitivity analysis of 95% confidence range for time t=25 for Cost _Bike.

COMPARISON OF PARAMETERS FOR BIKES

The sensitivity analysis for bikes parameters reveals that the Cost_Bike parameter exhibits the widest confidence interval, indicating a high sensitivity to input variations and a significant impact on bikes adoption. Consequently, Customer_Awareness_Bike is the next most influential factor driving the highest number of bikes. Based on these findings, the factors can be ranked in descending order of importance as follows: Cost_Bike, Customer_Awareness_Bike, Infrastructure_Expansion_Bike, and Government_Initiatives_Bike.

4.3.3 SENSITIVITY ANALYSIS FOR PUBLIC BUSES

Sensitivity analysis for all the parameters like Fare_Public_Bus, Government_Initiatives_Public_Bus, Customer_Awareness_Public_Bus and Infrastructure_Expansion_Public_Bus are assessed and compared in this section.

CUSTOMER_AWARENESS_PUBLIC_BUS PARAMETER

The initial value for the Customer_Awareness_Public_Bus parameter in this sensitivity analysis is roughly 73,174 at time 0 and increases to a median of roughly 89,975 by time 25. In the 95% interval small changes are observed throughout the simulation, suggesting that although modifications in customer awareness do influence the result, the general influence of the parameter is modest in comparison to those of parameters with more wide intervals. Figure 50 shows the graph of output of sensitivity analysis for parameter Customer_Awareness_Public_Bus parameter.

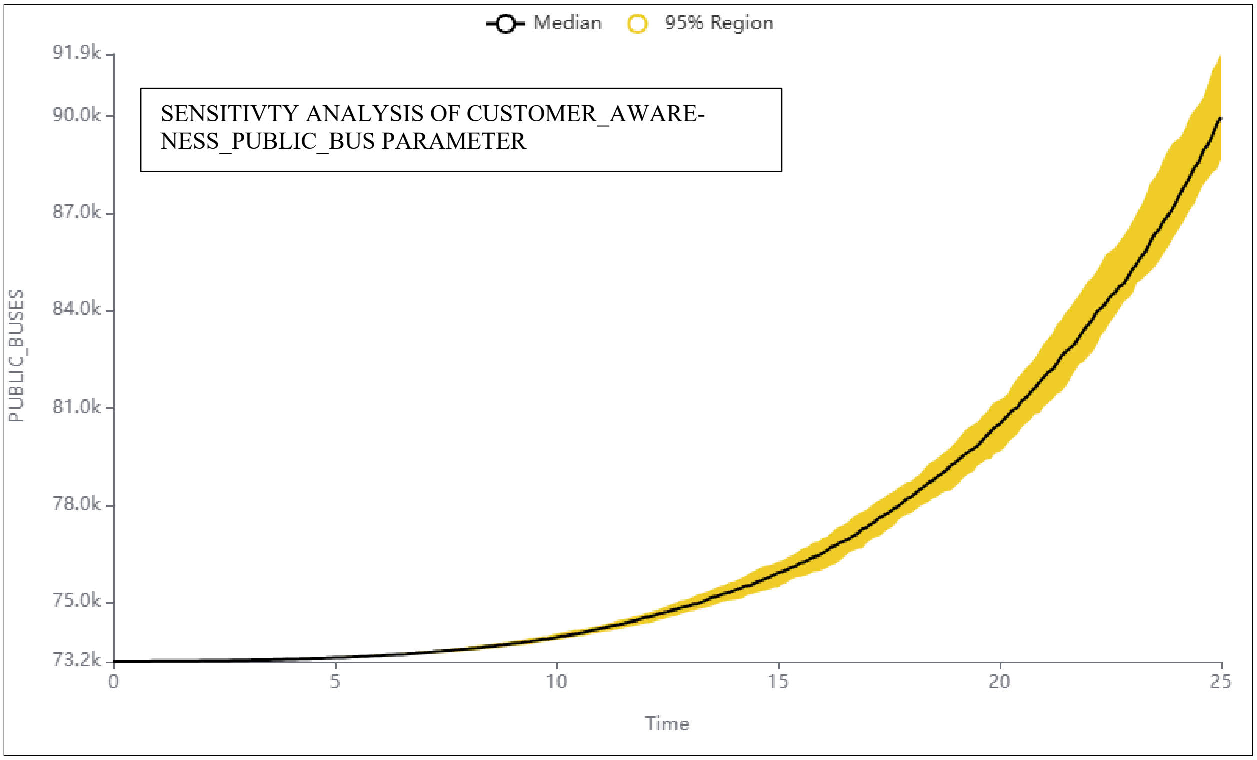

Figure 50 Sensitivity Analysis of Customer_Awareness_Public_Bus parameter affecting the Public Buses stock.

Table 53 shows the outputs of public buses at upperbound and lowerbound at time t=25 for Customer_Awareness_Public_Bus parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
88645.0896	91908.9523	0-3	3263.8627

Table 53 Output of sensitivity analysis of 95% confidence range for time t=25 for Customer_Awareness_Public_Bus Parameter.

GOVERNMENT_INITIATIVES_PUBLIC_BUS PARAMETER

Over the 95% confidence interval for GOVERNMENT_INITIATIVES_PUBLIC_BUS it is narrow, and changes in this parameter produce little difference in the output of the model. The general spread between the lower and upper bounds only slightly changes. Hence, the government initiatives have smaller impact on the system compared to parameters with much wider confidence intervals. The median value gradually increases from around 73,174 at the start to approximately 89,813 by the end time of 25. The consistent upward trend of the median shows that the

GOVERNMENT_INITIATIVES_PUBLIC_BUS help to increase the number of pubic buses but is less sensitive than other factors. Figure 51 shows the graph of output of sensitivity analysis for parameter GOVERNMENT_INITIATIVES_PUBLIC_BUS parameter.

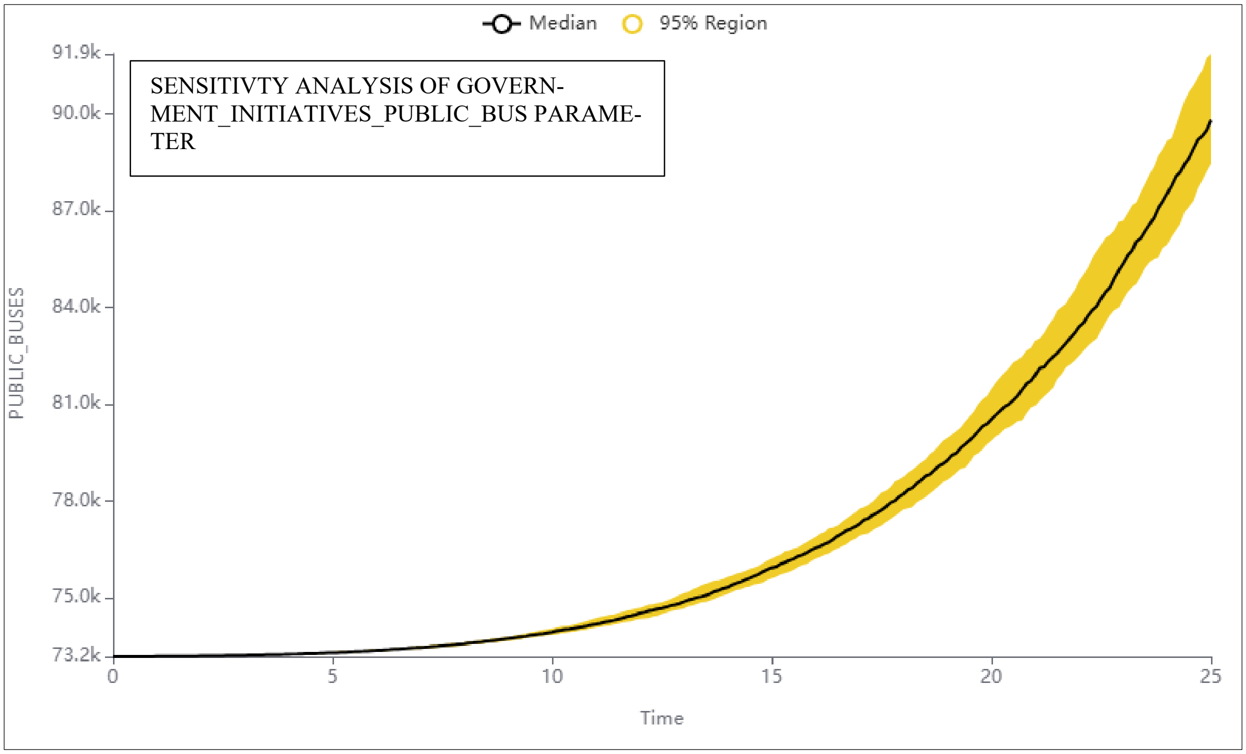

Figure 51 Sensitivity Analysis of Government_Initiatives_Public_Bus parameter affecting the Public Buses stock.

Table 54 shows the outputs of public buses s at upperbound and lowerbound at time t=25 for Government_Initiatives_Public_Bus parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
88460.6303	91853.2176	0-3	3392.5873

Table 54 Output of sensitivity analysis of 95% confidence range for time t=25 for GOVERNMENT_INITIATIVES_PUBLIC_BUS Parameter.

INFRASTRUCTURE_EXPANSION_PUBLIC_BUS PARAMETER

The 95% confidence interval in this sensitivity analysis for the parameter has small effect over time, suggesting that changes in this parameter have a modest but continuous effect on the system. Starting near 73,174, the median output rises over time to approximately 89,823. Although the lower and upper bounds both increase upward but their small spread indicates the growth of public buses in the model does not increase greatly. Figure 52 shows the graph of output of sensitivity analysis for parameter Infrastructure_Expansion_Public_Bus parameter.

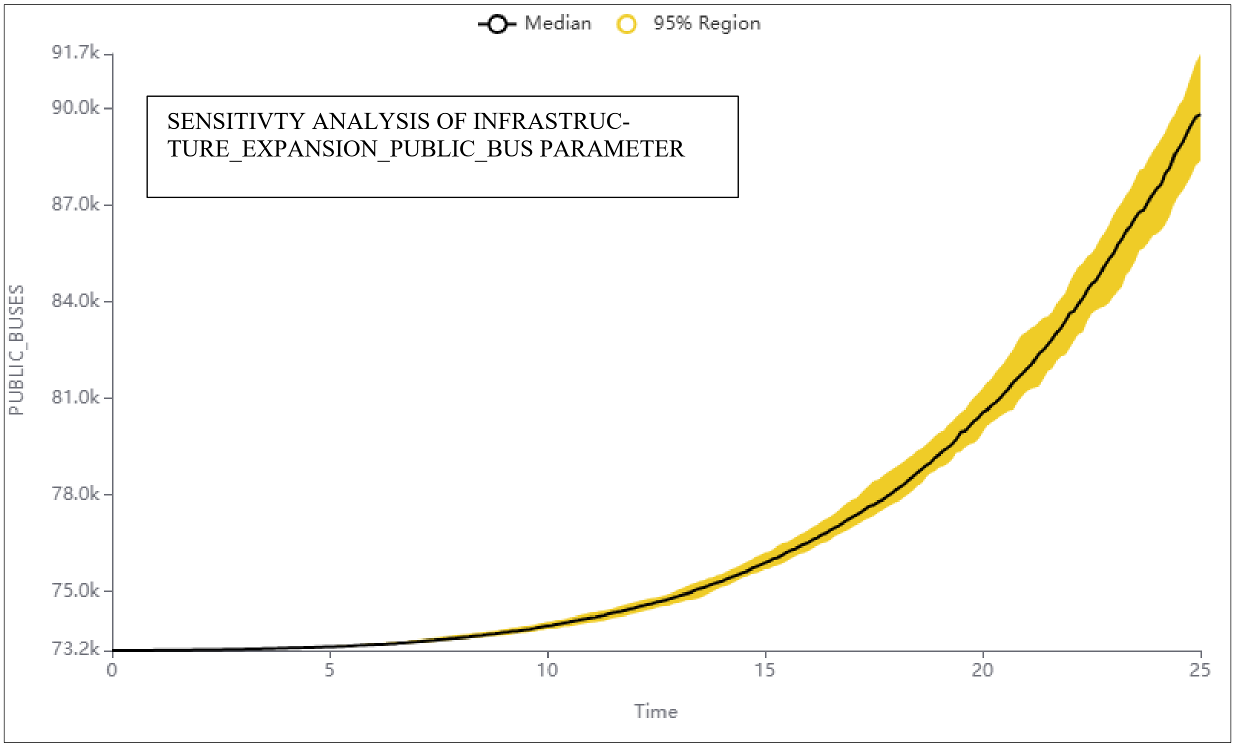

Figure 52 Sensitivity Analysis of Infrastructure_Expansion_Public_Bus parameter affecting the Public Buses stock.

Table 55 shows the outputs of public buses at upperbound and lowerbound at time t=25 for Infrastructure_Expansion_Public_Bus parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
88372.4671	91684.913	0-3	3312.4459

Table 55 Output of sensitivity analysis of 95% confidence range for time t=25 for INFRASTRUCTURE_EXPANSION_PUBLIC_BUS Parameter.

FARE_PUBLIC_BUS PARAMETER

The 95% confidence interval results for changes in the FARE _PUBLIC_BUS parameter from time 0 to 25 are shown in this figure. The lower and upper limits remain narrow and, the median fare price rises somewhat from roughly 73,000 to 134,000. The slow widening implies that the output of the system which is number of public buses increase over time but has limited influence in fare pricing. This suggests that, while fare price has moderate effect, the model is less sensitive to this factor over time. Figure 53 shows the graph of output of sensitivity analysis for parameter Fare_Public_Bus parameter.

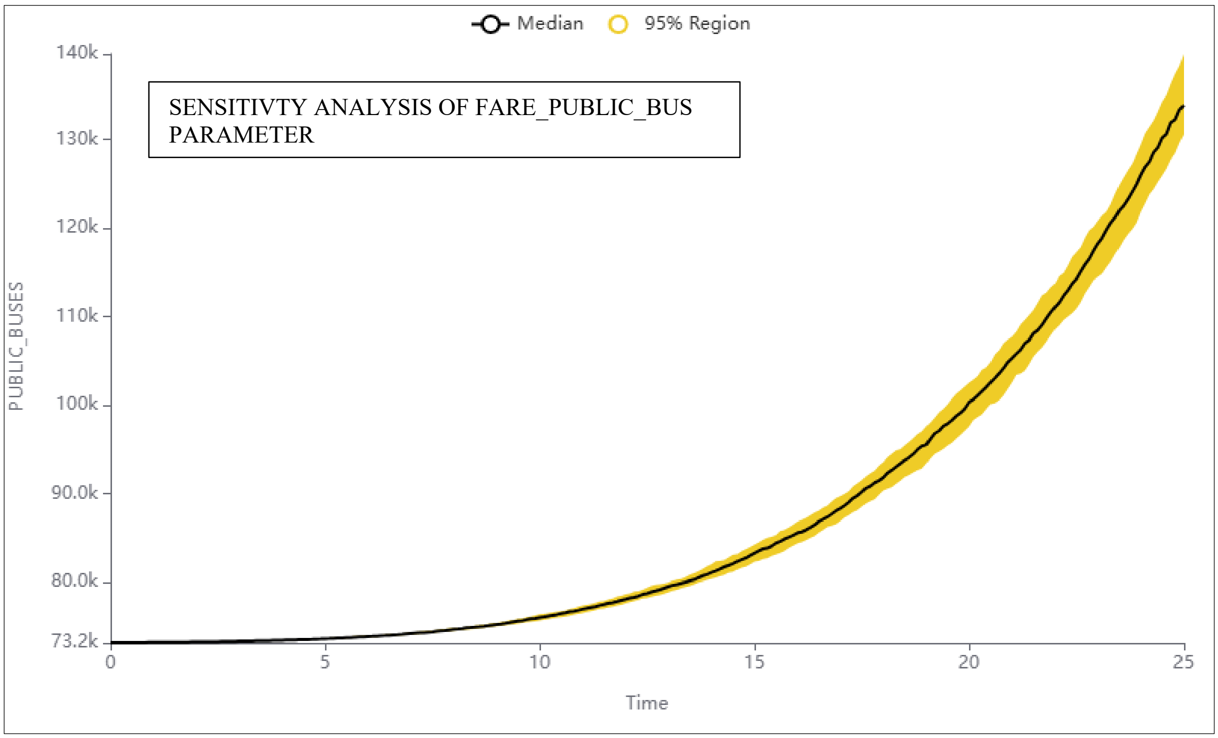

Figure 53 Sensitivity Analysis of Fare_Public_Bus parameter affecting the Public Buses stock.

Table 56 shows the outputs of public buses at upperbound and lowerbound at time t=25 for Fare_Public_Bus parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
130535.682	139642.596	0-3	9106.914

Table 56 Output of sensitivity analysis of 95% confidence range for time t=25 for Fare_Public_Bus Parameter.

COMPARISON OF PARAMETERS FOR PUBLIC BUSES

The sensitivity analysis for public buses parameters reveals that the Fare_Public_Bus parameter exhibits the widest confidence interval, indicating a high sensitivity to input variations and a significant impact on pubic bus adoption. Consequently, Government_Initiatives_Public_Bus is the most influential factor driving the highest number of public buses. Based on these findings, the factors can be ranked in descending order of importance as follows: Fare_Public_Bus, Government_Initiatives_Public_Bus, Infrastructure_Expansion_Public_Bus, and Customer_Awareness_Public_Bus.

4.3.4 SENSITIVITY ANALYSIS OF GASOLINE VEHICLE

Sensitivity analysis for all the parameters like Cost_GV, Fuelcost_GV, Government_Initiatives_GV, Customer_Awareness_GV are assessed and compared.

CUSTOMER_AWARENESS_GV PARAMETER

The 95% confidence interval for customer awareness factor of gasoline vehicles shows consistent increase and a considerable widening. At time 0, the lower, upper, and median values are aligned together, but by time 25, the interval widens to roughly 30,900 billion. This increasing trend emphasizes how significantly consumer awareness influences the gasoline vehicles adoption. Figure 54 shows the graph of output of sensitivity analysis for parameter CUSTOMER_AWARENESS_GV parameter.

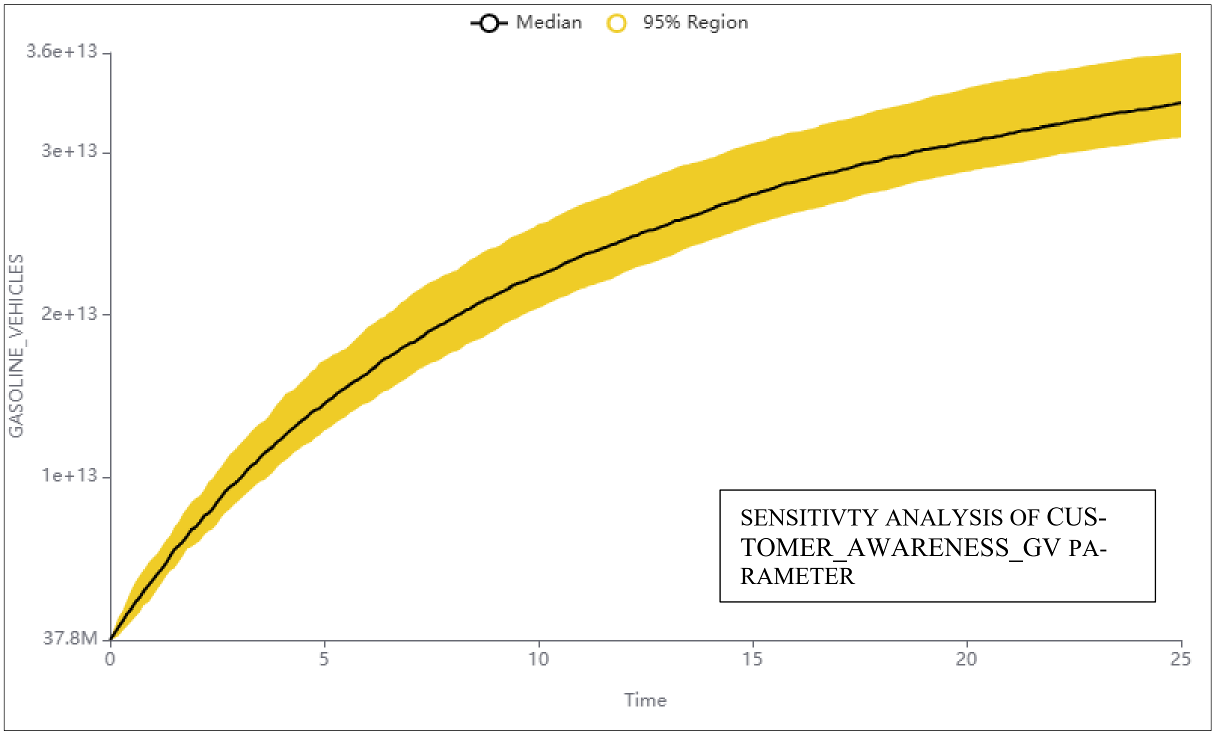

Figure 54 Sensitivity Analysis of Customer_Awareness_GV parameter affecting the Gasoline Vehicles stock.

The following table shows the outputs of gasoline vehicles at upperbound and lowerbound at time t=25 for Customer_Awareness_GV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
30938939200000	36129493800000	0-3	5190554600000

Table 57 Output of sensitivity analysis of 95% confidence range for time t=25 for Customer_Awareness_GV Parameter.

GOVERNMENT_INITIATIVES_GV

The model output gasoline vehicles for the government initiatives parameter for gasoline vehicles increases between time 0 and 0.1 indicating a strong initial impact of this parameter on the system. Although the difference between the lower and upper bounds lesser somewhat in later periods, the median and both confidence limits steadily rise over the whole simulation from time 0 to time 25. This trend implies that although government initiatives continue to be a major driver throughout the simulation, their effect on the gasoline vehicles becomes more predictable as time goes by.

Figure 55 shows the graph of output of sensitivity analysis for parameter Government_Initiatives_GV parameter.

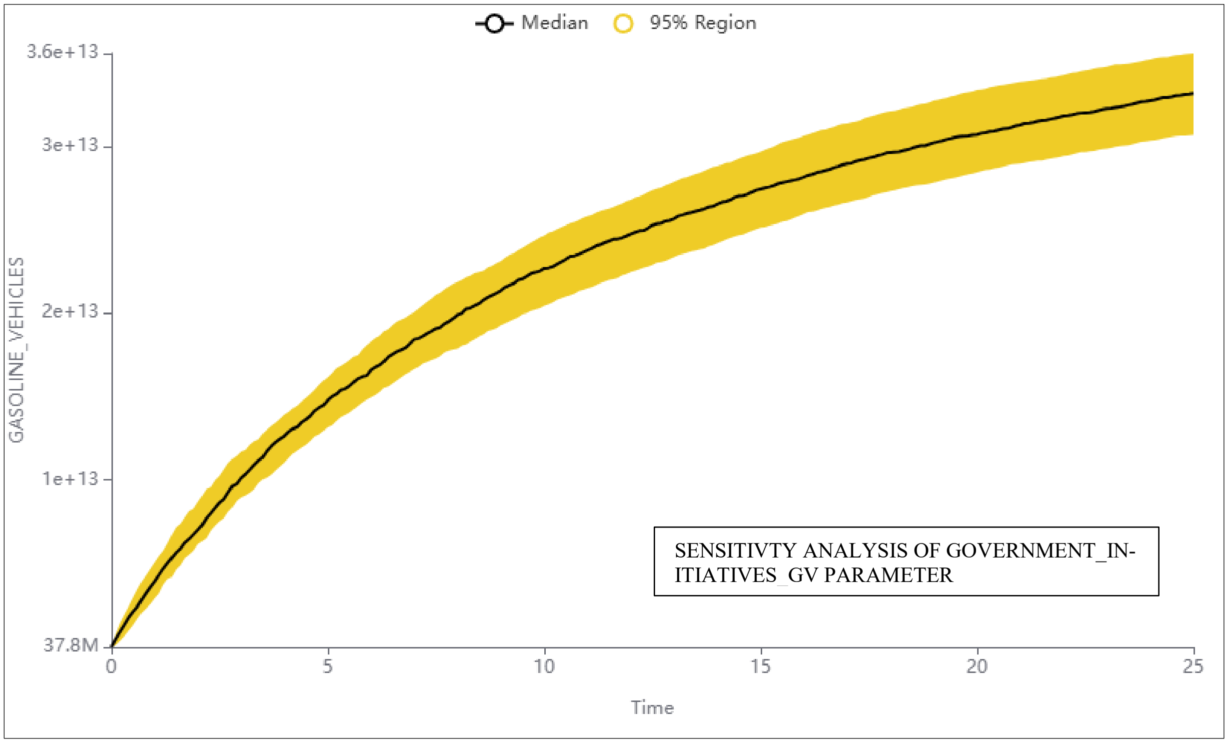

Figure 55 Sensitivity Analysis of Government_Initiatives_GV parameter affecting the Gasoline Vehicles stock.

Table 58 shows the outputs of gasoline vehicles at upperbound and lowerbound at time t=25 for Government_Initiatives_GV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
30682539200000	35578251100000	0-3	4895711900000

Table 58 Output of sensitivity analysis of 95% confidence range for time t=25 for Government_Initiatives_GV Parameter.

FUELPRICE_GV

From time 0 through time 25 the 95% confidence intervals for the FUELPRICE_GV parameter shows an increase but consistent trend in the gasoline vehicles. Initially the lower, median, and upper bounds show that variations in gasoline fuel cost significantly influence the number of gasoline vehicles. Although the difference between the lower and upper limits widens over time showing increasing uncertainty, its difference may not produce the same magnitude of impact as parameters with larger or more sensitive confidence intervals. Figure 56 shows the graph of output of sensitivity analysis for parameter FUELPRICE_GV.

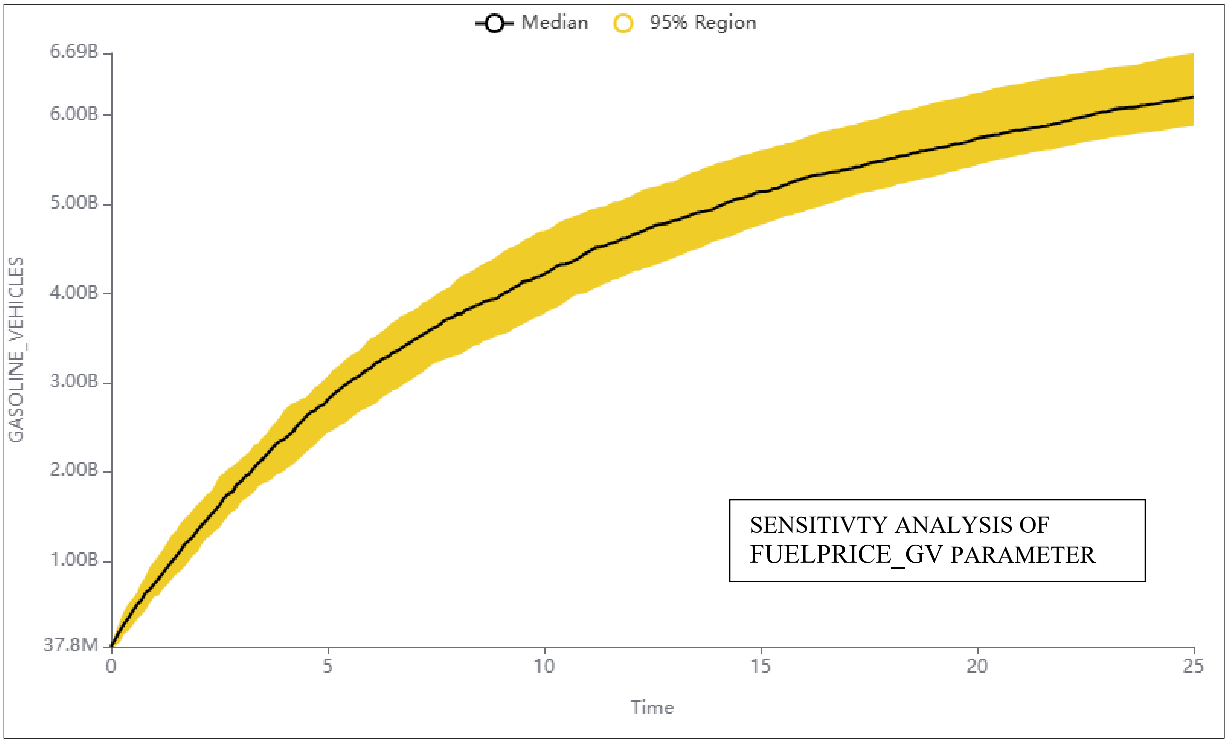

Figure 56 Sensitivity Analysis of FuelPrice_GV parameter affecting the Gasoline Vehicles stock.

Table 59 shows the outputs of gasoline vehicles at upperbound and lowerbound at time t=25 for FuelPrice_GV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
5875782910	6692283020	0.5-20	816500110

Table 59 Output of sensitivity analysis of 95% confidence range for time t=25 for FuelPrice_GV Parameter.

COST_GV

Rising values of the 95% lower and upper bounds as well as the median show how significantly the cost of gasoline vehicles parameter influences the output of the model over the simulation. Starting at a rather low level the output that is gasoline vehicles increases gradually by time 25.

Although the spread between the lower and upper bounds remains limited compared to more uncertain parameters, this development in the confidence interval emphasizes the increasing influence of the parameter over time. Figure 57 shows the graph of output of sensitivity analysis for parameter COST_GV.

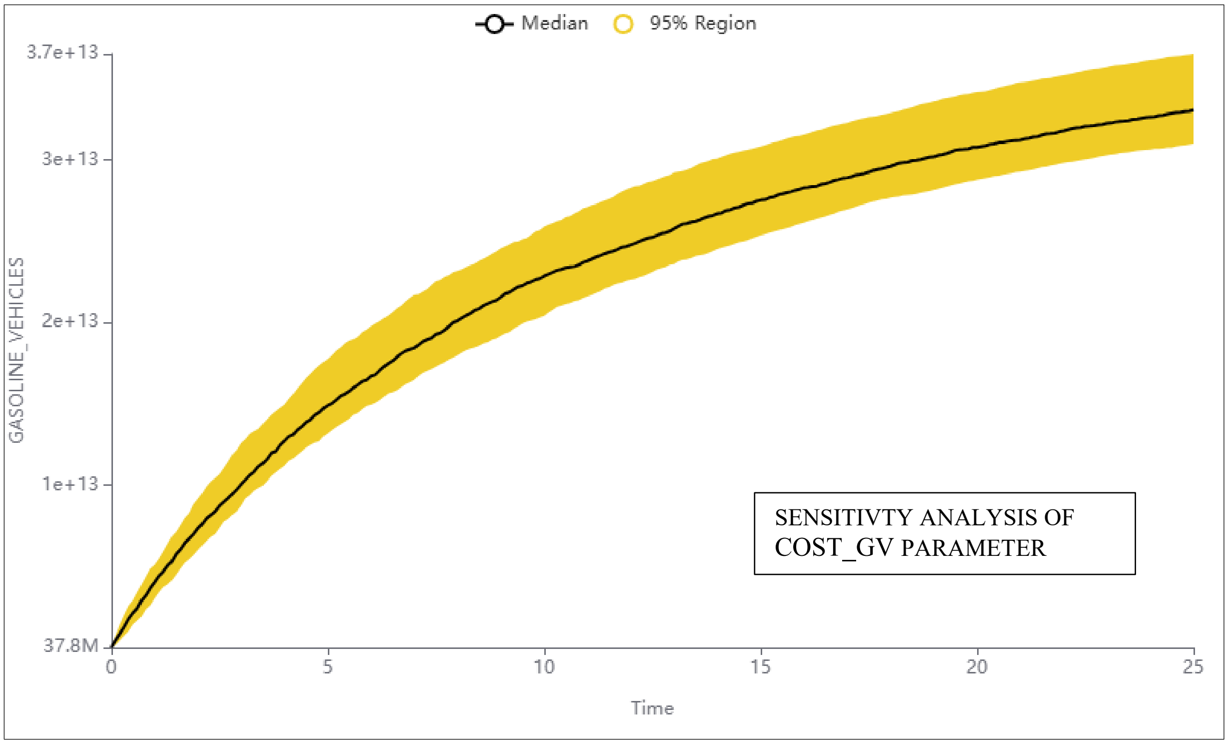

Figure 57 Sensitivity Analysis of Cost_GV parameter affecting the Gasoline Vehicles stock.

Table 60 shows the outputs of gasoline vehicles at upperbound and lowerbound at time t=25 for Cost_GV parameter.

95% lower bound	95% upper bound	One-at-a-time sensitivity analysis	Difference
31016759000000	36551004200000	10,000-100,000	5534245200000

Table 60 Output of sensitivity analysis of 95% confidence range for time t=25 for Cost_GV Parameter.

COMPARISON OF PARAMETERS FOR GASOLINE VEHICLES

The sensitivity analysis for gasoline vehicles parameters reveals that the Cost_GV parameter exhibits the widest confidence interval, indicating a high sensitivity to input variations and a significant impact on gasoline adoption. Consequently, Customer_Awareness_GV is the most influential factor driving the highest number of public buses. Based on these findings, the factors can be ranked in descending order of importance as follows: Cost_GV, Customer_Awareness_GV, Government_Initiatives_GV, and FuelPrice_GV.

4.3.5 SUMMARY OF RESULTS OF SENSITIVITY ANALYSIS

It is found that cost of a vehicle, cost of bike and fare cost of a public bus has the highest impact on the adoption of these vehicles and transit options. Table 61 summarizes the sensitivity analysis results of parameters.

NAME	CUSTOMER AWARENESS	GOVERNMENT INITIATIVES	COST OF VEHICLE/BIKE	FUEL COST OF VEHICLE	FARE OF PUBLIC BUSES	INFRASTRUCTURE DEVELOPMENTS
EV	5	4	1	2	-	3
BIOFUEL VEHICLES	5	4	1	2	-	3
HYDROGEN VEHICLES	5	4	1	2	-	3
GASOLINE VEHICLES	2	3	1	4	-	-
BIKES	2	4	1	-	-	3
PUBLIC BUSES	4	2	-	-	1	3

Table 61 Summary of sensitivity analysis of various factors.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 OUTPUT OF BASELINE SCENARIO

From Figure 58, we observe that the number of gasoline vehicles increases exponentially. And the rest of vehicles increase according to steady but not fast growth in the parameters or factors that affect the increment of vehicles like customer awareness, expansion of infrastructure, government initiatives and the cost. By the next 15 years it increased to 711 million vehicles and by the end of 2050 we see the total number of gasoline vehicles has increased to 802 million from 644 million in 2024 initially.

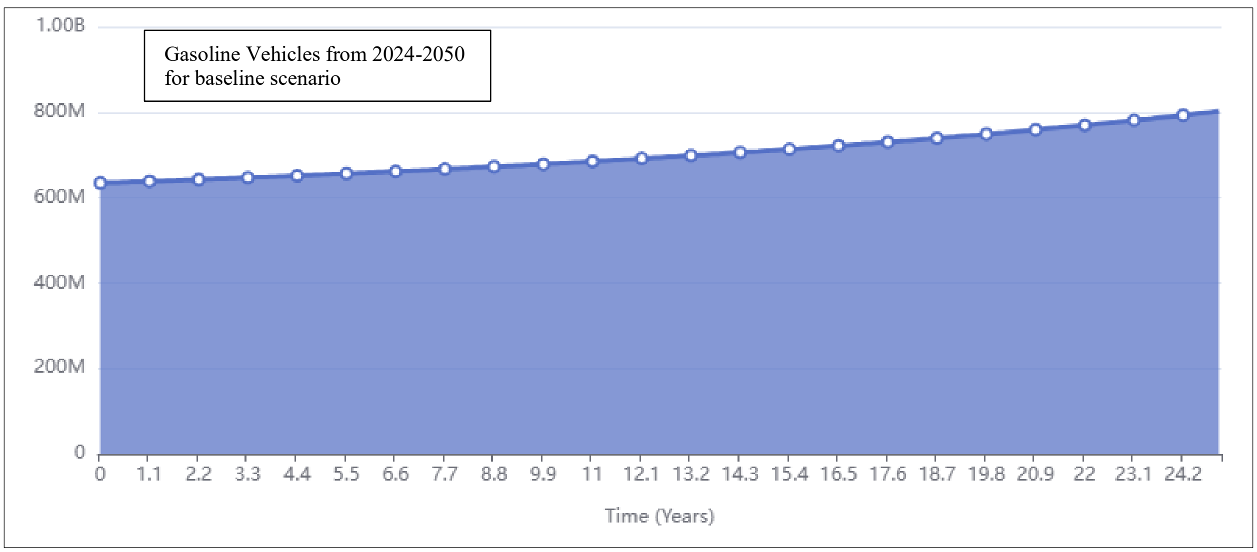

Figure 58 Time series graph showing the increase in gasoline vehicles from 2024 to 2050 in a baseline scenario.

Figure 59 illustrates the graphical representation of outputs of baseline scenario of 2024 to 2050 of alternative fuel-based technology and sustainable transportation option, EV vehicles increased from 1978449 in 2024 to 3929546 vehicles, biofuel vehicles increased from 908100 vehicles to 1292017 units, hydrogen vehicles increased from 1040 vehicles in 2024 to 18188, bikes increased from 811000 units in 2024 to 1207123 bikes by 2050. And, public buses increased from 84199 units in 2024 to 98,400 by 2050. There has been growth in adopting alternative fuel vehicles and an increased usage of bikes and public buses. But the growth has not been significantly high due to the model following the previous trends.

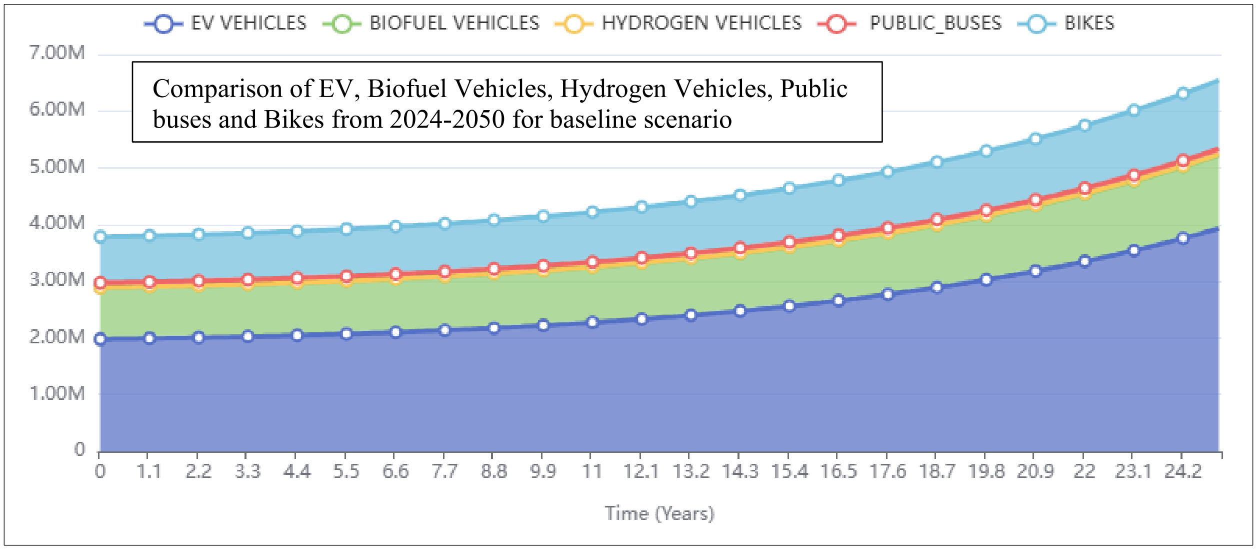

Figure 59 Time series graph showing the increase in alternative fuel vehicles and sustainable transportation options from 2024 to 2050 in a baseline scenario.

Figure 60 shows total GHG Emission generated by all the parameters of the model for a baseline scenario. In terms of emissions, it increased to 61,443 MTCO2 by the end of 25 years. The initial GHG emissions in 2024 was 24,982 MTCO2. In the business-as-usual scenario, the GHG emissions continue to increase over time.

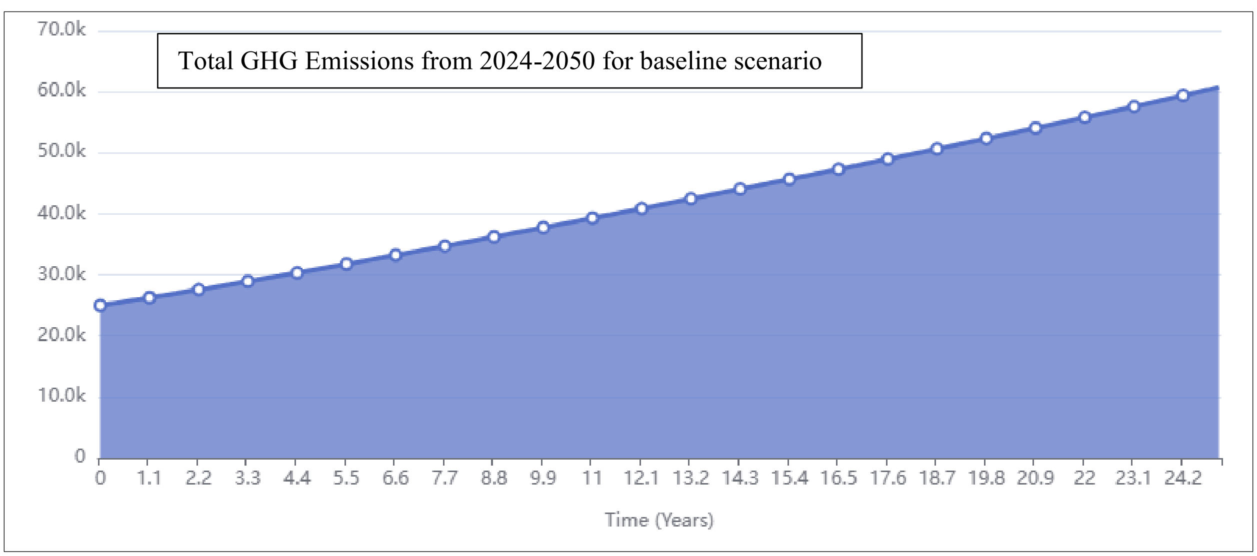

Figure 60 Time series graph showing the increase in GHG Emissions from 2024 to 2050 in a baseline scenario.

Figure 61 shows the output of the table generated in Insightmaker. It gives us a better and a precise value of the output. The final output at year 25 has been highlighted.

Time	EV VEHICLES	BIOFUEL VEHICLES	HYDROGEN VEHICLES	BIKES	GASOLINE_VEHICLES	PUBLIC_BUSES	TOTAL GHG EMISSIONS
23.5	3,617,721.55	1,234,092.64	15,967.9052	1,153,541.02	785,014,544	96,610.7112	58,933.0866
23.6	3,637,056.02	1,237,692.82	16,107.5458	1,156,941.16	786,103,760	96,724.5042	59,098.4082
23.7	3,656,589	1,241,328.7	16,248.3412	1,160,365.25	787,198,901	96,839.1334	59,264.0078
23.8	3,676,322.55	1,245,000.65	16,390.3025	1,163,813.42	788,300,013	96,954.6048	59,429.8873
23.9	3,696,258.72	1,248,709.04	16,533.4404	1,167,285.83	789,407,139	97,070.9242	59,596.0485
24	3,716,399.62	1,252,454.25	16,677.7663	1,170,782.61	790,520,323	97,188.098	59,762.4936
24.1	3,736,747.35	1,256,236.66	16,823.2912	1,174,303.91	791,639,611	97,306.1321	59,929.2246
24.2	3,757,304.06	1,260,056.66	16,970.0268	1,177,849.87	792,765,049	97,425.0328	60,096.2433
24.3	3,778,071.92	1,263,914.64	17,117.9843	1,181,420.64	793,896,683	97,544.8063	60,263.5519
24.4	3,799,053.12	1,267,811	17,267.1756	1,185,016.36	795,034,558	97,665.4589	60,431.1523
24.5	3,820,249.87	1,271,746.13	17,417.6123	1,188,637.18	796,178,723	97,786.9969	60,599.0468
24.6	3,841,664.42	1,275,720.45	17,569.3064	1,192,283.25	797,329,224	97,909.4268	60,767.2372
24.7	3,863,299.04	1,279,734.37	17,722.27	1,195,954.73	798,486,109	98,032.7549	60,935.7258
24.8	3,885,156.04	1,283,788.29	17,876.5152	1,199,651.76	799,649,428	98,156.9878	61,104.5147
24.9	3,907,237.73	1,287,882.65	18,032.0545	1,203,374.5	800,819,229	98,282.132	61,273.606
25	3,929,546.47	1,292,017.86	18,188.9001	1,207,123.11	801,995,561	98,408.1941	61,443.0018

Figure 61 Table in Insightmaker for outputs generated for baseline scenario.

Name	2024 (Input)	2050 (Output)	Unit
EV Vehicles	1978449	3929546	Units
Biofuel Vehicles	908100	1292017	Units
Hydrogen vehicles	1040	18188	Units
Gasoline Vehicles	634000000	801995561	Units
Public Buses	84199	98408	Units
Bikes	811000	1207123	Units
Total GHG Emission	24982	61443	MTC02

Table 62 Summary of inputs and outputs in baseline scenario [34].

5.2 OUTPUT OF SCENARIO-1 (EV'S HIGHEST BY 2050)

We looked at the output concerning the change in gasoline vehicles for this scenario. Figure 62 shows the declining gasoline vehicle time series graphical depiction over a 25-year span. Five years later, gasoline vehicle count dropped to 114,791,000 units. Ten years later the total dropped to 5,180,390 vehicles. Fifteen years later, gasoline vehicle count dropped to 211,000 units. Gasoline cars show to almost be extinct at the end of 25 years. This change emphasizes how alternative fuels mostly EVs and other developing technologies are progressively replacing conventional internal combustion engines (ICE) vehicles.

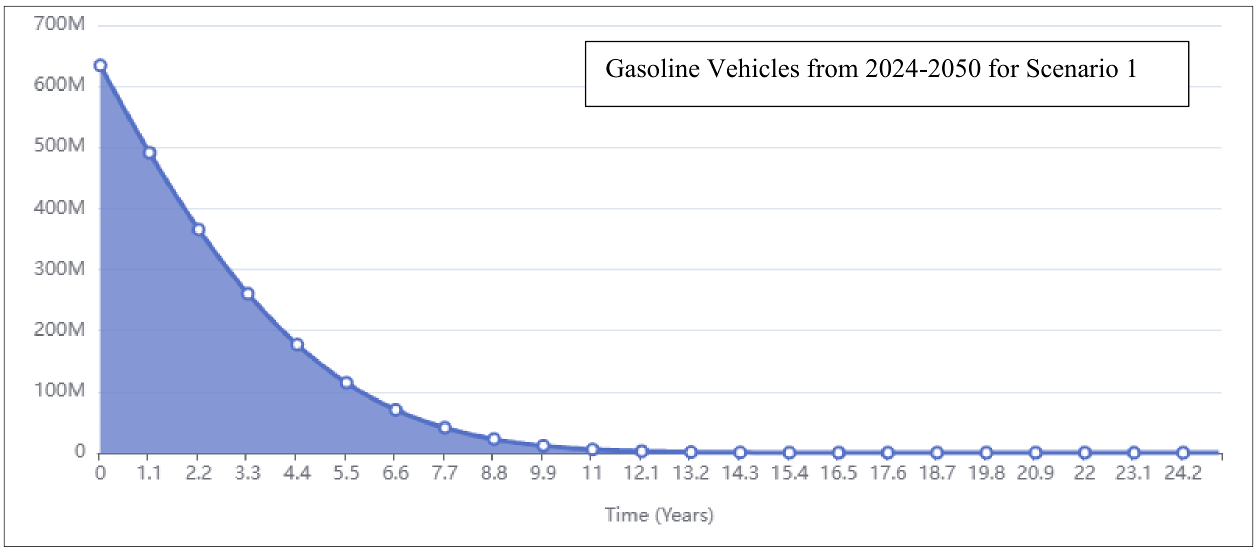

Figure 62 Time series graph showing the decrease in gasoline vehicles from 2024 to 2050 in Scenario 1.

Figure 63 shows the time series graph of various alternative fuel vehicles and sustainable transportation option like public buses and bikes. There are 1978449 EVs in use at t=0; this number increases to 50153921 units by t=25. Due to rising consumer acceptance, improving technology, and supporting government measures, this accelerating adoption rate. This consistent increasing trend suggests that over the simulation period EVs start to account for a sizable share of the total vehicle fleet. Starting at roughly 908100 units at t = 0, biofuel vehicles expand to almost 28972747 units. Though this increase is noteworthy, the fast spread of electric vehicles somewhat offsets it. According to the trend, biofuel technologies acquire popularity but do not rule the market as much as electric vehicles do.

Starting at about 811000 units, bicycles show modest but consistent increase to reach about 1113925 units by t=25. This consistent rise may point to a continuous interest in low-cost, low-impact personal mobility. Starting at almost 84,200 at t=0, public bus numbers rise to almost 293,900 by 25 t=25. This growth shows a continuous investment in public transportation infrastructure, implying that government might be supporting bus systems as component of more public transportation and environmental concerns. Starting at just over 1,000 units at t=0, hydrogen-powered vehicles climb to almost 3367070 units by t=25. Although this increase is rather large, the total size stays less than that of EVs. Still, the trend shows that hydrogen fuel cell technology is progressively getting popular.

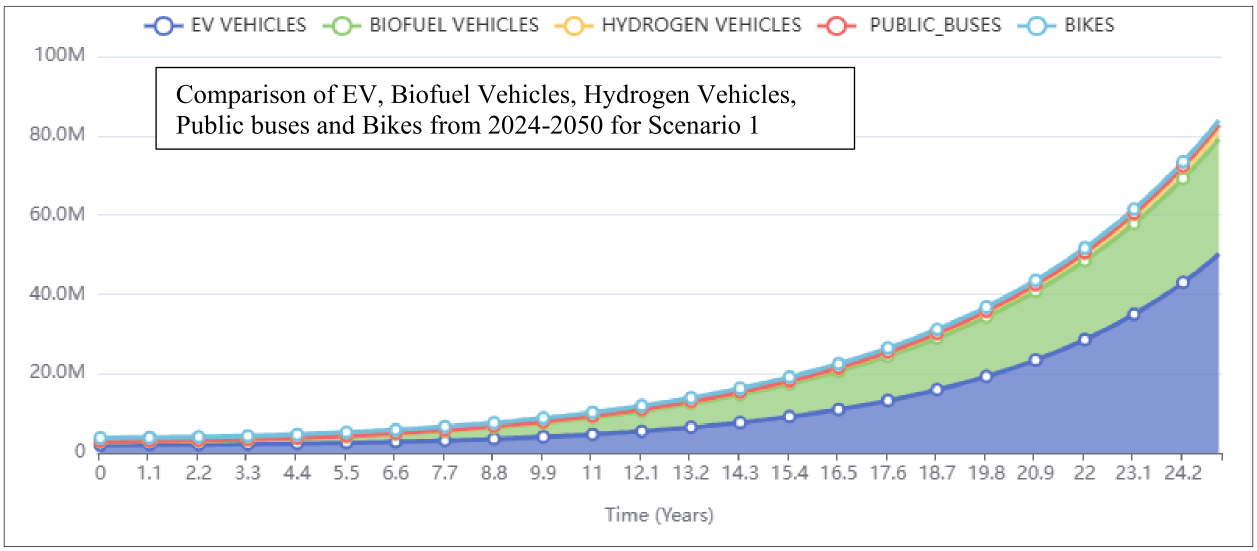

Figure 63 Time series graph showing the increase in alternative fuel vehicles and sustainable transportation options from 2024 to 2050 in Scenario 1.

From almost 25,000 units at t=0 to roughly 4,800 by t=25, overall greenhouse gas (GHG) emissions drop over the years. This significant cut matches the decline in gasoline-powered cars and the increase in greener alternative fuel-based vehicles. It implies that over the simulation timeline, switching from conventional ICE vehicles toward EVs, biofuel, and hydrogen alternatives greatly reduces transportation-related carbon emissions. Figure 64 illustrates the time series graph of GHG emissions over 25 years from 2024 to 2050.

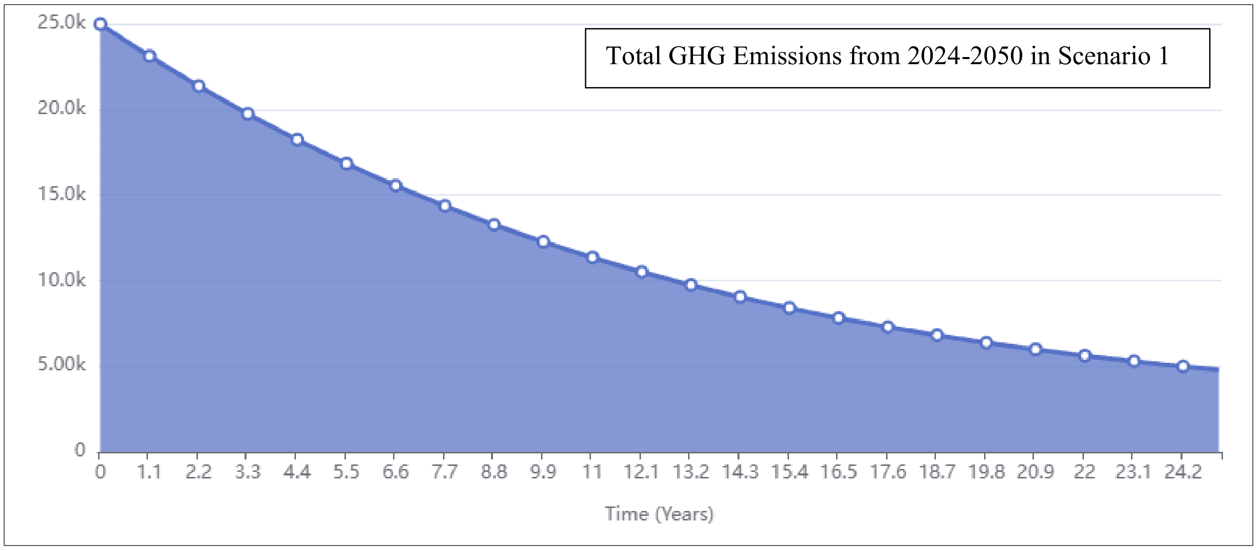

Figure 64 Time series graph showing the decrease in GHG Emissions from 2024 to 2050 in Scenario 1.

Figure 65 depicts the output generated in tabular form in Insightmaker tool.

Time	EV VEHICLES	BIOFUEL VEHICLES	GASOLINE_VEHICLES	BIKES	PUBLIC_BUSES	HYDROGEN VEHICLES	TOTAL GHG EMISSIONS
23.4	36,953,663.9	23,746,417.1	5.40401354	1,078,576.99	239,756.19	2,494,739.11	5,202.53583
23.5	37,652,721.9	24,045,081.9	4.60730656	1,080,702.48	242,669.167	2,540,175.71	5,174.85294
23.6	38,366,631.4	24,347,262.1	3.92539286	1,082,838.96	245,638.43	2,586,640.32	5,147.38828
23.7	39,095,766.4	24,653,001.5	3.3422508	1,084,986.46	248,665.294	2,634,166.3	5,120.13868
23.8	39,840,512.7	24,962,344.8	2.84402194	1,087,145.03	251,751.115	2,682,788.58	5,093.10096
23.9	40,601,268.4	25,275,337.2	2.41873135	1,089,314.69	254,897.293	2,732,543.69	5,066.27192
24	41,378,444.2	25,592,024.7	2.05604311	1,091,495.5	258,105.271	2,783,469.94	5,039.64835
24.1	42,172,464.3	25,912,453.9	1.74704663	1,093,687.49	261,376.54	2,835,607.48	5,013.22702
24.2	42,983,766.6	26,236,672.2	1.48407092	1,095,890.69	264,712.641	2,888,998.43	4,987.0047
24.3	43,812,803.4	26,564,727.5	1.26052371	1,098,105.16	268,115.165	2,943,687.03	4,960.97811
24.4	44,660,041.9	26,896,668.6	1.07075407	1,100,330.93	271,585.756	2,999,719.75	4,935.14399
24.5	45,525,964.9	27,232,545.1	0.90993789	1,102,568.04	275,126.114	3,057,145.48	4,909.49904
24.6	46,411,071.4	27,572,407	0.773989809	1,104,816.53	278,737.997	3,116,015.65	4,884.03995
24.7	47,315,877.4	27,916,305.5	0.65951352	1,107,076.44	282,423.226	3,176,384.46	4,858.76339
24.8	48,240,916.5	28,264,292.3	0.563832854	1,109,347.81	286,183.682	3,238,309.03	4,833.66601
24.9	49,186,740.8	28,616,419.9	0.485274026	1,111,630.69	290,021.315	3,301,849.66	4,808.74445
25	50,153,921.3	28,972,741.7	0.424702848	1,113,925.11	293,938.145	3,367,070.02	4,783.9953

Figure 65 Table in Insightmaker for outputs generated for Scenario 1.

Name	2024 (Input)	2050 (Output)	Unit
EV Vehicles	1978449	50153921	Units
Biofuel Vehicles	908100	28972747	Units
Hydrogen vehicles	1040	3367070	Units
Gasoline Vehicles	634000000	0	Units
Public Buses	84199	293938	Units
Bikes	811000	1113925	Units
Total GHG Emission	24982	4783	MTC02

Table 63 Summary of inputs and outputs in Scenario 1 [34].

Table 63 shows the summary of comparison of inputs taken for 2024 and the outputs generated by the simulation for 2050.

5.3 OUTPUT OF SCENARIO-2 (HYDROGEN VEHICLES HIGHEST BY 2050)

With almost 634 million units at time 0, gasoline vehicles rule the market. But their population collapses to almost zero over the 25-year simulation by the end of 2050. This rapid drop points to a clear shift away from conventional internal combustion engines, most likely resulting from changing consumer preference for greener alternatives, stricter policy against gasoline usage, and technical changes. Figure 66 depicts the time series graph of gasoline vehicles decrease over time.

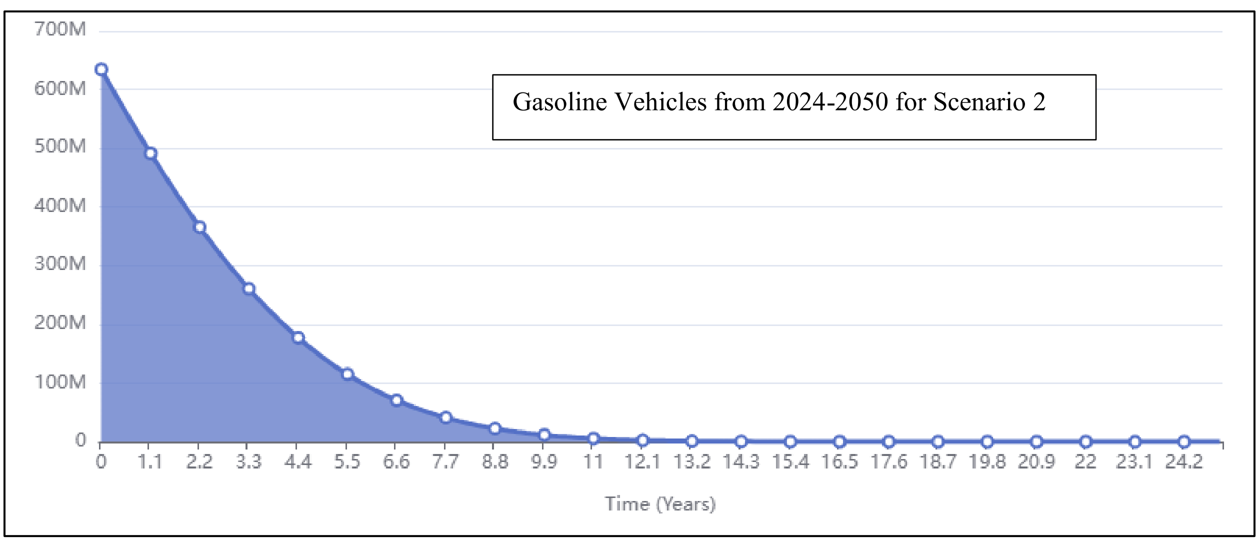

Figure 66 Time series graph showing the decrease in gasoline vehicles from 2024 to 2050 in Scenario 2.

Figure 67 shows comparison of EV, biofuel vehicles, hydrogen vehicles public buses and bikes. They are all a part of sustainable transportation system. From 1,000 units at time 0 to almost 74 million by time 25, hydrogen vehicles show the most exponential increase. Under favorable assumptions that is, declining production costs, better infrastructure, and strong government support this surge suggests that hydrogen can become a major actor in the future transportation scene, maybe surpassing other low-emission vehicles. EVs start at 1978449 units and grow to over 5832253 vehicles by time 25. While this represents a substantial increase, it remains modest compared to the initial dominance of gasoline vehicles. The upward trend indicates ongoing improvements in EV technology, cost reductions, and supportive policies. Starting at roughly 908100 units, biofuel cars grow to reach roughly 2558810 vehicles by the end of the simulation. Though this expansion is noteworthy, other developing technologies especially hydrogen outpace it. According to the trajectory, biofuels seem to take front stage as the main substitute for gasoline. Over the simulation period, bicycles range in count from 811000 to 5497933 units. According to the trend, active transportation like biking stays a crucial part of a diversified and sustainable transportation system. Public bus use increases from about 84199 to 1059204 units over 25 years. This growth reflects ongoing investments in transit infrastructure and policies encouraging public transportation for lowering emissions.

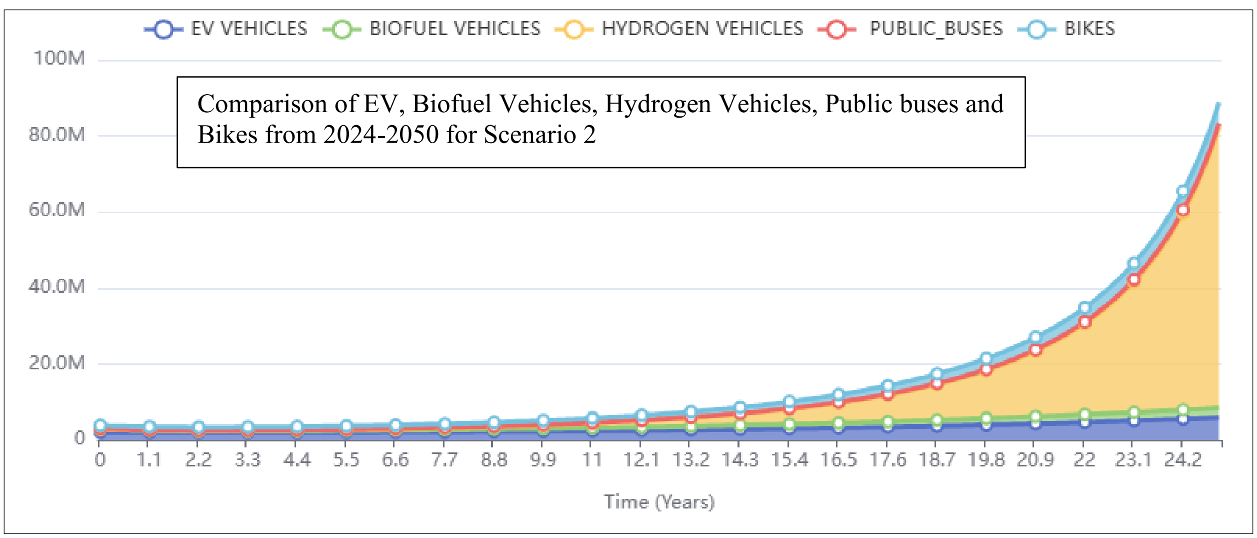

Figure 67 Time series graph showing the increase in alternative fuel vehicles and sustainable transportation options from 2024 to 2050 in Scenario 2.

From almost 24,982 units at time 0 to roughly 2,321 by time 25, greenhouse gas emissions fall dramatically. Along with the modest but significant increases in bike and public bus use, this decline corresponds with the sharp drop in gasoline vehicles and the concurrent rise in cleaner alternatives including EVs, hydrogen vehicles, and biofuels. The total change emphasizes the possibility for significant emissions reductions when several low-emission technologies and transportation choices become popular together. Figure 68 shows the greenhouse gas emissions for the next 25 years for scenario 2.

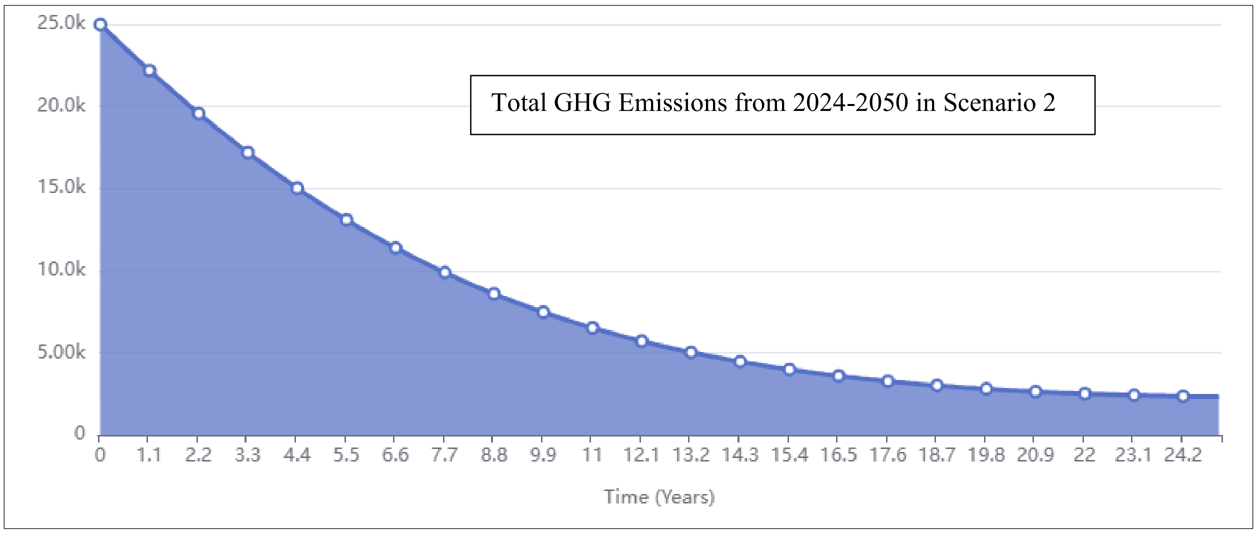

Figure 68 Time series graph showing the decrease in GHG Emissions from 2024 to 2050 in Scenario 2.

Figure 69 shows the tabular output in Insightmaker tool.

Time	EV VEHICLES	BIOFUEL VEHICL...	GASOLINE_VEHI...	HYDROGEN VEH...	BIKES	PUBLIC_BUSES	TOTAL GHG EMI...
23.4	5,136,835.23	2,273,986.23	5.40401354	38,122,137.9	4,452,835.22	712,055.144	2,388.62115
23.5	5,177,261.98	2,290,974.08	4.60730656	39,533,366.2	4,510,812.56	728,412.262	2,382.54919
23.6	5,218,077.31	2,308,067.38	3.92539286	41,017,181.1	4,569,685.89	745,314.74	2,376.72385
23.7	5,259,284.58	2,325,266.78	3.3422508	42,578,941.8	4,629,471.53	762,789.73	2,371.14391
23.8	5,300,887.22	2,342,572.9	2.84402194	44,224,554	4,690,186.2	780,866.384	2,365.80834
23.9	5,342,888.68	2,359,986.4	2.41873135	45,960,543.2	4,751,847.04	799,576.058	2,360.71634
24	5,385,292.45	2,377,507.92	2.05604311	47,794,140.2	4,814,471.63	818,952.536	2,355.8673
24.1	5,428,102.06	2,395,138.12	1.74704663	49,733,382.4	4,878,077.99	839,032.287	2,351.26087
24.2	5,471,321.07	2,412,877.66	1.48407092	51,787,232.7	4,942,684.62	859,854.76	2,346.89697
24.3	5,514,953.1	2,430,727.19	1.26052371	53,965,721.3	5,008,310.5	881,462.715	2,342.77578
24.4	5,559,001.79	2,448,687.39	1.07075407	56,280,115.1	5,074,975.09	903,902.605	2,338.89781
24.5	5,603,470.84	2,466,758.92	0.90993789	58,743,121.5	5,142,698.39	927,225.01	2,335.26392
24.6	5,648,363.97	2,484,942.47	0.773989809	61,369,135.1	5,211,500.92	951,485.148	2,331.87533
24.7	5,693,684.96	2,503,238.72	0.65951352	64,174,539.4	5,281,403.77	976,743.448	2,328.73369
24.8	5,739,437.62	2,521,648.34	0.563832854	67,178,077.6	5,352,428.58	1,003,066.24	2,325.84111
24.9	5,785,625.8	2,540,172.04	0.485274026	70,401,312.7	5,424,597.6	1,030,526.53	2,323.20021
25	5,832,253.42	2,558,810.51	0.424702848	73,869,204.5	5,497,933.71	1,059,204.96	2,320.81418

Figure 69 Table in Insightmaker for outputs generated for Scenario 2.

Name	2024 (Input)	2050 (Output)	Unit
EV Vehicles	1978449	5832253	Units
Biofuel Vehicles	908100	2558810	Units
Hydrogen vehicles	1040	73869204	Units
Gasoline Vehicles	634000000	0	Units
Public Buses	84199	1059204	Units
Bikes	811000	5497933	Units
Total GHG Emission	24982	2320	MTCO2

Table 64 Summary of inputs and outputs in Scenario 2 [34].

Table 64 shows the inputs taken for 2024 and the outputs generated by the model. It gives us a summary of the vehicles by the end of 2050.

5.4 LIMITATIONS

- The model relies on historical data and assumptions, which may not be able to accurately represent future technological developments, government initiatives, or market dynamics. Despite the fact that three scenarios were developed a baseline scenario, one with increasing adoption of electric vehicles and biofuel vehicles, and one where hydrogen vehicles and bicycles are prioritized, these scenarios are based on projected rates of adoption and infrastructure investments that may differ from reality.
- All the parameters considered in the model has been assumed to change linearly.
- The model also analyses data at a national level, which may not depict differences in regions within Canada in terms of infrastructures, population growth, and financial aspects.
- External influences or unforeseen circumstances such as recessions, pandemics, tariffs, or rapid policy changes that could severely affect the transportation sector are another weakness of the model. It is possible that the model does not properly represent these types of events that cause disruption.
- The outcomes of the simulation must be regarded with caution due to the existence of data restrictions and the difficulties associated with quantifying qualitative inputs such as the perception of customers, success of government initiatives, and infrastructure improvements.
- The model does not fully incorporate the specific transportation requirements, cultural implications, and social and economic differences in population.
- Practical implications could differ from scenario analysis.

5.5 DISCUSSION

In the discussion section of the thesis, the effects of the three scenarios in terms of the future greenhouse gas emissions profile of Canada are addressed. These scenarios include the baseline scenario, higher electric vehicles and biofuel vehicles, and increased hydrogen and bike usage. Influenced by historical data trends, the baseline scenario shows the transportation sector mostly dependent on gasoline vehicles, hence produces higher greenhouse gas (GHG) emissions. Though other alternative fuel-based vehicles that include electric vehicles (EVs), public buses, bikes, biofuel vehicles, and hydrogen vehicles also show increase in growth, their total integration into the current transportation system is still rather low. This result emphasizes the slow progress of current infrastructure and customer awareness when government support or technological changes are not implemented drastically.

Driven by EVs' increasing popularity and the viability of replacing gasoline with biofuels, Scenario 1 emphasises a move towards electric and biofuel vehicles. Rapid decarbonization policies show great promise as seen by the significant reduction in GHG emissions when gasoline vehicles almost totally disappear by 2050. Though at a slower rate than EVs and biofuels, bikes, public transportation, and hydrogen vehicles also see growing interest and acceptance. This situation underlines how much coordinated government policy measures, technological developments, and growing consumer awareness can change market dynamics.

Emphasizing hydrogen and bikes in scenario 2 increases the shift to zero-emission technologies faster. While the strong increase of bikes highlights the attractiveness of zero pollution, low-cost mobility, and health benefits, hydrogen vehicles fast growth supports fuel cell invention and infrastructure expansion. EV's, biofuel vehicles and public buses also saw a significant growth. Gasoline vehicles are again limited to almost zero. From personal mobility to public transportation, this scenario emphasizes the transforming power of methodically supporting several low-emission solutions. Sensitivity studies across several contexts show that adoption is driven mostly by cost considerations. The most important factors for EVs, biofuel, and hydrogen vehicles are their initial cost as well as their running fuel consumption. Regarding public buses and bikes, respectively, the cost of fare and bicycle rates show great influence for user acceptance and thus increasing the growth and demand. Though they are phased out in the later scenarios, gasoline vehicles remain extremely sensitive to vehicle cost and consumer awareness. These results show how strongly taxes, subsidies, general market incentives can affect consumer decisions. All together, the findings show that cost reductions, technological developments, and strong government policy interventions can greatly reduce GHG emissions and rebuild the transportation sector toward sustainable modes. The great cost sensitivity of all vehicle types emphasizes the need of financial levers as accelerators for vehicle adoption such as high taxes on gasoline-fueled cars and targeted subsidies and rebates for alternative fuel vehicles. In the end, these situations highlight the need of inclusive plans combining consumer involvement, government policy frameworks, and technological advancement to accelerate the change to low carbon transportation system.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 CONCLUSION

The findings of the system dynamic model play a huge role in shaping the transportation sector for the future. The results from the scenario analysis indicate that significantly increasing the customer perception, government initiatives and initiatives, enhancing and improving the infrastructure, reducing the cost to fuel the vehicles and also the cost to purchase alternative fuel-based vehicles can drive the growth of such vehicles. Due to their advantage of producing low greenhouse gas emissions, this in turn helps in reducing the greenhouse gas emissions. By following through historical trends and gasoline vehicles that have been benefitted from ease of availability of fuel, well developed infrastructure, abundant options for vehicles and they thrived in the market which eventually increased its adoption. This scenario depicted how the number of vehicles increased to almost 802 million by the end of 2050. This also had a negative consequence on the total green house gas emissions as it increased to 61,443 MTCO2. Therefore, two future scenarios were created with an intention to integrate alternative fuel-based vehicles into the current system, to completely make the gasoline cars extinct, increase awareness for using public transportation such as buses and adopt more biking that also helps in overall health. In a scenario with exponential growth of EV's and biofuel vehicles were created to analyse how various factors affect the growth of vehicles. Due to EV's increasing to more than 50 million by the end of 2050 and biofuel vehicles increased to almost 29 million, the total GHG of the system saw a significant decrease to 4783MTCO2. Other modes of transportation and alternative vehicles also saw a growth slow and a steady growth. Even ambitious scenario to reduce the GHG emissions further to was created. In this scenario hydrogen vehicles were shown to dominate the markets by 2050 exponentially to almost 74 million vehicles by the end of 2050. Despite the fact that every option has its own set of advantages, the analysis reveals that the overall effectiveness in lowering emissions will be dependent on a mix of technology developments, laws and government initiatives that are supportive of the effort, and significant investment in infrastructure. From sensitivity testing it was also found that, the most influential key driver among all the factors is cost of vehicles, cost of fuels, cost of a bike and cost of a fare for a public bus. Emphasizing these elements will enable Canada to quickly reach its net zero target and help accelerate the acceptance of new alternative fuel technologies.

6.2 FUTURE WORKS

- Future projects should prioritize the gathering of deeper, province-specific data like for Alberta which is dependent on fossil fuels to more accurately reflect the diversity of transportation requirements and behaviors throughout Canada. This involves improving the assumptions regarding urban and rural dynamics and incorporating specific economic and demographic shifts.
- Considering that the existing model is based on assumed qualitative evidence, the most important goal for future projects is to acquire empirical data via extensive surveys and targeted research. These surveys should seek to determine consumer views of electric vehicles, biofuel vehicles, and sustainable transportation alternatives, while also collecting insights on government initiatives and infrastructure development. This data will provide more precise modeling of the simulation and minimize uncertainty.
- It is essential to address the existing shortcomings in research involving Indigenous communities. Subsequent research needs to collaborate directly with indigenous communities to integrate traditional knowledge, cultural concerns, and particular mobility constraints. Such collaborations can facilitate the development of specific models that more accurately depict the transportation context and environmental requirements of these communities.
- Investigating upcoming technologies such as driverless vehicles, enhanced battery storage systems, and developments in smart grids to evaluate their possible effects.
- Integrating more sophisticated behavioral models and adaptive policy responses will enhance the simulation's forecasting precision. As technological developments occur and new policies are enacted, it is essential to revise the simulation settings. Future research should explore adaptive models capable of integrating real-time data and new patterns, thus enabling policymakers to dynamically modify strategy.

- Future work could apply Monte Carlo simulation to explore a wide range of input uncertainties for multiple scenarios. This would enable outcomes in a probabilistic way, offering more robust insights.
- Future research should focus on electricity availability for EVs in Canada and model scenarios for implementing clean energy to support sustainable grid growth.
- Future research could include more vital issues, like public health, economic cost-benefit assessments, and social equality, beyond greenhouse gas emissions. This comprehensive approach allows for more informed decision-making that matches with environmental sustainability and helping the community.

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