The Use of Microscopic Traffic Simulation Model for the Analysis of Vehicle Emission

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Abstract

Road transport is a significant contributor to greenhouse gas emissions and urban air pollution in New Zealand, particularly in the rapidly growing Bay of Plenty region. The high vehicle density during peak hours and the reliance on petrol and diesel fuels in most fleets contribute significantly to vehicle emissions, which contribute to climate change and air quality degradation. This research investigates the use of a microscopic traffic simulation model to analyse vehicle emissions in order to identify practical measures to reduce transport-related emissions. SUMO (Simulation of Urban Mobility), an open-source software was used to construct the road network, generate realistic vehicle demand, and execute the simulation, while the HBEFA (Handbook Emission Factors for Road Transport) emission model was used to estimate vehicle emissions. This simulation utilised vehicle count data provided by the Tauranga City Council, and MongoDB was employed as the main database to facilitate effective storage, retrieval, and real-time querying of the simulation output. Three targeted emission reduction scenarios were developed and tested based on the simulation results: increasing electric vehicle ownership by 20%, introducing trackless trams on high-demand routes, and encouraging carpooling to reduce single-occupancy vehicle usage. As a result of the simulation, each measure resulted in significant reductions in vehicle emissions, and the effectiveness of each scenario was examined and compared. The findings of this study provide practical, data-driven insights for local councils, transport planners, and policymakers in implementing effective strategies to reduce vehicle emissions and contribute to New Zealand's emission reduction targets.

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Acronyms

AADT Average Annual Daily Traffic

ACO Ant Colony Optimization

AI Artificial Intelligence

Aimsun Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks

CA Cellular Automation

CFMs car-following models

CO Carbon Monoxide

CO_2 Carbon Dioxide

COPERT COmputer Programme to calculate Emissions from Road Transport

E-BSS Electric Bike Sharing Systems

EV Electric Vehicle

FCD Floating Car Data

FDOT Florida Department of Transportation

GA Genetic Algorithm

GIS Geographic Information System

HBEFA Handbook Emission Factors for Road Transport

HC Hydrocarbons

IDM Intelligent Driver Mode

IoT Internet of Things

ISSRC International Sustainable System Research Center

ITLs Intelligent Traffic Lights

IVE Integrated Vehicle Emission

LNG Liquefied Natural Gas

MATES Multi-Agent based Traffic and Environment Simulator

Matsim Multi-Agent Transport Simulation

MOVES MOtor Vehicle Emission Simulator

N_2O Nitrous Oxide

NO_x Nitrogen Oxides

NZTA New Zealand Transport Agency

OD origin-destination

OIS Optical Information Systems

OSM Open Street Map

OSRM Open Source Routing Machine

PHEM Passenger car and Heavy-duty Emission Model

PM Particulate Matter

SCATS Sydney Coordinated Adaptive Traffic System

SUMO Simulation of Urban Mobility

TCP Transmission Control Protocol

TraaS TraCI as a Service

TraCI Traffic Control Interface

UCR University of California at Riverside

VANETs Vehicular Ad Hoc Networks

VEPM Vehicle Emission Prediction Model

VISSIM	Verkehr In Städten - SIMulationsmodell
VKT	Vehicle Kilometres Travelled
VOC	Volatile Organic Compounds
XML	Extensible Markup Language

Chapter 1

Introduction

In recent years, road transport has evolved into a major source of urban air pollution as well as a major contributor to greenhouse gas emissions. It is imperative to have a clear understanding of vehicle emission dynamics in order to develop sustainable urban transport solutions and emission reduction initiatives. With the advancement of traffic modelling, especially microscopic simulation, we are able to analyse traffic behaviour and its consequences on the environment at a highly detailed level. The purpose of this study is to explore the application of a microscopic simulation model to analyse transport-related emissions from light-duty vehicles. By integrating real-world data, microscopic modelling makes it possible to accurately estimate emission levels across different scenarios.

1.1 Motivation

Vehicle emissions have emerged as a significant environmental issue in New Zealand, especially since transportation constitutes one of the major sources of greenhouse gas emissions. According to the Ministry of Environment and Stats NZ Reports, road transport emissions constituted 37 percent of the total carbon dioxide emissions in 2021, with light-duty vehicles responsible for almost 64 percent of all transport-related carbon dioxide emissions [54]. These emissions contribute not only to climate change, but also to air quality degradation which directly impacts human health [54]. As the population and ownership of vehicles has increased, urban areas are experiencing significant traffic congestion and declining levels of air quality. Hence, in order to address the vehicle emission issue, a thorough examination of traffic patterns is necessary along with an estimate of emission levels. Furthermore, identifying effective interventions that could mitigate vehicle emission is also important.

SUMO, a microscopic traffic simulation tool, provides an opportunity to replicate real-world traffic patterns by simulating individual vehicle movements based on real-world traffic data in order to get accurate estimates of the pollution output. It is a low-cost method of investigating the impact of different interventions in a controlled environment. By using this simulation, it is able to identify which interventions deliver the biggest impact on emission reduction before they are implemented to the real-world. The motivation behind this study is to evaluate the environmental impact of traffic flow more accurately through the analysis of emissions and to explore the effectiveness of emission reduction strategies.

1.2 Research Objectives

The primary objective of this research is to analyse the vehicle emissions caused by light-duty vehicles through the use of microscopic traffic simulation. Furthermore, this study evaluates the effectiveness of several emission reduction strategies based on the analysis of each proposed method. The main objectives of this research can be summarised as follows.

1. Develop vehicle traffic simulation using a microscopic vehicle traffic simulation model to replicate the flow of traffic in selected congested areas based on the patterns of traffic that have been observed.

2. Calculate and analyse vehicle emissions caused by light duty vehicles with the use of vehicle traffic simulation.

3. Explore different interventions that could effectively mitigate vehicle emissions.

4. Give recommendations on how to reduce vehicle emissions resulting from light-duty vehicles during peak hours by taking into account the most effective measures that could be implemented, based on the analysis.

As a result, this study aims to address the following research questions.

1. How can microscopic traffic simulation be applied to council collected data to simulate real-world traffic scenarios?

2. How can we apply traffic interventions and analyse their effectiveness on emission reduction to enable data-driven decision making?

1.3 Thesis Structure

This thesis is organised into eight chapters. Chapter 1 presents an overview of this study, including its motivations, objectives, research questions, and the outline of the thesis structure. Chapter 2 is the background chapter which provides an overview of vehicle emissions, current levels of vehicle emission in New Zealand, and how they have increased over the past few years. Additionally, this chapter discusses data collection methods and the theory behind traffic simulation and emission modelling.

Chapter 3 presents a comprehensive literature review based on prior studies conducted by various researchers, organisations, etc., with respect to vehicle emissions. The traffic simulation and emission models used in the previous studies and the modern trends in emission reduction plans are also discussed in this chapter. Chapter 4 outlines the research methodology, including the data collection procedures, models, and software selected for the implementation and detailed process of the development plan.

Chapter 5 is the case study chapter which gives a detailed description of the study area of this research and the data that have been used in its execution. Chapter 6 presents the detailed implementation procedures undertaken in this research. Chapter 7 presents the results of the simulation and the vehicle emission estimates through visual representations to interpret vehicle patterns and emission outputs.

Chapter 8 is the discussion chapter which discusses how the findings of the study can be applied to the decision-making process, the recommendations, and the limitations of this study. This thesis concludes with Chapter 9, where we discuss future work and concluding remarks.

Chapter 2

Background

Human actions and natural phenomena influence the quality of the air we inhale. Almost all air pollution in New Zealand is generated locally, as it is a remote island that is far from sources of pollution in other countries [53]. In Aotearoa, the major sources of air pollution are home heating and transportation [53]. Agriculture, construction, and industry are some of the other human activities that contribute to air pollution [53]. The objective of this research is to analyse transport-related emissions that most significantly affect the environment, air quality, and human health. The investigation of vehicle emissions in the Bay of Plenty is intended to be conducted using a microscopic traffic simulation model as a case study.

The first section of this chapter provides an overview of vehicle emissions, emission components, and their effects. The current state of vehicle emissions in New Zealand is then discussed, along with government measures for emission reduction programmes aimed at achieving a low-emission transportation system. Next, it illustrates the key components that can be utilised in the process of simulating vehicle traffic, including traffic simulation models, data collection methods, and SUMO traffic simulation software. This chapter concludes with some information regarding the emission models and traffic simulators.

2.1 Vehicle Emission

There are two types of emissions, namely, greenhouse gas emissions and air pollutant emissions, both of which have an impact on the environment, air quality and human health. The main source of these emissions is vehicles, whose internal combustion engines release a variety of pollutants through their exhaust. The quantity of each pollutant discharged is contingent upon the engine technology and the fuel utilized [49]. Greenhouse gas emissions absorb solar heat in the earth's atmosphere, leading to climate change and the greenhouse effect. Carbon Dioxide (CO_2) is the main greenhouse gas produced by vehicles, however they also produce Nitrous Oxide (N_2O) and Methane (CH_4). Air pollutant emissions can contribute to smog and negatively impact human health. Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Particulate Matter (PM), and Volatile Organic Compounds (VOC) are among the air pollutants released by motor vehicle exhaust [3].

2.1.1 Emission Components and their Impact

Vehicle emissions comprise numerous hazardous substances that can adversely affect human health and the ecosystem. Carbon Dioxide (CO_2) is the main component derived from the complete combustion of fossil-fuelled engines that contributes to global warming through the greenhouse effect [7]. Carbon monoxide (CO) is a poisonous and odourless gas that results from the incomplete combustion of fossil fuels. This compound is harmful to human health because, once inhaled, it decreases the oxygen carrying capacity of blood cells and may result in death by asphyxiation. Cardiovascular and psychomotor disorders can be caused by high concentrations of this gas [7].

During combustion of fuel, nitrogen oxides (NO_2), including NO and NO_2, are generated at high pressures and temperatures. NO_x molecules have the ability to react with ammonia and humidity to produce nitric acid, which can cause severe respiratory damage when inhaled [7]. Furthermore, nitrogen oxides are the primary cause of photochemical smog, which occurs in cities during warm and sunny weather [46].

Hydrocarbons (HC) refer to the unburned or partially combusted fuel released by the engine, together with fuel vapour exhaled from other vehicle components or during refuelling. This substance causes carcinogenic effects and contributes to the formation of photochemical smog when it reacts in the atmosphere. HC is commonly treated as a volatile organic compound (VOC) due to its reactivity. Methene (CH_4) is also a potential cause of the greenhouse effect [7].

Particulate Matter (PM) is primarily the result from the incomplete combustion of diesel. $PM_{2.5}$ contains tiny particles that have the ability to enter the bloodstream and deeply penetrate the lungs, leading to major cardiovascular and respiratory problems. Long-term exposure to these contaminants can lead to chronic respiratory diseases such as asthma, cardiovascular diseases, and an increased risk of heart attacks and strokes. Furthermore, NO_x and PM_x can shorten life expectancy and impact a child's lung development [18].

2.1.2 Vehicle Emission in New Zealand

In New Zealand, one of the main causes of greenhouse gas emissions is transportation. It is responsible for approximately 17 percent of gross domestic emissions and 39 percent of total domestic CO_2 emissions [11]. As part of the government's efforts to reduce these transport emissions, three areas have been targeted [11]:

1. Reduce reliance on cars and support people to walk, cycle and use public transport.
2. Rapidly adopt low-emission vehicles.
3. Begin work now to decarbonise heavy transport and freight.

To support these focus areas, the government has set four transportation targets that will align with those of the sector sub-targets for transportation. The reduction in transport emissions by 2035 is approximately equivalent to a 41 percent reduction compared to 2019 [11].

1. Target 1 – Reduce the total kilometres travelled by the light fleet by 20 percent by 2035 through improved urban form and providing better travel options, particularly in our largest cities [11].
2. Target 2 – Increase zero-emissions vehicles to 30 percent of the light fleet by 2035 [11].
3. Target 3 – Reduce emissions from freight transport by 35 percent by 2035 [11].
4. Target 4 – Reduce the emissions intensity of transport fuel by 10 percent by 2035 [11].

Several key actions are being taken to reduce the reliance on cars and encourage people to walk, cycle, and use public transportation, including improving the accessibility, frequency, and quality of public transportation and making it more affordable for low-income New Zealanders, promoting walking and cycling, increasing the use of electric bikes, and ensuring safe streets and well-planned urban areas [11].

The second focus area is the rapid adoption of low-emission vehicles. Some of the good initiatives in this area include encouraging the adoption of low- and zero-emission vehicles through the Clean Vehicle Discount programme, expanding access to low- and zero-emission vehicles for low-income households by supporting social leasing programmes, and trialling an equity-orientated vehicle scrap-and-replace programme. Additionally, it is extremely important to improve the Electric Vehicle (EV) charging infrastructure throughout Aotearoa [11].

Among the steps involved in decarbonising heavy transport and freight are the provision of funding to the freight industry to purchase zero or low-emission trucks, the purchase of zero-emission public transportation buses, and the implementation of a sustainable aviation fuel mandate and a sustainable biofuels obligation to encourage the use of low-carbon liquid fuels [11].

Compared to other countries, air quality in Aotearoa, New Zealand, is generally good. In the IQAir World Air Quality report 2024, New Zealand was among the top ten countries with the cleanest air quality [76]. However, there are some places and times where there is poor air quality, which has negative health consequences for residents. According to New Zealand's Environmental Reporting Series, air pollution was responsible for 13237 hospitalisations and 3239 premature deaths in 2019 [53]. This accounted for nearly 10% of the total deaths in New Zealand [53]. Air pollution from motor vehicles alone was responsible for 71 percent of the estimated total hospitalizations (almost 9,400 cases) and 68 percent of total premature deaths (nearly 2,247 cases) in 2019 [53]. Additionally, it was estimated that the annual social cost of air pollution in 2019 was $15.3 billion, with motor vehicle emissions responsible for 69% of those expenses [53]. The impacts of motor vehicle air pollution are significant, causing serious health problems for thousands of people each year along with a significant social cost [53]. Hence, immediate action needs to be taken to mitigate these motor vehicle emissions. Furthermore, the effects of vehicle emissions are not limited to New Zealand; they also affect nations worldwide. Therefore, finding and implementing globally applicable, efficient methods to reduce vehicle emissions is essential.

2.1.3 Alternative Modes of Transport

Reducing private vehicle dependence is essential to mitigate vehicle emissions and improve air quality. In order to achieve this, alternative transport modes should be taken into account. Public transport options are one of the main transport methods that can carry more passengers with fewer emissions. These options include electric buses and advanced solutions, such as trackless trams, cable cars, and ferries, which are supported by sustainable infrastructure.

It is able to significantly reduce emissions by replacing diesel buses with electric buses that do not emit pollutants. Advantages of this method include zero emission, reduction in environmental noise and low traffic due to reduction of private vehicles [69]. The main disadvantage of this method is the initial high cost of electric buses and charging infrastructure [69].

The trackless tram is a new approach to urban transit that combines the efficiency of the light rail transit system with the price of buses [51]. They operate on rubber wheels guided by sensors and optical systems. The trackless tram can travel at 70km/h through the streets and is capable of carrying between 300 and 500 passengers with the use of 3 or 5 carriages. Compared to other transport modes, it has higher passenger volumes and significantly reduced emissions as it is powered by electricity [16].

Cable cars or gondolas are increasingly being adopted as sustainable public transportation solutions in heavily congested cities. Electricity is used to power them and they emit no carbon dioxide if renewable energy is used in the generation of electricity. It can provide additional transport dimensions to avoid traffic as it is capable of transporting passengers above the ground using aerial cables. Cable cars have capacities up to 2000 persons/h for aerial tramways and up to 4000 persons/h for gondolas. Despite these benefits, cable cars have some limitations such as low speed, limited capacity, only suitable for short distances and expensive infrastructure cost [67].

Ferries are a sustainable transport option, used in coastal cities and regions that are open to waterways. It is an effective instrument in mitigating road congestion in urban areas, as they use waterways to commute. Electric ferries have significantly reduced emissions nowadays compared with the traditional diesel-powered ferries [58]. Electric vehicles are the main alternative to conventional combustion engine vehicles which are capable of reducing vehicle emissions. Compared to petrol and diesel vehicles, they may significantly reduce greenhouse gas emissions when driven by renewable energy sources [56].

Walking and bicycling are two active transportation modes which can lower emissions associated with transportation while also improving public health by encouraging more physical activity. These methods are effective for short distance trips to avoid road congestion and vehicle emission. Cycle lanes, pedestrian pathways and safe road crossings encourage the walkability and cyclability, and this can be integrated with the public transport systems to facilitate better transportation [34][42]. Electric scooters are another alternative transport option to cover short urban trips with low emission. They are powered by rechargeable batteries and they provide great flexibility to the people while reducing the reliance on private cars [27].

Carpooling is an alternative mode of transport in which two or more people share the same vehicle for their commute. It helps to reduce the number of single occupancy vehicles on the road which leads to low traffic congestion and low vehicle emissions [33].

2.2 Traffic Simulation Models

Traffic simulation is a commonly used technique in the study of modelling, planning, and development of traffic networks and systems. The goal of traffic modelling is to use mathematical models to precisely recreate traffic as observed and measured on the road. Traffic simulation models can be classified mainly into three categories, namely microscopic, macroscopic, and mesoscopic modelling [6]. Next, we describe each of these definitions.

2.2.1 Modelling Definitions

In a microscopic model, all vehicles are considered individually and fundamentally, and the interactions among them are mathematically modelled. We aim to collect data parameters such as flow, density, speed, travel and delay time, pollution, and fuel consumption. The characteristics of microscopic modelling techniques are based on car-following models, lane-changing models, and gaps of individual drivers [30][6]. In macroscopic models, the traffic stream is represented as an aggregate that is measured in terms of properties like speed, flow and density. The speed-flow-density correlations have been examined by researchers and developed mathematical models, such as the Greenshield's and Greenberg models, to depict these curves [6]. Microscopic and macroscopic modelling are combined to create mesoscopic models. Mesoscopic models outline the analysed transportation elements in small groups [6].

Car-following algorithms introduced the concept of a driver recognising and following a leading vehicle at a reduced speed. In the event that the main vehicle was driven at a lower speed, the subsequent vehicles will also reduce their speed. This led to the occurrence of car platoon and traffic congestion [6]. A lane-changing model is a decision-making procedure that estimates the behaviour of the driver in making a lane change within a specific period of time. There are two forms of lane changing: Mandatory lane change and Discretionary lane change. During a mandatory lane change, it is required to move into the right lane when the driver wants to make a right turn at the next intersection. A discretionary lane change occurs when the driver switches to the next lane in order to avoid following trucks and increase speed [6]. The Gap acceptance model determines the size of gap that will be accepted or rejected by a driver who is seeking to merge or cross an intersection. The critical gap can be defined as the number of accepted gaps shorter than its equal to the number of rejected gaps. Acceleration rate, intended speed, and speed acceptance are the parameters of the gap acceptance model. Most important among them are the acceleration rate, the maximum give-way time, and the visibility distance at the intersection [6].

2.2.2 Modelling and Simulation Software

There are several tools that can be used to simulate microscopic structures, namely Vissim, AIMSUN, SUMO, FRESIM, CORSIM, and Paramics. Visum is a macroscopic simulation software [6]. PTV Vissim is a commercial software programme that offers 3D visualisation and an easy-to-use interface [44]. MATSim is an activity-based traffic simulation that is open source and freely accessible online [44]. Lastly, SUMO is also an open-source programme, published under Eclipse Public Licence V2 [44].

According to Diallo et al. [17], modern traffic simulation tools are based on a variety of principles and have emerged from two main sources: industrial and academic. Industrial simulators such as Vissim and Aimsun are developed for commercial purposes and they are easy to use. Academic simulators are created as part of research projects and originate from research laboratories [17].

Krajzewicz et al. [35] describes the implementation of a second generation of pollutant emission models. This study distinguishes between two classes of emission models: inventory emission models and instantaneous (or modal) emission models. The inventory emission model includes data for a majority of the vehicle emission classes. To simulate the emissions of a single vehicle, instantaneous emission models are employed. Initially, HBEFA version 2.1 was implemented by extracting data from HBEFA and fitting it to a continuous function derived by simplifying the function of the power the vehicle engine must produce to overcome the driving resistance force. The PHEMight is a simplified version of the PHEM (Passenger and Heavy Vehicle Emission Model), which is available as an add-on for commercial use. It has been designed and implemented by the Technical University of Graz as part of the COLOMBO project. PHEMight uses characteristic emission curves which establish the emission amount [g/h] in relation to the actual engine power of the vehicle. SUMO's open-source release only includes two emission classes: a gasoline-powered Euro-4 passenger car and a diesel-powered passenger car with the same emission class. The new HBEFA version 3.1 was released with the new measures for contemporary Euro-Norm-6 vehicles in light of the lessons learnt during the implementation and use of the original HBEFA v2.1-based emission model. All emission classes included in HBEFA version 3.1 could have their emission curves fitted in this model, yielding coefficients for about a hundred distinct emission classes in SUMO [35].

According to Borge et al. [9], three different driving patterns: rural, urban, and motorway, are taken into account by the COPERT IV model, which is currently integrated into the EMEP/EEA technique for emission computation. The alternative calculation approach was HBEFA 3.1, and the novel feature of this model is the definition of 256 distinct traffic scenarios, represented by four main parameters: area (rural, urban), road type, road speed limit, and service level (free flow, heavy, saturated and stop & go) [9].

2.3 Data Collection Methods

Data collection for traffic simulations is crucial, as the outcomes of the simulation rely entirely on the input data provided. Leduc et al. [40] presented the traditional and emerging road traffic data collection methods along with their advantages and disadvantages. According to the study, there are two types of traffic count technologies: intrusive and non-intrusive. Intrusive methods consist of a data recorder and a sensor placed on or in the road such as pneumatic road tubes, piezoelectric sensors, and magnetic loops, while non-intrusive methods are based on remote observations. Some of the non-intrusive methods include manual counts, passive and active infrared, passive magnetic, microwave radar, ultrasonic and passive acoustic, and video image detection.

Floating Car Data (FCD) is another real-time data collection technique, which locates the vehicle via mobile phones or GPS over the entire road network. In this approach, every vehicle is equipped with a mobile phone or GPS, serving as a road network sensor. Various data such as location of the car, speed, and direction of travel are transmitted anonymously to a central processing centre. Useful data, such as traffic conditions and alternate routes, can be redistributed to drivers once it has been collected and extracted. There are two main types of FCD, namely GPS and cellular-based systems. Although many service providers currently use GPS-based systems extensively as a source of real-time information, the number of vehicles equipped with these systems is limited and equipment costs are higher than those of floating cellular data. Since the majority of the vehicles are equipped with one or more cell phones, cellular-based systems are less costly, easier to install, quicker to set up, and require less maintenance [40].

Average Annual Daily Traffic (AADT) and Vehicle Kilometres Travelled (VKT) are two significant categories of traffic data that are provided by transport centres worldwide. The average number of vehicles passing a point in a specific counting section each day over a year is known as the AADT. The method of calculating AADT typically rely on data from two kinds of counts: permanent automatic traffic counts and short-period traffic counts. VKT is the distance travelled by vehicles on the roads. There are four methods to calculate vehicle- kilometres namely, odometer readings, traffic counts, driver survey, and fuel consumption. Additionally, this study outlined the on-line data sources that provide real-time traffic data in Europe and the United States. According to this study, high-quality real-time traffic data can be obtained by combining traditional on-road sensors with floating car data techniques [40].

2.4 Traffic Simulation using SUMO

SUMO stands for "Simulation of Urban MObility" and is a microscopic, multi-modal traffic simulation software developed since 2000 by the Institute of Transportation Research at the German Aerospace Centre. SUMO is very fast, capable of simulating around 100,000 to 200,000 vehicles in real time on a desktop computer, encompassing the simulation of traffic signals, right-of-way regulations, and lane changes. It was developed using a C++ programming language, which makes it portable with a variety of operating systems, including MS Windows, Linux, and MacOS. In this package, two simulation programmes are included, one for running at the command line in order to perform faster simulations and one for visualising the simulation using the OpenGL-API [36].

According to Lopez et al. [44], the primary components required for the simulation are the network data (e.g., roads and footpaths), additional traffic infrastructure (e.g., traffic lights), and traffic demand. The SUMO GUI application enables viewing the simulation at various speeds and with a range of colour options to emphasise different elements such as speeds, traffic densities, road elevation or right-of-way rules. Furthermore, SUMO simulation generates a variety of output files that include vehicle trajectories, emissions, and energy consumption that can be visualised using SUMO tools or imported into other applications. It provides many tools that are capable of converting output files into other formats or importing them with Python or Matlab [44].

Santana et al. [60] provided a brief overview of how to setup and utilise SUMO to create a basic simulation. There are two XML files in the SUMO configuration file. The first one is the street map where the simulation will take place, and it can be obtained from a variety of sources, including Google, OpenStreetMap, Mapbox or even a customised map. JOSM (Java Open-

StreetMap Editor) is another tool for creating or retrieving a real map from a specific location. This map will be saved as an osm file, which can be converted to an XML file using the SUMO NetConvert tool. The second XML file specifies the type of vehicle that should be included in the simulation, along with the route taken by each vehicle class. There are two options to introduce vehicles for simulating traffic jams. The first method involves declaring each vehicle individually in the file with its routes is inefficient because it requires copying a declaration for each vehicle that needs to be simulated in the traffic jam. The second method is to create an automatic file that automatically declares a group of vehicles and their routes. The final route file can be created using the tool Duarouter by combining the net file (map) and the flow file (vehicle and route). TraCI (Traffic Control Interface) enables SUMO to be connected to a script, preferably written in Python, via the port and perform necessary actions within the simulation in real time [60].

Monga & Mehta [50] compares and analyses several VANET simulation software and differentiates between their GUIs, repute, simplicity of use, input needs, output visualisation capabilities, and model accuracy. Two different direction conventions were used in this study to conduct recreation and correlation, namely Adhoc on Request Distance Vector Routing (AODV) and Adhoc at Requests Spread Spectrum Seperation Vector Steering (AMODV). This study was carried out using SUMO with its collection of software tools. The "od2trips" feature in SUMO can be used to transform the O/D (Origin-Destination) matrix to single trips, and the routes are decided by allocating traffic and employing a routing technique that includes shortest-path computations under different cost factors. It is also possible to calculate routes over a network using the "jtrrouter" programme, and to calculate routes with loop detector data using the "df router" programme. "NetGenerate" or "NetConvert" are frequently used to generate SUMO road networks using digital road maps. In this study, C++ was used to construct urban mobility simulations, and finally the latest releases of the SUMO package for the Microsoft Windows and Linux environment were outlined [50].

Clemente [14] described the process of creating a comprehensive scenario with SUMO and conducting simulations, beginning with the preparation of the network using Open Street Map. It involves preparing the transportation network, traffic definition, setting a routing algorithm, and executing the simulation. The route-choice method, routing-algorithm, and car-following-model are few numerous configurations available for SUMO simulation. As the first step of the simulation, it is required to select a suitable area and download it from Open Street Map. Subsequently, this study presents a few tools and commands, including Osmosis, Netconvert, Polyconvert, Sumopy, Netedit, OD matrices, and Duarouter. This study also outlined the XML output files that can be obtained as the output of the simulation. These include fcd-output, which contains floating car data, tripinfo-output, which contains detailed information about the trips, vehroute-output, which contains detailed information for each vehicle, and summary output, which provides some general information for every stage of the simulation. Furthermore, this study explained how to save the relevant data in the MongoDB Atlas cloud database using the SUMO output files and their parsing through a custom Python code [14].

Lopez et al. [44] explains the “Real World Bologna” scenario, which is based on a part of inner-city Bologna, Italy, to describe the concepts and workflow of SUMO. First, the scenario was simulated using SUMO, and then the exhaust emission was calculated using the database HBEFA (Handbook Emission Factors for Road Transport). SUMO networks are created using the NETCONVERT and NETEDIT applications. NETCONVERT is a command line tool that can be used to import road networks from various data sources, including OpenStreetMap (OSM), OpenDRIVE, Shapefile, and other simulators such as MATSim and Vissim. Network files can be created, analysed, and edited using NETEDIT, a graphical network editor. TraCI enables the coupling and evaluation of simulation results from different simulators, and in order to validate the data, a calibration process should be carried out [44].

2.5 Summary

This chapter outlined the context of vehicle emissions and their impact on the environment as well as human health. The primary component of emissions is CO_2, and the effects of each type of emission were explained. Furthermore, New Zealand’s current vehicle emission status and the government initiatives regarding vehicle emissions were described in detail. This chapter has also described a range of alternative transport modes that could encourage to reduce the transport realated emissions. It included the public transportation systems such as electric buses, trackless trams, cable cars and ferries. The active travel options such as walking and cycling, shared mobility solutions such as carpooling also outlined in this chapter.

The chapter also introduced analytical tools and traffic simulation models, which are commonly used to implement traffic simulation and emission calculation. Building upon this background, the following chapter examines a collection of prior studies on vehicle emissions and sustainable transportation methods which is capable of mitigating vehicle emissions.

Chapter 3

Literature Review

Vehicle emissions constitute a major environmental issue that contributes to air pollution, climate change, and health complications. Consequently, the examination of vehicle emissions is crucial for mitigating greenhouse gas emissions and fostering sustainable urban transportation systems. Over the years, numerous studies have been conducted to analyse vehicle emissions, their effects on the environment and human health, and strategies to minimize them.

This review of the literature will explore prior studies that employ diverse approaches to analyse vehicle emissions through traffic simulation models and the impact of various factors on these emissions. In addition, the traffic simulation software and vehicle emission models that have been used in various studies over the past few decades will be outlined in this review. This chapter also delineates the studies conducted to introduce new technology and alternatives aimed at reducing vehicle emissions.

3.1 Traffic Simulation

Traffic simulation is a prevalent technique employed in the study of modelling, planning, and the development of traffic networks and systems. The purpose of traffic simulation is to accurately reproduce the real-life phenomenon of traffic flow as observed and measured on the street [6]. According to Haddouch et al. [30], road traffic refers to the movement of motor vehicles on roadways, whereas traffic can be defined as the flow of vehicles quantified over a specific time interval. For a realistic simulation of vehicle traffic, two essential components are necessary, namely flow and assignment. Flow is the progression of vehicles on the tracks and assignment is the distribution of vehicles on the network.

3.1.1 Traffic Models

According to Azlan & Rohani [6] and Haddouch et al. [30] traffic simulation models can be classified into three categories, namely microscopic, macroscopic, and mesoscopic modelling. Additionally, Lopez et al. [44] proposed a fourth category referred to as submicroscopic which allows the explicit simulation of every vehicle and its internal functions.

In microscopic modelling, each vehicle is modelled individually according to their characteristics while it is moving through a traffic flow. The interactions between vehicles are usually modelled mathematically. The characteristics of this modelling method are based on the car-following model, the lane-changing model, and the gaps of the individual drivers. The Car Following model utilizes the concept that a driver recognizes and follows a leading vehicle at reduced speed. When the main vehicle is driven at a lower speed, the following vehicles are also forced to slow down, resulting in the formation of car platoons and congested traffic flow.

The Lane Changing model is a decision process used to estimate the driver's behaviour when changing lanes within a specified time frame. Lane changing can be categorized into two types, namely Mandatory Lane change and Discretionary Lane change. Mandatory lane change occurs when a driver wants to make a turn at the next intersection, then it is necessary to change the lane to the right or left according to the turning direction. In discretionary lane changes, the driver changes lanes in order to avoid following trucks and to increase speed. The gap acceptance model determines the size of the gap that will be accepted or rejected by a driver who intends to merge or cross the intersection.

In macroscopic models, the traffic stream is depicted as an aggregate measured in terms of characteristics like speed, flow, and density. Researchers have examined the speed-flow-density relationships and developed mathematical models to represent these curves, such as the Greenshield's model and the Greenberg model. Greenshield's model is used to model uninterrupted traffic flow and is a fairly accurate and simple model. According to this model, speed and density are linearly related, whereas flow and density are parabolic.

Mesoscopic modelling which is a combination of microscopic modelling and macroscopic modelling examines the analysed transportation elements in small groups. Furthermore, this model is regarded as the next generation tools for traffic modelling and simulation. There are two methods of mesoscopic modelling which are platoon dispersion and vehicle platoon behaviour. In platoon dispersion, as a platoon moves downstream from an upstream intersection, there may be a distance between vehicles due to the different speeds of the vehicles or vehicle interactions. A group of vehicles travelling at the same speed and with a short headway is known as vehicle platoon behaviour.

In simulating vehicle traffic scenarios, each model has its own capabilities and limitations. According to Lopez et al. [44], macroscopic models have a fast execution speed, while microscopic and submicroscopic models provide greater precision especially when it comes to simulating emission or individual routes. In order to propose a specific model for the implementation of vehicle traffic simulation, a thorough assessment of the study is needed and performance capabilities of the existing models is required.

3.1.2 Traffic Simulation Scenarios

Krajzewicz et al. [36] illustrates the application of SUMO in simulating the city of Magdeburg and the highway ring encircling Munich, alongside the development and testing of contemporary traffic management scenarios. Another project implemented in SUMO was the simulation of the city of Cologne in Germany during the World Youth Day ceremony, which had over 1,000,000 participants [36]. Furthermore, this study outlines concepts for utilizing SUMO within the RoboCup community to mimic the rescue of individuals and the reachability of places for rescue teams [36]. This study proved that SUMO is an interesting tool for modelling large traffic scenarios and can be easily customized to meet specific needs.

Another study outlined a simulation framework to generate a variety of pedestrian demands to simulate vehicle-pedestrian interaction [4]. Open Street Map (OSM) was used to import a network for simulation in the 2D scenario. The network was edited using netedit because the conversion process had some imperfections that caused the simulation to deviate from reality. Following the creation of the 2D scenario, SUMO was linked to Unity 3D through the use of the Traffic Control Interface (TraCI) protocol and the TraCI as a Service (TraaS) library. The Transmission Control Protocol (TCP) integrates the Unity 3D game engine with the SUMO open source traffic simulator, and the motion in Unity occurs subsequent to the instantiation of pedestrians sourced from SUMO. The framework was evaluated by implementing a bidirectional communication system between pedestrians and vehicles, which detected whether pedestrians were within a 40-meter range. Pedestrians were colour-coded to visualise that V2P communication had been achieved in the simulated 3D environment. If the distance increases to more than 40m, the pedestrian object is reversed to white which was previously red coloured when the distance is less than 40m [4]. This study demonstrated SUMO's capability of simulating pedestrian demand as well as visualising it in a 3D environment using a Unity 3D game engine.

Haddouch et al. [30] simulated the traffic in the city of Kenitra using the SUMO simulator. Through the use of OpenStreetMap, the road network was created and the vehicle demand was simulated. The simulation was used to identify the variation of the peak hours, and the results of the traffic data were presented. This study mentioned that future research should compare the simulation data with the real data gathered during the experiment to verify the validity of the traffic. The researchers intend to create a model that utilises real traffic flow data to enable simulations and link their tool to a computerised GIS information analysis environment in order to take advantage of a real graphic representation of the road network. Additionally, future studies will concentrate on the integration of optimisation algorithms and route planning, which decreases the time required for a given trajectory. In addition, SUMO is an intriguing road traffic simulation tool that has the potential to incorporate new features in the future.

Luxen & Vetter [45] demonstrated both a server and hand-held device-based implementation working with OpenStreetMap data. Both applications offer a real-time and exact shortest-path computation on continental-sized networks with millions of street segments. Server-based web services and hand-held-based navigation are the most important applications for fast routing. While the Open Source Routing Machine (OSRM) project is a server-based implementation, MoNav is implemented for hand-held devices such as tablet computers or smartphones. MoNav can be defined as a Desktop or Mobile application that offers state-of-the-art fast and exact routing with OpenStreetMap Data. Both implementations were written in C++ and their performance was evaluated using a number of OpenStreetMap extracts. The study demonstrated the real-time capabilities of both routing engines with special emphasis on executing shortest-path queries, draggable routes, and computation of roundtrips on OSRM. Future work should improve the server by adding metrics for at least bicycle and pedestrian routing. Further algorithms should be developed to handle semi-time dependencies, such as ferries or roads that are only accessible during specific hours of the day. This research is highly beneficial for identifying the technical challenges and performance issues associated with the server and hand-held device-based implementation methods when working with OpenStreetMap data.

Singh et al. [62] described the development of the traffic simulation for the Madhubani city with the integration of SUMO. SUMO version 0.22.0 was used to run the simulation, and traffic flow data were collected by observation of the study location by traffic survey during peak traffic hours from 9:00 AM to 11:00 AM and 04:00 PM to 06:00 PM. Additionally, the route data, which includes the basic properties of the vehicles such as length, acceleration, deceleration, and maximum speed, is necessary for the SUMO simulation. In the first step of the simulation, OpenStreetMap was used for the map creation of the city road network and it was necessary to be in the XML format. The second step involved establishing a demand file and providing vehicle characteristics. The next step was to develop a configuration file that contained both the network file and the demand file. The last step was to run the simulation. The NETCONVERT tool was used to convert OSM files into road network structure file format, and Google Maps was used to verify and properly name the street. In addition, the calibration process was conducted in order to identify possible parameters that could be improved. According to the findings of the simulation, traffic congestion can be reduced by rerouting some traffic onto other routes and designing traffic signals specifically for Ganga Sagar Road. To reduce traffic congestion, personal four-wheeler vehicle entry should be restricted, and integration of this road network with public transport is necessary. Stadium Road will be used to integrate the road network for airport connectivity, which will not interfere with city traffic. This study also proved that SUMO is one of the most effective simulation tools for predicting vehicle traffic during road planning and traffic management.

3.1.3 Traffic Congestion

The problem of traffic congestion is one of the most pressing issues in the modern world, particularly in urban areas, and continues to worsen with the rapid growth of urbanisation, population and the increase in the use of private vehicles. Traffic congestion affects both individuals and society in a variety of ways, including air pollution, time waste, economic costs, and health issues. There are numerous innovative solutions being explored by researchers around the world in order to reduce traffic congestion.

Krajzewicz et al. [37] presents the testing of traffic lights with Optical Information Systems (OIS) using the open source traffic simulation SUMO. This project was developed using the agent-based traffic light control algorithm. This algorithm measures the jam length on the incoming lanes by investigating the incoming lanes. In one of these lanes, if the jam exceeds the threshold, that lane remains green for a longer period of time. For this project, they used a database that contained the Berlin road network derived from a digital map provided by NavTech. Two scenarios were used in this study: one used OIS-detectors, and the other scenario operating with normal traffic lights as they are implemented in real life. Aerial detectors were used to simulate OIS sensors, and SUMO's representation of typical light logics was expanded to implement traffic light control. This traffic control mechanism was ideal for intersections where the flow changes significantly from time to time. Moreover, they have investigated the interrelationship between consecutive traffic lights in order to avoid long delays at the succeeding intersections. Unless such mechanisms are present, agent-based traffic lights are most effective when used alone, at a greater distance from other traffic lights.

Kustija et al. [39] presents the implementation of the Sydney Coordinated Adaptive Traffic System (SCATS) as a solution to overcome traffic congestion in DKI Jakarta. The study was conducted at two locations with intersections using quantitative research methods based on the Indonesian Road Capacity Manual (MKJI) 1997 approach. A CCTV monitor was used for data collection and the researcher used a hand counter application on the phone to record each vehicle based on its type that crossed the specified limit. Data on the number of vehicles in interchange traffic were collected once every 15 minutes for five days during peak hours when people were on their way to work (07:00 to 09:00) and returning home from work (16:00 to 18:00). There are two types of data that were gathered: primary and secondary data. Primary data in the form of vehicle units per hour were taken straight from the survey data at the observation site. Secondary data were acquired through literature reviews carried out by researchers from a variety of sources, including affiliated agencies. The SCATS application can dynamically adjust the cycle time of sensor-based traffic lights according to the results. Through the use of an Internet communication network, the operator can remotely control traffic settings and condition them for emergencies or special cases. Moreover, researchers have concluded that this application can be implemented in all major cities in Indonesia to reduce traffic congestion.

Wei et al. [74] offers a public transportation network optimization technique for the city of Zhengzhou, China based on the Ant Colony Optimization (ACO) algorithm, in conjunction with existing bus routes. A Geographic Information System was used to abstract road networks and existing bus routes as line-structured data, which was then integrated with origin-destination (OD) passenger flow data. New bus-line planning was then achieved by combining the ACO algorithm with current line structure constraints and ant transfer rules at neighbouring nodes. Ultimately, the best bus-line network optimization plan was identified based on the shift in direct passenger flow throughout the network. The algorithm uses the Softmax technique to achieve path diversity and expand the path search range during the node transfer computation process, all the while preventing premature convergence and local optimization. The results of the analysis demonstrate that the algorithm can produce more affordable bus lines without altering the current line network's structure.

According to Palša et al. [55], the smart city can be defined as a city that utilizes information and communication technology which is linked to devices that are connected to the Internet or the Internet of Things (IoT). At the beginning of the traffic lights, there were only red and green lights which were not automatic, and they were operated by a police officer in a booth. Nowadays, there are automated traffic lights that change their lights at predetermined times. This caused unnecessary waiting because the light would be red even when there were no vehicles on the opposite side. Several wireless technology systems, such as Vehicular Ad Hoc Networks (VANETs), have emerged as reliable networks that vehicles use to communicate while driving on highways or in urban areas. The benefit of smart traffic lights is that they can be used in conjunction with sensors, GPS, and laser radars to either improve pedestrian safety or alert drivers to possible vehicle traffic hazards, such as erratic traffic patterns. Tesla automobiles already make use of this technology.

A smart traffic light can gather more information by monitoring traffic flow and, by utilizing Artificial Intelligence (AI), it will be able to share information across the city and determine the most effective traffic management option. The issue with this smart traffic light system is that it will function optimally if the cars are also utilizing smart technology, such as GPS. Given the environmental impact of automobiles, smart traffic lights will be a higher priority because they not only lower CO_2 emissions, but also have the potential to encourage people to take buses by giving them priority, which will lower the number of vehicles on the road [55].

Intelligent Traffic Lights (ITLs) can be configured using Multi-Interface Mobile nodes. There are two nodes, one which communicates with the field vehicles it covers and one which communicates with other smart traffic light systems or the city control network. One advantage of these ITLs is their ability to gather thousands of data points and instantly share them with other ITLs, the city emergency services or smart vehicles. However, SCATS is the most widely used intelligent traffic system in the world [55].

3.2 Vehicle Emission

According to the U.S. Environmental Protection Agency [5], vehicle emissions are pollutants discharged into the atmosphere from the exhaust of cars, predominantly those utilising internal combustion engines and the evaporation of the fuel itself. These pollutants exacerbate air pollution and can adversely affect human health, the environment, and the climate.

3.2.1 Emission Modelling

Lopez et al. [44] explains the "Real World Bologna" scenario, which is based on a part of inner-city Bologna, Italy, to demonstrate the concepts and workflow of SUMO. First, the scenario was simulated using SUMO, and then the exhaust emission was calculated. The Handbook Emission Factors for Road Transport (HBEFA) database has been used for the emission simulation. The model allows simulation of CO, CO_2, NO_x, PM_x, HC emissions, as well as fuel consumption for each vehicle. Passenger car and Heavy-duty Emission Model (PHEM) also can be used for the simulation, since both PHEM and HBEFA incorporate emission data from actual vehicles. As per the study, it was mentioned that SUMO already supports a number of features related to intermodal railway simulation, such as timetables, railway crossings, railway signals, and train dynamic models.

Another study describes the development of an integrated vehicle emission computation system which is implemented for a central urban region of Nanjing City. This system used Paramics, a commercial microscopic traffic simulation programme, to replicate real-world traffic conditions and compute vehicle emissions using the Integrated Vehicle Emission (IVE) Model, which was created collaboratively by researchers at the University of California at Riverside (UCR) and the International Sustainable System Research Center (ISSRC). Vehicle types were identified using the license plate and traffic flow data was collected using a video recording technique. Simulated traffic activity data was stored using the relational database technique and emission calculations were performed using these data. The Genetic Algorithm (GA) implemented in Matlab was used to calibrate the simulation model. Hourly vehicle emissions of three different vehicle types were calculated using the suggested system during the afternoon peak period, and the results were compared with those calculated straight from the IVE software to ensure the validity of the system. A difference of approximately 1 kg was observed for the emission results of all pollutants and vehicle types, indicating that the developed system is highly accurate. According to emission results, buses were the main focus for controlling CO and VOC in the chosen urban region, trucks were the main focus for controlling NO_2 and CO_2, and cars were crucial for controlling CO [75].

Abou-Senna et al. [1] examines four different approaches to capture the environmental impacts of vehicle operations on a limited-access urban highway corridor in Orlando, Florida. The corridor was modelled using Verkehr In Städten - SIMulationsmodell (VISSIM) and MOtor Vehicle Emission Simulator (MOVES)2010a. Based on traffic data from the Florida Department of Transportation (FDOT), the traffic composition was set at 60% passenger cars, 37% passenger trucks, and 3% heavy-duty diesel trucks. The study period included the evening rush hour from 5:00 to 6:00 p.m., which carries over 6,000 vehicles per hour. A substantial amount of output data, which is essential for determining air pollutant emissions, is produced by the VISSIM model, and this output is used as input into the MOVES model. A VISSIM/MOVES integration module called VIMIS was developed to facilitate the conversion process of VISSIM files to MOVES files. Average speeds (AVG), link drive schedules (LDS), and operating mode distribution (OPMODE) were the three approaches used to estimate vehicle emissions, and hand calculation was carried out as the fourth approach for comparison purposes. This study examined the impact of several methodologies on projected emissions of NO_x, $PM_{2.5}$, PM_{10} and CO_2. The findings indicated that acquiring exact and comprehensive operating mode distributions on a second-by-second basis yields more accurate emission prediction.

Rosswog et al. [59] focused on the route choice, microscopic driving modelling and possible applications to the modelling of emissions. It explains the queuing model that is used to move vehicles along the links during the route choice iteration. When a vehicle enters a link, its travel time is determined by its velocity and the length, capacity, and number of lanes of the link. Furthermore, Rosswog et al. outlined the Krauβ model which is suited to be used for large scale problems. Finally, this study compared the jamming behaviour of the Cellular Automation (CA) and the Krauβ model (SK) and described the cumulated NO_x emissions for a simulation of the street network of the city of Cologne.

In 2014, the NZ Transport Agency [31] introduced a vehicle emission mapping tool to automate the calculation of both harmful air pollutants and greenhouse gas emissions. It was developed in stages and is now applicable to all public roads throughout New Zealand. The tool is housed within a Geographic Information System (GIS) framework, to facilitate the presentation of data as maps that help interact with both technical and non-technical audiences. The tool extracts data from the Agency's information systems, and then New Zealand Vehicle Emission Prediction Model (VEPM) 5.3 was used to calculate pollutant mass emission rates. For each regional authority area, VEPM look-up tables were developed to reflect variations in average temperatures throughout New Zealand, which affect cold start emissions. Separate VEPM look-up tables were developed for light and heavy vehicles as well. This tool enables the consistent and repeatable calculation of emissions for each authority and organises the results into different outputs for analysis and visual representation as maps. The outcomes showed that the tool can be used to create vehicle emission datasets as a reliable and consistent way across New Zealand at different geographic scales.

Malik et al. [48] describes a smart solution to the problem of traffic congestion using SUMO. An incident, which is any occurrence that disrupts the regular flow of traffic, was simulated. This was accomplished by causing traffic congestion to stop vehicles in a lane. The simulation is run for 500 seconds and the accident is introduced for 300 seconds. The simulation metrics were observed while the experiments were conducted with and without the incident. This study illustrates the comparison between CO_2 emission before and during congestion, and statistics were observed in three different time steps. The variation in fuel consumption is also analysed in three different time steps again. To alleviate traffic congestion, a re-routing mechanism was implemented and all vehicles with the blocked lane on their route list were rerouted to alternate routes. There was a significant impact on the average travel time of vehicles before and after re-routing, and it can be applied to emergency for an efficient reduction in the travel time.

Li [41] proposed Method Based on Threshold (MBT) to reduce fuel consumption and emissions based on the co-simulation platform developed to simulate the entire process of vehicle crossing through the intersection. SUMO, TraCI, and Python were used in this study to build the co-simulation platform, and two car-following models (CFMs) named Krauss CFMs and Intelligent Driver Mode (IDM) were selected to verify their method. CFM is a method that uses dynamics to describe the driving state of the following vehicle in a single lane when it follows the leading vehicle. The Krauss car-following model is a modification of the model and the intelligent driver model is a time-continuous car-following model. Initially, they conducted simulation tests on the 1000-meter road with and without traffic lights. According to the data, the presence of traffic lights extends travel times overall and raises emissions and fuel consumption. As the second phase, they analysed the driving data of vehicles at traffic lights. According to the simulation results, the suggested approach can reduce fuel consumption by up to 16.5% when compared to not employing assisted driving. Additionally, it reduces CO_2 emissions by 16%. The proposed method, however, cannot be applied to multiple intersections, which should be taken into account in the future.

Mahmoud [47] describes the process used to measure the emissions generated by vehicles using SUMO. This study examines the relationship between vehicle emissions and fuel usage by using SUMO to extract real-time emissions from cars during their trip on the network of routes. First, they downloaded the OSM map from the OpenStreetMap site and exported it to their PC to be able to use it in SUMO. Next, the trips were planned by utilising TAZ to determine the work zone and generating an origin-destination (OD) matrix to determine the origins and destinations of the vehicles in that zone. Duarouter and shortest-path computation were used to calculate vehicle routes. Finally, the amount of CO_2, CO, NO_x, fuel, electricity, and noise emitted by the car was determined using the emission output. The findings of this study were displayed as graphs showing the correlation between each exhaust gas and fuel consumption. Furthermore, they hope to develop an expert system using fuzzy logic to process the extracted data in the future.

Gao et al. [26] proposed an approach for integrating the traffic and vehicle simulations, which are implemented by SUMO and GT-Suite software, respectively. First, they obtained the 2D real-road network and integrated the road elevation into the 2D real-road network. Then, the targeted route for the simulation was extracted, and the real-road network and traffic information were loaded into the SUMO software. Finally, the traffic simulation results were entered into GT-Suite software to finish the vehicle simulation. TraCI4Matlab was used to integrate the SUMO traffic simulator with Matlab, and the vehicle model was validated using WLTC (Worldwide harmonized Light vehicles Test Cycles). The sensitivity of vehicle speed and road grade to fuel economy and exhaust emissions was examined in this study. According to the study, the tendency of fuel consumption and NO_x emissions as a function of road grade and vehicle speed was similar. The trend of the NO_x and soot emission rates matched the fuel consumption rate, which peaked primarily during the acceleration process.

Fujii & Yoshimura [23] used a microscopic traffic simulator called Multi-Agent based Traffic and Environment Simulator (MATES) in conjunction with an accurate database of exhaust gases released by different car models to estimate the amount of CO_2 emissions from vehicles. It is based on the intelligent multi-agent approach, a well-known technique for simulating complex systems. This method involves each agent gathering information from the environment, evaluating it independently based on its own knowledge and preferences, and acting in the environment. In MATES, each driver is modelled as an intelligent agent, and after planning the driving route, a route search algorithm is applied. The JCAP2 (Japan Clean Air Project 2) emission map files, developed by JPEC (Japan Petroleum Energy Centre), were used in this study as vehicle emission data. It was possible to estimate the amount of momentary emissions from each car and determine the total amount of emissions in a given region by comparing the output of MATES with the database mentioned above. They verified variations in the amount of momentary CO_2 emissions by simulating a car driving on a simple road segment with a slope. According to the developed estimation method, the total amount of emissions in this area was 17005.93 kg- CO_2, whereas the conventional method showed 14453.59 kg- CO_2.

Diaz et al. [18] used advanced simulation tools to evaluate and optimise urban mobility while lowering pollutant emissions in critical areas of Cali.

Realistic traffic scenarios were produced by integrating SUMO with Netedit and OSM Web Wizard. Data were collected at key locations found using Google Maps, and the types of vehicles operating and the times of traffic lights were recorded using direct measurement techniques. Additionally, this study examined the effects of several traffic management techniques, such as the use of sensor-equipped smart traffic lights that dynamically modify signal timings in response to traffic conditions. SUMO and TraCI4Matlab were used to create critical traffic scenarios to test vehicle safety features. A significant benefit of this method is that it reduces congestion as well as emissions of CO_2, NO_x, and PM_x by eliminating unnecessary vehicle stops and starts. HBEFA4/PC_petrol_Euro-4, a standard gasoline engine was used in the first simulation, and then the fuel type changed to to HBEFA4/PC_diesel_Euro-6ab. The transition of vehicle fuels to HBEFA4/PC_diesel_Euro-6ab also having effective reduction in all forms of emissions compared to HBEFA4/PC_petrol_Euro-4 vehicles.

3.3 Traffic Simulators and Emission Models

Ejercito et al. [20] describes the comparison between four traffic simulation software named SUMO, VISSIM, Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (Aimsun), and Multi-Agent Transport Simulation (Matsim). They were compared based on the eight criteria. VISSIM and Aimsun are proprietary programs that are only available in 30-day demo versions with restricted functionality, whereas MATsim and SUMO are open-source. Aimsun is compatible with Linux, Windows, and MacOS, whereas SUMO and MatSim are compatible with both Linux and Windows. VISSIM only works on Windows. The traffic network can be manually written up in an XML file using SUMO, or it can be automatically generated and imported from other simulation programs. The traffic network in VISSIM and Aimsun needs to be drawn manually using their graphical network editor. Every simulation package offers a variety of vehicle pattern techniques. Origin-Destination (OD) matrices, flow definitions, and flow and turning ratios are examples of manual vehicle route definitions available in SUMO. Additionally, Aimsun has OD matrices that use vehicle route randomization and traffic supply and demand. VISSIM offers vehicle routing decision technique and OD matices using supply and demand of traffic.

The online documentation for MatSim is accessible on their website, while the PDF documentation for VISSIM, Aimsun, and MatSim can be downloaded online. The Aimsun and SUMO GUIs are simple to use and understand. VISSIM's GUI is comprehensive, but its thorough documentation made it easy to use. Due to the frequent errors that occurred during package installation, MatSim was not used to its full potential. Most traffic simulation packages display their data in two dimensions, and only Aimsun and VISSIM offer three-dimensional displays. Furthermore, each software is capable of providing different kinds of output data during the simulation. VISSIM, Aimsun, and SUMO are capable of handling massive traffic networks. However, during simulation, the frame rate slowed down with increasing network size. As per this study, every simulation software has its capabilities and limitations. Therefore, the simulation package should be selected based on the known data and the needs of the traffic network to be simulated [20].

Mądziel [46] outlined the comparisons of the selected emission models with their characteristics regarding input data, scale of detail, selected features, and information on availability of updates. Additionally, this study provides a summary of the emission calculation options for specific vehicle categories for specific emission models as well as the emission calculation options for specific vehicle exhaust components for specific emission models. COPERT, MOBILE, HBEFA, CMEM, ESTM BOSH, EMPA are some of the emission models that were used for the comparisons in this study, and some of the traffic simulation models are VISSIM, AIMSUN, SUMO, VISUM, MATSim, and EMME 4.0.

Diallo et al. [17] presents a comparison of the most popular traffic simulation tools based on a generic method in two steps. The first step involves a comparison part using a weighted system of evaluation criteria to automatically select the candidate simulators, and the second step involves a deep study of the candidate simulators according to a simulation scenario. Furthermore, this study described the qualitative and quantitative approaches of comparisons, and the comparison criteria were grouped into five categories: Nature of software, Creation of the Road Network and Transport Demand, Simulation realism, Documentation and GUI, Modeler specifications. The two categories of simulation software that have been examined are Generic Multi-Agent System (MAS) simulators (GAMA) and Microscopic Agent-based Road Transport Simulators (MATSim, SUMO, Aimsun, PTV Vissim). For the comparison of the two simulation tools MATSIM and SUMO with respect to the intermodal routing problem, the emphasis was placed on the four aspects: Creation of a complete multomodal transportation network, availability of transportation modes, cost function of the modal choice, and difficulty for new intermodal behaviours. MATSim was chosen as the best simulation tool for this study to replicate intermodal mobility behaviours on a large scale.

Borge et al. [9] compared two methods to estimate road traffic emissions in Madrid (Spain): the COmputer Programme to calculate Emissions from

Road Transport (COPERT4 v.8.1) and the Handbook Emission Factors for Road Transport (HBEFA v.3.1), representative of the ‘average speed’ and ‘traffic situation’ model types respectively. In contrast to CORPERT, the PHEM is used to calculate the emission factors in HBEFA, which are more indicative of actual traffic emissions. The input information was provided by the macroscopic simulation traffic model developed by the Madrid City Council along with observations from field campaigns. Hourly emissions were calculated for almost 15,000 road segments spread across 9 management areas that encompass the city of Madrid and its surroundings. These emission factors were multiplied by vehicle intensity and link length for each road segment and interval to determine hourly emissions. The emissions that came from using the COPERT and HBEFA models were then compared. The total annual NO_x emissions predicted by HBEFA were 21% higher than those of COPERT. The results of the comparison show that the main factors influencing the variations in NO_x emissions estimation are buses, heavy-duty vehicles, and passenger cars. The most significant variations are associated with diesel vehicle emissions under “stop & go” traffic conditions.

3.4 Emission Reduction

Transport is one of the largest sources of greenhouse gas emissions in New Zealand. It is responsible for approximately 17% of gross domestic emissions. Hence, the government will focus on various approaches to reducing this vehicle emission in the next several years. These vehicle emission reduction pertains to the initiatives, technologies, and methodologies designed to decrease the harmful emissions emitted by vehicles.[11]

3.4.1 Alternative Transport Modes

Težak et al. [67] describes the advantages and disadvantages of cable cars in public transport within urban areas. The primary advantages include zero CO_2 emissions due to electric power, absence of exhaust emissions and diminished noise pollution. However, there are a number of disadvantages associated with cable cars, including speed limitations, limited passenger capacity, extensive maintenance, and only suitable for distances up to 7 km. The Aerial cable cars are divided into gondolas and aerial tramways based on the operating principles. Aerial tramways have limited capacity up to 2000 persons/h, as they can only carry one or two cabins that move back and forth on cables. Gondolas are uni-directional aerial cable cars that have multiple circulating cabins that can carry up to 30 people each. They can carry up to

4000 person/h, which is more than aerial cars can. In this study, cable car model with the possibility of 3D modelling was implemented using a CAD program. Based on the results, a comparison was made between the new model of cable car and existing systems of passenger transportation in urban environments. By utilising two platforms at the same level for entry and exit at the stations, gondolas can accommodate up to 8,000 passengers/h. The station floor would need to have a much larger surface area because there would be two platforms. Using two platforms on two separate floors could eliminate this weakness.

Mouritz et al. [51] presented the potential for city shaping offered by the Trackless Trams systems. Further, this study outlined the evolution of trackless trams from rail to level 4 autonomous optically guided buses. The trackless tram system is an optical guidance mechanism designed for high-speed rail, eliminating the necessity for steel wheels on steel tracks, and employing advanced battery technology, enabling electric operation without the requirement for an overhead catenary. As a result, its local effects on air quality and noise are much better. The features of the trackless tram system were also compared to those of the light rail and bus rapid transit systems in this paper. This study then applied the technology to Australian cities using the theory of urban fabrics and demonstrated how this technology can support urban regeneration in all three urban fabric types—walking, transit, and automobile. The integration of the Trackless Tram into the urban regeneration process was examined using a framework of seven design approaches. It demonstrates how Trackless Trams could contribute to the transformation of Australian cities in a variety of urban fabrics. To achieve this, new governance structures and modifications to planning regulations will be required.

Rødseth et al. [58] describes the technical and economic feasibilities of a battery-powered high-speed ferry service in Oslo, Norway. Although the passenger-only ferries can be an effective way to reduce road congestion in urban areas, they are among the most polluting modes of transportation. This study examined the possibility of replacing the current conventional vessels with zero-emission battery-powered vessels. The main drawback of battery-powered boats is their limited range and frequent charging requirements. A mathematical model for a battery-powered ferry service called the MIP model is presented in this paper. The cost savings from route planning are also examined in this paper, which considers a shorter ferry route with replacement transport as an alternative to the current route. Separate models for battery-powered and conventional vessels were developed in this study to compare the immediate costs and benefits of adopting zero-emission vessel technology. Further research is proposed to expand the current model to include the best fleet balance between battery-powered and conventional ferries, as well as the best time to invest for different scenarios with a gradual phase-in of zero-emission technology.

In order to facilitate campus mobility, Lokitha et al. [43] proposes the design and development of a small, lightweight, and portable electric skating scooter which saves time and benefits elderly professors and people with disabilities. Battery is the primary energy source of the vehicle and DC-DC converter is used to step down the voltage of the battery to 6 or 12v for the purpose of need. CADD software was used to estimate the scooter performance. RFID is used to unlock the scooter within 3 seconds, when the tag is placed close to the reader. Then, the user data is sent to the server, and the scooter is monitored. Information about the user accessing the scooter is displayed by the vehicle's database link. Additionally, it is connected to Google Maps and the microcontroller for tracking and sensor data. Finally, the study showed that how electric scooter is helpful in reducing pollution as it has zero exhaust emissions.

Kubik [38] was carried out to determine the CO_2 that is emitted into the atmosphere by using the electric scooters. This study outlined the CO_2 emissions and energy consumption of an electric scooter, which were computed using the CO_2 emission value required to generate a specific energy value in kWh. The electric scooter is powered by a low-power electric motor and has a battery that allows it to travel for several dozen kilometres. CO_2 emissions were calculated based on electricity consumption and results were analysed. The findings showed that moving an electric scooter over a 1km distance on a paving stone produced the highest CO_2 emissions. The lowest emissions were recorded for a scooter that travelled on an asphalt road covering a distance of 5 km. Selecting the appropriate mode will reduce the user's CO_2 emissions based on the results that are shown, which have little variation. The findings of this study demonstrated the relationship between the range of motion of the electric scooter, surface type, and riding mode.

Gebhardt et al. [27] explored which personal motorized transportation trips in Germany could be substituted with e-scooters and the potential impact on greenhouse gas emissions. Trips up to 2 km and trips up to 4 km were the two scenarios that were computed. This study used the LCA database ecoinvent 3.7, and Umberto software to incorporate the data into a material flow model. Additionally, they estimated the possible emission savings by substituting e-scooters for passenger car trips in Germany and compared the results to those of passenger cars. According to the analysis, 13% of daily car trips corresponding to 2% of all car kilometres driven in Germany can be replaced. The findings demonstrated that the type of vehicle replaced, and the general circumstances of the particular use case have a significant impact on the potential savings in greenhouse gas emissions. When e-scooter driving replaces trips in conventional cars, a potential daily CO_2 savings of roughly 5.8 kt could be achieved.

Fogelberg [22] performed energy calculations and system design on solar powered E-bike pools. This study explained Bike Sharing Systems (BSS), which provide users with a flexible mode of transportation in the form of shared bicycles. E-bikes are utilized in place of conventional bikes in Electric Bike Sharing Systems (E-BSS). It was demonstrated that installing 0.2–0.8 m2 of solar panels on the roof of the E-bike station could provide enough energy to make the E-bike self-sufficient each year. The primary tool for all of the calculations in this study was the Matlab program from Mathworks. About 300 tonnes of CO_2 would be avoided annually if 10% of the trips replaced cars and 30% replaced buses. Positioning the bike stations near bus stations, homes, and workplaces will expand the size of the transportation network. Additionally, the weather and season will affect how often the e-bikes are used. Bicycle use is probably going to be higher in the summer than in the winter, and more people will use them when the weather is nice.

Costa & Seixas [15] analyses the energy and climate mitigation impacts associated with the mass introduction of electric cars in Sao Paulo, Brazil. The Nissan Leaf, Ford Focus, and BMW i3 are the three battery-electric models that were selected for this study and its goal was to replace gasoline-powered vehicles with electric vehicles at a rate of 10% by 2020 and 20% by 2030. As per the study, Sao Paulo can reduce its CO_2 emissions by approximately 11.0 MtCO2 by 2030 by replacing 20% of its gasoline-powered vehicles with battery-electric vehicles, while only negligible increasing its CO_2 emissions from electricity use. According to this scenario, gasoline consumption will drop by roughly 7% in 2020 and 13% by 2030. Thus, the city can benefit greatly from the introduction of electric vehicles from an energy, environmental, and economic perspective. Additionally, according to this study, Sao Paulo would save roughly 6.2 billion US dollars in 2030 by implementing electric vehicles.

Petrović et al. [56] updates the existing model for calculating well-to-wheels CO_2 emissions over the life cycle of the car (fossil fuel and electric). There are two stages to the model development. First, formulas for figuring out CO_2 emissions at every stage of an automobile's life cycle are established. In the second stage, the analytical formula for determining optimal lifetime and optimal car's kilometres driven during a lifetime in the process of replacing the FFC with a new EC is established based on ecological criteria. The study found that the type of fossil fuel and the weight of fossil fuel and electric cars affect the reduction of CO_2 emissions. The biggest potential for lowering CO_2 emissions is to replace gasoline-powered fossil fuel vehicles with lighter electric vehicles. Electric vehicles, however, do not significantly lower CO_2 emissions in countries where thermal power plants are the main source of electricity. Future studies should examine the possibility of lowering CO_2 emissions from alternative fuels and other vehicles.

Doucette & McCulloch [19] analyses the CO_2 emissions from electric (EV) and plug-in hybrid electric (PHEV) vehicles and compares the findings with published figures for CO_2 emissions from conventional vehicles based on internal combustion engines (ICE). The 2010 Ford Focus has been selected as the platform for the three different powertrains. Ford manufactures the conventional ICE-based version of the Focus, which has CO_2 emissions data issued by the manufacturer. OVEM (Oxford Vehicle Model) was utilised as the vehicle simulator in this study, and a vehicle modelling tool was used to estimate the emission performance of the EV and PHEVs. Additionally, the vehicle model was validated by successfully predicting the performance of a conventional vehicle, an EV, and a PHEV to increase confidence in the model results. In comparison to EVs, PHEVs require fewer batteries, making them lighter and more efficient. PHEVs are able to run their onboard ICEs more efficiently than traditional cars. This led to the hypothesis that, under specific power generation mixes with different CO_2 intensities, PHEVs might be able to emit less CO_2 than both EVs and conventional cars.

Tettamanti et al. [66] explained the development of an adaptable HEV engine/ fuel consumption model based on the 2010 Toyota Prius, utilizing variables such as speed and acceleration to facilitate real-time applications. SUMO served as the modelling tool in this study, and the TraCI allowed for real-time simulation control and modification for dynamic experiments. HBEFA (Handbook Emission Factors for Road Transport) version 4 was used for the emission calculations in this study. Two different vehicle types are defined in the simulation environment: Petrol_mode, which represents a vehicle with the emission class <HBEFA4/PC_PHEV_petrol_Euro-4_(P)> that runs on petrol and Electric_mode, which uses the emission class <HBEFA4/PC_PHEV_petrol_Euro-4_(El)> to indicate the electric operational mode of the HEVs. This study also explained the mode-switching logic that a vehicle uses to switch between petrol and electric modes. The simulation combines the gathered emission data, adding up the total CO_2, NO_x, PM_x, and fuel consumption for both regular and mode-switch vehicles independently. Finally, it was observed that the mode-switch system significantly reduced emissions, especially CO_2.

Todoruț et al. [69] discusses the benefits of switching to electric buses from diesel ones in the fleet of Compania de Transport Public (CTP) Cluj-Napoca and the environmental impact of this change. This study assesses and emphasises the reduction of CO_2 as the largest bulk component of greenhouse gas (GHG) emissions after 11 electric buses were introduced into urban transportation to replace the same number of diesel buses. Advantages of replacing diesel buses with electric buses for public transport include local zero pollution, high efficiency of electric motors compared to diesel engines. The initial high cost of electric buses and charging infrastructure, and the requirement to implement regionally specific technological solutions are some drawbacks. The energy required for charging is derived from both renewable sources such as nuclear, geothermal, biomass, wind, solar, hydro and polluting sources such as coal, gas and oil in different proportions. Following data analysis, they discovered that switching from diesel to electric buses immediately eliminated local emissions in Cluj-Napoca's circulation areas and that the CO_2 emissions produced by the electric power used by electric buses are 2605 times lower than those produced by diesel buses. Additionally, replacing diesel buses with electric buses has short-term benefits such as lower pollution emissions, reduced environmental noise, and medium- and long-term benefits lower maintenance and operating costs.

AlKheder [2] explains how public transportation can reduce the number of private vehicles to reduce traffic congestion, enhance the cost-effectiveness, reliability, and a positive environmental impact. For this study, Kuwait City block 9 was chosen, and information was gathered from a variety of sources, including the Kuwait Public Transport Company (KPTC), Kuwait Municipality, and the Ministry of Interior (MOI). The Mydriving App was also used to obtain processed data. Google Form was used to create two different kinds of questionnaires: one for those who frequently ride buses and another for those who do not. These surveys focused on the bus quality in Kuwait, delays, peak hours, people opinion regarding services, and the tendency of people to ride buses if fees are imposed on cars entering Kuwait City during the peak hours. The findings indicated a decrease in fuel consumption and gas emissions, representing a good initiative for environmental impact. In certain streets, the results indicated a roughly 45% decrease in traffic. There was a noticeable reduction in the amount of gas produced, which improved the environmental impact.

Thomas & Serrenho [68] describes the ways to reduce UK passenger transport emissions using different transport modes. First, trip data from a nationwide survey were divided into stages for solo and group travel. Then a list of feasible modes of transportation is generated, and the least carbon-intensive mode of transportation is selected from among these. Modal shift offers a substantial opportunity to cut emissions and energy use, with an immediate annual reduction of 31% in emissions and a 33% reduction in energy use. By switching the modes of transportation used for personal travel, emissions could be reduced by roughly 30% compared to the current use of passenger transport. This is achievable if the use of cars is reduced by about 27% and primarily replaced by trains. Furthermore, it can reduce emissions by increasing bicycle and motorcycle availability, increasing the capacity of coach and surface rail, and increasing the time typically spent travelling. Electric bicycles and scooters are examples of micro-mobility modes that play a limited role in achieving the highest possible emissions reductions from modal shift. In many cases, e-bikes and e-scooters are suitable replacement modes for walking and cycling that emit fewer emissions and consume less energy.

Keall et al. [34] provides a case study of an intervention that was implemented in New Zealand, which included the building infrastructure for walking and cycling. The government of New Zealand selected two small cities, Hastings and New Plymouth, as New Zealand's two walking and cycling model communities in 2010. Odometer readings around 71,000 passenger vehicles per year recorded in the New Zealand licensed vehicle administration system were used to calculate the distance travelled by vehicles and the New Zealand Household Travel Survey was used to analyse household travel patterns. Government estimates of emissions from fossil fuels used by automobiles each year were used to estimate carbon dioxide emissions. The average distance travelled per passenger vehicle decreased by 1.6% in the third year of the intervention, which is consistent with the increases in walking and cycling trips that have been observed in the past. The distance driven per vehicle and the related carbon dioxide emissions decreased by 1% on average during the intervention period. In the first three years, if the same one percent reduction could be achieved throughout the country by replacing passenger vehicle travel with walking and cycling, at least 0.23 million tonnes of CO_2 could be avoided.

Lindsay et al. [42] estimated the effects on health, air pollution and greenhouse gas emissions if short trips were undertaken by bicycle rather than motor car. The initial dataset, the "New Zealand Household Travel Survey" made it possible to calculate and convert light vehicle kilometres travelled in urban areas to cycling kilometres. The average light vehicle emissions per km for carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), exhaust particulate matter (PM_{10}), brake and tire PM_{10}, and fuel consumption were determined using data from the VEPM (Vehicle Emissions Prediction Model) version 2.3. If 5% of the short trips were switched to cycling, approximately 223 million vehicle miles could be reduced, 22 million litres of fuel would be saved, $37 million in fuel bills would be avoided, 50,000 tonnes of CO_2 would be avoided, and other pollutants such as PM_{10} and volatile organic compounds would be reduced. The health effects would include an additional five cyclist deaths from traffic accidents, 5.6 fewer deaths from local air pollution from vehicle emissions, and

116 deaths prevented by increased physical activity each year. Public health will be enhanced, and air pollution and greenhouse gas emissions will be decreased with the support of transportation policies that promote bicycle use.

Gounni et al. [28] examined the feasibility of diminishing greenhouse gas emissions through the utilisation of Liquefied Natural Gas (LNG) as an alternative fuel technology for light-duty cars. A scenario-based traffic simulation approach was used in the survey to simulate microscopic traffic emissions. The two scenarios used in this study were optimistic, which assumed 100% LNG and 0% conventional fuel in the event of a total state intervention and pessimistic, assuming 100% conventional fuels and 0% LNG in the absence of state intervention. Since natural gas is readily available and has a negative impact on the environment, it is the best substitute for conventional fuels. When compared to diesel, the combustion of LNG produces approximately 80% less nitrogen oxides (NO_x), 20% less carbon dioxide and 99% less particle (PM) and sulphur oxide (SO_x) emissions. The results of this study were generated using PHEMLIGHT, which is a simplified model of PHEM (Passenger Car and Heavy-Duty Emission Model). Public version of PHEMLIGHT only includes two emission classes: passenger cars with gasoline engines (PC_G_EU4) and passenger cars with diesel engines (PC_D_EU4). Finally, this study demonstrated that increased use of LNG by vehicles results in lower levels of CO_2, NO_x, and PM_x emissions.

Grahn et al. [29] described the role of biofuels for transportation in CO_2 emission reduction scenarios. Regionalised version of the Global Energy Transition model, GET-R 6.0 was used in this study. Two distinct CO_2 reduction scenarios were used, both of which met the target atmospheric CO_2 concentration of 450 parts per million by the year 2100. The first scenario is “global cap” (GC), which uses a global cap on CO_2 emissions and allows global emissions trading. Second, regional caps (RC) allow industrialised regions to reduce their CO_2 emissions by 2010. By 2040, CO_2 emissions are assumed to be distributed equally among all six regions at 1.0 tC/capita and then follow a common path toward approximately 0.2 tC/capita by 2100. Their analysis yields three key findings: biofuels are never dominant in the transportation sector, their use in industrialised regions is much higher in RC than in GC, and their use actually rises in RC as the CO_2 concentration target is weakened.

Rhys-Tyler et al. [57] addresses the research question “Are more stringent exhaust emissions standards, as applied to light vehicle type approval, resulting in reduced vehicle pollution in an urban area?” Using roadside remote sensing absorption spectroscopy techniques (UV and infrared) in conjunction with Automatic Number Plate Recognition for vehicle identification, the exhaust emissions of a sample of more than 50,000 road vehicles operating in London were measured. Vehicle class, fuel type, and Euro emissions standard were used to report the levels of carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO), and smoke (particulate) exhaust emissions. There is a notable decrease with the implementation of each subsequent Euro emissions standard, starting with Euro 1. Compared to Euro 1 or Euro 3 standard diesel cars, Euro 2 diesel cars were found to emit statistically higher NO emissions. However, the smoke (particulates) from diesel cars decreases significantly as one moves from Euro 2 to Euro 3 and then from Euro 3 to Euro 4. It was discovered that the mean NO emissions from Euro 4 diesel vehicles were six times greater than those from Euro 4 gasoline vehicles. Compared to the previous TX1 or later TX4 model variants, the smoke emissions from the TXII London taxis were found to be statistically higher.

Jung & Koo [33] examines the environmental impacts of roundtrip car sharing services by investigating transport behaviour. To investigate individual behaviour related to modes of transportation, preferences, and intentions for using car-sharing services, an online survey was conducted. The availability of fuelling and charging stations, fuel type, vehicle type, vehicle pickup and delivery service, one-way trip options, and the cost of the car-sharing service were the six characteristics that were found to influence modal choice for car-sharing services in this choice experiment. Additionally, this study uses three different types of models to analyse the effects of this modal shift on greenhouse gas emissions: a mixed logit model to analyse preferences for car sharing services, a binary logit model to analyse whether people are willing to forgo planned purchases or private vehicle ownership in favour of using car sharing services, and a linear logit model regression to ascertain the extent to which car sharing would replace the use of private vehicles or public transportation and the resulting mobility effects. Electric car sharing would be more likely if there were 50% more EV charging stations than gas-fuel stations. This would result in a 655,773 tCO2e reduction in emissions.

3.4.2 Emission Reduction Strategies

Wu et al. [77] describes a number of vehicle emission control strategies and policies in Beijing that can be broadly divided into seven categories. The first category is the control of new vehicles. SEPA implemented a new rule requiring new cars to meet Euro 1 and Euro 2 emission standards nationwide in 2000 and 2004, respectively, to enforce stricter emission standards. Beijing launched a program a called “Strategies and Implementation Plan for Controlling Motor Vehicle Emissions in Beijing” in 1997 to set up a step-by-step implementation Plan (IP) of Euro emission standards for Beijing. The

Beijing Environmental Protection Bureau (EPB) increased vehicle emission standards to Euro 1 for light-duty vehicles on January 1, 1999, and mandated that new gasoline-powered vehicles have three-way catalysts and electronic fuel injection (EFI). Additionally, Beijing EPB promoted new emission standards that focus on HDDV controls, such as Euro 5 in 2012 and Euro 6 in 2016.

The second category, according to Wu et al. [77], is the control of In-Use Vehicles. In 2001, Beijing EPB started implementing an improved I/M program using the ASM test protocol to improve NO_x emission control. In 1998, an environmental labelling policy for in-use vehicles was implemented by issuing a label either in yellow or green to each vehicle registered in Beijing, indicating the emission standard of the vehicle. Improvements in fuel quality are the third category. In order to meet the new Euro 4 emission standards, the sulfur content of gasoline and diesel has decreased to 50 ppm since 2008. Forth category is the penetration of alternative fuel vehicles and advanced vehicles. The Beijing bus fleet introduced compressed natural gas (CNG) buses in 1999. Compared to diesel buses, dedicated CNG buses have moderately to significantly lower NO_x emissions and significantly lower particle emissions. Gasoline taxis were being converted to FFVs using either gasoline or LPG as part of a significant retrofit programme.

The fifth category involves economic policies, including fiscal incentives and vehicle emission taxes/fees. The State Ministry of Finance and Administration of Taxation announced in 2000 that light-duty vehicles that met Euro 2 emission standards would be eligible for a 30% excise tax reduction or 5% of the price of a typical Chinese car. To phase out vehicles with yellow labels, the Beijing EPB started a scrapping program in late 2008. Up to 6000 RMB Yuan could be given to the owners of the car with the yellow label in exchange for scrapping it. Planning of Public Transportation System is the sixth category. Beijing's bus fleet will include a significant number of hybrid electric diesel buses in the next five years. By increasing the use of subways and light rails, traffic congestion and emissions will be reduced. The last category is the temporal Traffic Control Measures, which were implemented during the 2008 Olympic Games. As a result, vehicle emissions of VOC, CO, NO_x and PM_{10} inside Beijing during the 2008 Olympics decreased by 55.5%, 56.8%, 45.7%, and 51.6%, respectively [77].

Gallivan et al. [24] outlined the strategic options to reduce greenhouse gas (GHG) emissions and compared them regarding the potential for GHG reductions and cost-effectiveness. In this study, sixteen strategies were analysed in four categories. First category is the promotion of alternative travel modes. Ride-sharing and transit pass programmes were conducted for Los Angeles employers to promote carpooling and transit. The Metro Employee

Transit Subsidy Programme was carried out to encourage metro employees to use public transit for their commute trips. Furthermore, they constructed Transit-Oriented developments (TODs) on sites owned by Metro. The number of people who commute by combining bicycles with their transit should be increased. Moreover, Metro can promote bicycling to transit by providing financial incentives, such as assistance for purchasing a bicycle. Dedicated paths and other amenities for bicyclists along key transit corridors should be provided. Bicycle and pedestrian facilities combined with transit facilities offer a higher multimodal level of service.

The second category is the transit service, which can expand Metro's existing vanpool programme. Vehicle Technology is the third category. It involves replacing conventional CNG buses with more fuel-efficient GEH buses, replacing Metro's standard 40-ft buses with forty-five-foot composite buses, increasing the number of hybrid vehicles in Metro's fleet of non-revenue light-duty vehicles and utilising regenerative braking technology. The fourth category is the facility energy use, such as replacing current 80 W lights with more efficient lights, replacing existing lighting in Metro facilities with more efficient lighting. Among these strategies, ridesharing and transit programmes for employers, transit-oriented development, vanpool subsidy, and onboard railcar energy storage are the greatest potential strategies for GHG emission reductions [24].

3.5 Summary

This literature review reveals that vehicle traffic simulation, vehicle emission analysis, and emission reduction strategies are very crucial topics in transport and emission-related research. Traffic simulation provides a controlled environment to replicate the real-world conditions, allowing researchers to investigate and test the impact of the various interventions before they are implemented in the real world. This literature review finds the different types of traffic simulation models in several prior studies, which were discussed and compared. It was found that the microscopic model has greater precision, especially when it comes to simulating emission. Subsequently, various research studies related to distinct traffic simulation scenarios were outlined together with their respective simulation technologies. It was discovered that numerous traffic simulation research projects have been conducted using SUMO, an open-source simulation tool. Furthermore, it demonstrated how these traffic simulations can be employed to predict traffic and find solutions to mitigate traffic congestion.

As the second part of this literature review, vehicle emission was examined, and many studies revealed that CO_2 is the main pollutant of transport-related emissions that contributes to air pollution. Integrating the simulation output with the appropriate emission model could enable the researchers to get insights regarding different scenarios. Several emission modelling scenarios with their modelling techniques were also examined in this literature review. It is crucial to select the appropriate emission model in accordance with the study's needs, as there are numerous emission modelling tools available for calculating vehicle emissions. As part of this literature review, different kinds of traffic simulation software and emission modelling tools were compared along with their capabilities and limitations. It was highlighted that it is necessary to select the appropriate software based on the study requirements.

The last part of this literature review focused on the emission reduction by the introduction of alternative transport modes and emission reduction strategies. A wide range of emission reduction strategies were identified through these, prior reviews and their potential towards emission reduction was also discussed. These initiatives are crucial for enhancing air quality, mitigating greenhouse gas emissions, and tackling climate change. The emission reduction methods related to technological advancements, the utilisation of cleaner fuels, and modifications in transport legislation were outlined in this review. Furthermore, it was highlighted how these emission reduction methods will aid in mitigating vehicle emissions.

This analysis establishes the basis for the current study, which aims to enhance existing knowledge by utilising a traffic simulation framework to assess vehicle emissions and potential emission reduction measures within the New Zealand setting.

Chapter 4

Methodology

The objective of this chapter is to provide an overview of the tools and methods that are used to analyse vehicle emissions using a microscopic traffic simulation model and how they are used to investigate different modes of sustainable transport. There is a brief description of the proposed methodology for implementing this research, followed by a description of the data sources that will be used for this study. This section also describes the procedures for assessing the model and tool selection, the detailed descriptions of the selected tools, and the languages to be used for the implementation. The final part of the chapter outlines the analytical procedures for quantifying and analysing emissions based on different traffic scenarios.

4.1 Proposed Approach

A quantitative simulation-based methodology has been used in this study in order to assess vehicle emissions in various traffic scenarios. It involves the integration of a microscopic traffic simulation model with a database of emission factors in estimating vehicle emissions. The high-level diagram of the proposed approach is presented in Figure 4.1.

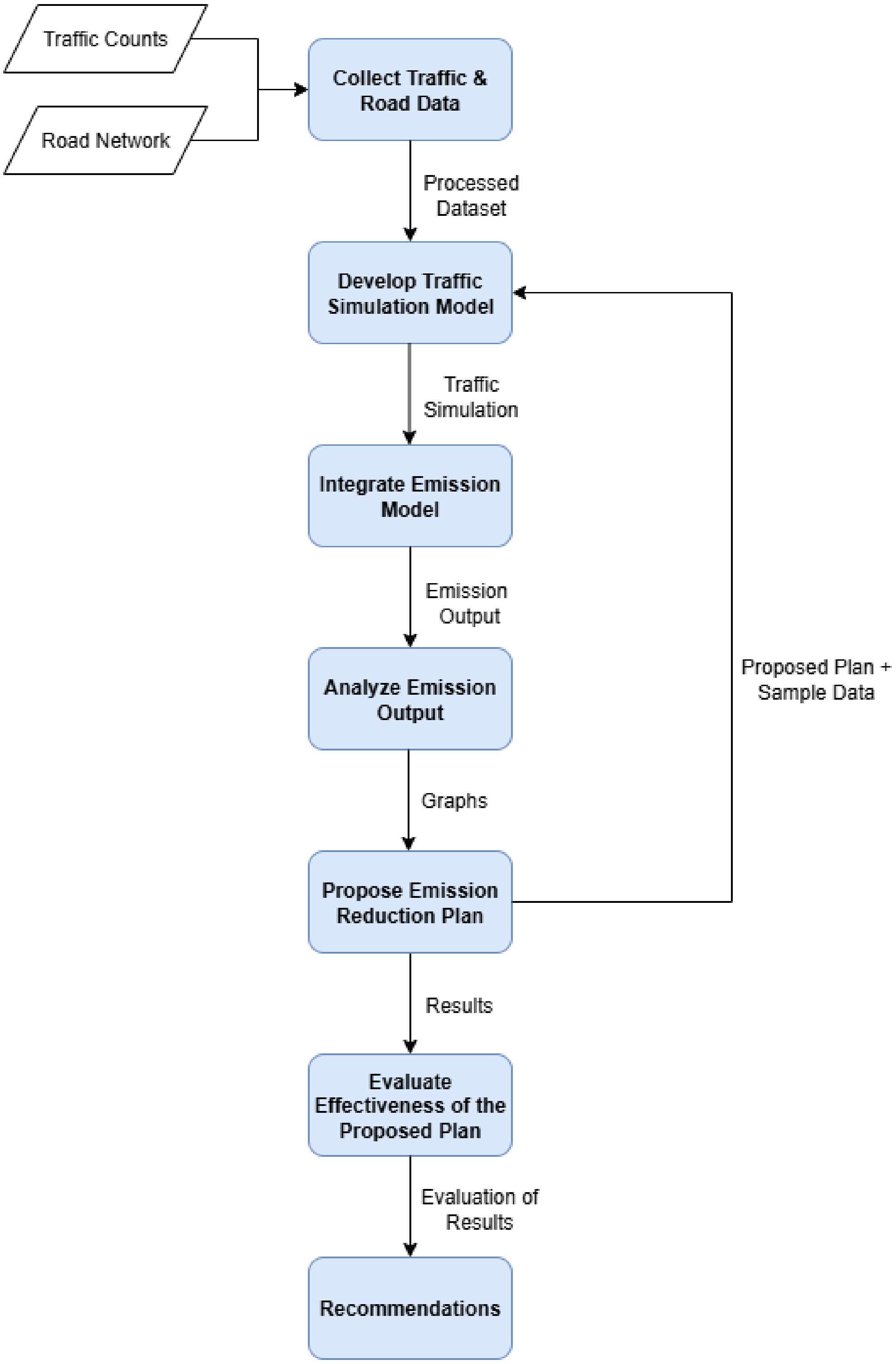

Figure 4.1: High-level diagram of the proposed plan

First, we gather road network data and traffic counts in order to produce the simulation. Subsequently, a traffic simulation model will be created in accordance with the specifications of simulation scenario, and an emission model will be integrated into the model. Once both models have been integrated, the simulation will run using the traffic data counts that have been gathered. Afterwards, emission output will be analysed using several graph types in conjunction with the results of the simulation. Then, we provide a plan to reduce emissions and repeat the simulation using the sample dataset in accordance with the suggested scenario. As a result of analysing the emissions output of that scenario, we are possible to evaluate the effectiveness of the plan that has been proposed. Similarly, several kinds of emission reduction strategies can be suggested and assessed. The final emission reduction plan will be presented based on the evaluations of the proposed methods.

4.2 Traffic and Road Data Collection

Data collection is one of the most important steps in the development of a realistic traffic simulation model. The success of this research is heavily dependent on the accuracy of the data used for the simulation. There are two types of data that need to be collected, namely data regarding the road network and data regarding traffic counts. Road traffic data involves the acquisition of comprehensive geometric and infrastructural data of the simulation area. This includes road layout and traffic control elements, such as number of lanes, intersections, roundabouts, road speed limits, and traffic lights.

Data on traffic counts include the number of classified vehicles at key intersections and road segments during peak and off-peak hours. Data are collected through the use of manual or automated traffic counting methods. The collected data will then be cross-checked and cleaned to remove any inconsistencies or errors. Subsequently, the data set should be rearranged in the specified Excel file format that the simulation requires.

4.3 Development of Traffic Simulation Model

A traffic model is a mathematical representation designed to precisely replicate observed and measured traffic conditions on the roadway [6]. The development of a traffic simulation model that can replicate real-world scenarios is intended to be the second phase of this approach. To accomplish this, a suitable traffic model and traffic simulation software that satisfies the study's requirements must first be selected.

4.3.1 Traffic Model Selection

Choosing the right traffic model in traffic simulation is extremely important as it may affect the accuracy of both the traffic flow and the emissions estimates. In this regard, the selection of the traffic model should be based on the research requirements, available resources, the capability, and limitations of each model. In order to accomplish the goals of this research, the model must capture vehicle-level movements and be capable of estimating emissions in an accurate manner.

Three types of traffic simulation models, microscopic, macroscopic, and mesoscopic models, were taken into account for the traffic model selection process. As stated previously in Section 2.2.1, the microscopic model simulates each vehicle and its dynamics individually, and the macroscopic model considers the traffic flow as a continuous stream using aggregate measures. Mesoscopic model is a combination of microscopic and macroscopic models. As per the research requirements, each vehicle and its characteristics should be modelled individually. Therefore, the microscopic model is the most appropriate option among the three.

Obtaining accurate results from this study requires that real-world data be incorporated into the simulation. Compared to the other two models, the microscopic model can take input data to adequately model the road network [30]. Since traffic lights are an important component of road network simulation, the model should be able to simulate them accurately. The microscopic model is the only one that can simulate traffic lights among the three models. The macroscopic model has limited capability in simulating traffic lights, whereas the mesoscopic model relies solely upon heuristics methods [30]. Furthermore, the most crucial component of this study is the accuracy in the traffic simulation and the emission analysis. The microscopic model provides greater precision when simulating individual routes and emissions compared to the other two models. Hence, the microscopic model is the most suitable method for analysing emissions [44].

Compared with the other two models, the microscopic model has some limitations, such as the calibration and validation processes taking a considerable amount of time and money, and the execution speed is also slow [30]. Despite this, the microscopic traffic model was the most appropriate choice for this research. This is because the microscopic traffic model best aligned with the primary criteria of this study such as the precision in emission estimation, nature of the simulation and applicability of integrating different simulation scenarios.

4.3.2 Selection of Simulation Software

The selection of suitable traffic simulation software is essential for the precise modelling of real-world traffic scenarios in accordance with study requirements. Based on the findings of the literature review, the five most widely used microscopic traffic simulation software, namely MATSIM, SUMO, AIMSUN, VISSIM, and GAMA, were selected for the final software comparison procedure. As part of the selection process for selecting the best simulation software for the proposed approach, these five software were evaluated based on six selection criteria: 1) Software Category, 2) Operating System Portability, 3) Modelling Capability and Customisation, 4) Visualisation and Output, 5) Scalability and Performance, 6) Documentation and the GUI. The detailed software selection procedure is described in Appendix A.

The final score for each simulator was calculated as a weighted average using the following formula.

$$Score = \frac{\sum_{i=1}^{n} mark_i \times coeff_i}{\sum_{i=1}^{n} coeff_i}$$

i: Criteria number
n: Number of criteria
$mark_i$: Mark value of the simulator for each criteria
$coeff_i$: Coefficient of assigned to the criteria

The final score table of the software selection procedure is shown in Table 4.1.

Table 4.1: Final Score of each Traffic Simulator

Simulator	**Criteria**						**Score**
	1	**2**	**3**	**4**	**5**	**6**	
MATSIM	10	10	8	3	10	10	8.27
SUMO	10	10	10	5	10	10	9.04
AIMSUN	3	10	8	10	7	6	7.35
VISSIM	3	3	8	10	3	8	5.88
GAMA	10	10	7	5	3	8	7.15

SUMO, which received the highest score in Table 4.1, was chosen as the traffic modelling software for the proposed approach. The following aspects of the SUMO software were best aligned with research needs during the selection process.

As described in Section 2.4, SUMO is a free, open-source software programme that allows modelling at the microscopic level. All of the major operating systems, including Linux and Windows, are compatible with SUMO. Comprehensive multi-modal network modelling is made possible by its support for detailed simulation of a variety of transportation modes, including as cars, buses, trams, bicycles, pedestrians, and rail. Since this study needs to expand the simulation with a variety of transport modes, multi-modal networking in SUMO would be more beneficial for this study. SUMO offers the capability of integrating other visual tools as well as direct creation of the road network. It is easy to import the road network from OpenStreetMap and handle transport demand using SUMO. This makes it possible to directly import the road network which is needed to be simulated using OpenStreetMap and incorporate into SUMO. The source code for SUMO is publicly available for use and modification. Consequently, it can be easily customized to meet the needs of the study. It includes in-built HBEFA/PHEMlight model to facilitate emission modelling. Thus, the emission calculation process of this study can be handled easily with SUMO.

In addition, it provides a 2D visualisation of the simulation and statistical outputs for analysing traffic simulations. SUMO was designed especially to simulate massive networks. It can replicate networks with millions of nodes and links. It possesses efficient memory management and fast computation with minimal usage of CPUs and GPUs. These features provided by SUMO will make it possible to visualise and simulate traffic in this study more accurately and efficiently. SUMO offers a number of official and community-driven support solutions together with up-to-date and well-explained documentation. It includes annual user conferences, online documentation support, tutorials, community initiatives, and the SUMO forum for community discussion and support. As a result, it will be possible to enhance the knowledge and develop the simulation without any prior experience. Its interface is user-friendly and easy to understand. This makes it helpful for debugging, presenting, and simulating different scenarios. All of the above attributes of SUMO were in accordance with the requirements of this study. Hence, it was decided to carry out this simulation using SUMO.

4.3.3 Develop Traffic Simulation

Following the selection of the appropriate simulation model and software, the traffic simulation model will be implemented using SUMO in accordance with the requirements of the simulation scenario. The development process will include network modelling and traffic demand modelling.

In network modelling, the network geometry of the selected area will be extracted from OpenStreetMap and imported into the SUMO simulation. The traffic demand will be generated by converting the traffic count data excel sheet into the SUMO readable XML format. Each vehicle trip should be defined with attributes such as departure time, vehicle type, route, and speed.

After the preparation of the network and demand file, the simulation will be executed by feeding the road network data and the vehicle count data that are processed in the initial stage of this study. The simulation can be executed using the SUMO command-line interface (sumo) or its GUI version (sumo-gui).

4.4 Emission Model Integration

As part of the evaluation of the emission impact of the traffic scenarios, it is intended to expand the simulation by incorporating the emission modelling capabilities of SUMO. The first step towards achieving this is to select an emission model that can be integrated with the SUMO traffic simulation.

4.4.1 Selection of Emission Model

The primary objective of this research is to analyse vehicular emissions derived from traffic dynamics simulated with the microscopic traffic simulation software SUMO to assess various transportation interventions. Selecting an appropriate vehicle emission model is important since it must be capable of calculating emissions accurately from individual vehicle movements generated by the simulation. Three criteria were considered when selecting an appropriate emission model for this study.

The first criterion is its compatibility with SUMO, as the emission analysis must be performed on the basis of the results from the SUMO traffic simulation. SUMO mainly consists of two emission models, HBEFA (Handbook Emission Factors for Road Transport) and PHEMlight. Each model has unique characteristics and applications [63]. PHEMlight is a simplified version of PHEM (Passenger Car and Heavy Duty Emission Model) implemented by the Technical University of Graz [28]. Therefore, the focus was done between these two emission models to select the best suitable emission model for this study.

The second criteria is the coverage of pollutants. For the emission analysis procedure, the chosen emission model should accommodate the primary pollutant categories. HBEFA and PHEMlight both cover CO, CO_2, NO_x, PM_x, and HC in this scenario [63]. The last criteria is computational efficiency. The computation of HBEFA polynomial functions is faster than that of PHEMlight's power-load computations [35]. Based on the aforementioned criteria, HBEFA was selected as the emission model to use in this study.

4.4.2 Emission Calculations

To facilitate precise emission estimations, each vehicle is assigned a specific emission class based on the vehicle category provided in the dataset, such as the emission class HBEFA3/PC_G_EU4 for petrol passenger cars in the Euro 4 standard and HBEFA3/HDV_D_EU4 for heavy vehicles. The emission output will then be generated through the execution of the simulation.

4.5 Emission Output Analysis

Following the execution of the simulation programme, the emission output will be retrieved and analysed to evaluate the emission consequences of the traffic circumstances across various scenarios. It is intended to use both quantitative evaluation and comparative assessments for the analysis of the emission results in order to find trends and improvements.

The pollutant values for each vehicle for each time step will be included in the XML-formatted emission output generated by SUMO. First, the output data will be preprocessed in a tabular format using a custom parser in Python. For further analysis, the output data will be uploaded to a database to make the analysis process more efficient.

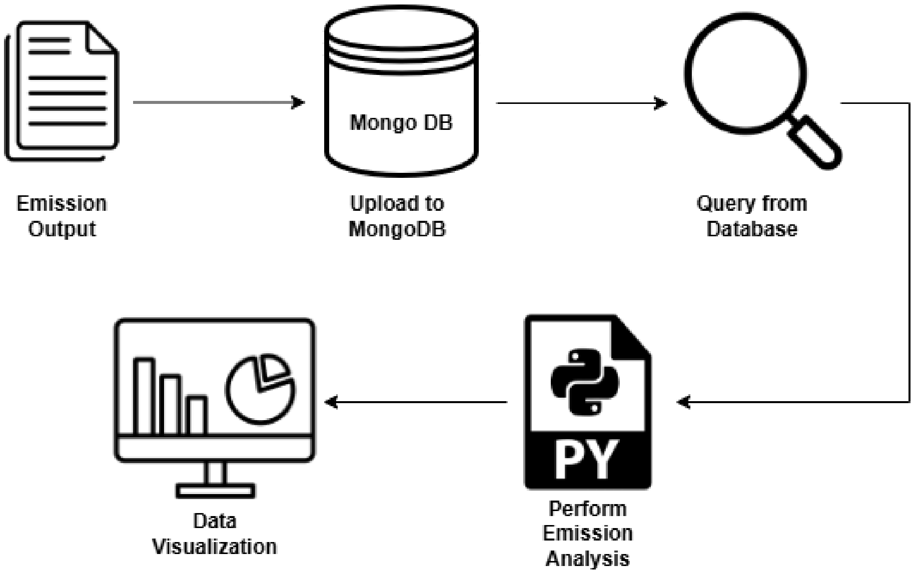

Figure 4.2: Emission Analysis Process

The emission output data for each scenario will be stored in a MongoDB database to enable data retrieval at any time for emission analysis. The Python programming language is intended to be used in the implementation of this suggested approach. Visualisation and interpretation of the emission effects of each scenario will be accomplished with various types of graphs, including line graphs, bar graphs, and pie charts. These graphs will be selected based on the characteristics of each graph found in the literature review [1][48]. Line charts can be used to show fluctuations in emission levels over time and provide a visual representation of the emission patterns. Using bar charts, it is possible to compare total vehicle volumes across different scenarios. The most effective way to illustrate the percentage contribution of each pollutant is through a pie chart.

4.6 Proposal of Emission Reduction Plan

In addition to the emission analysis process, we explore several feasible solutions to reduce emissions based on the emission results obtained from the initial simulation. These plans will be designed to address the most significant sources of emission and trends identified through the analysis process.

As part of the each reduction plan, it is intended to perform a re-run of the simulation utilising a suitable dataset for each reduction plan. Afterward, similar to the earlier steps, the emission output will be stored in the database and the emission analysis process will be conducted for the newly suggested plan.

4.7 Effectiveness of the Proposed Plan

Based on the emission analysis of each scenario, it is able to assess the feasibility and impact of the proposed emission reduction plan. Based on the result of the analysis, it will be possible to quantify the effectiveness of each plan in terms of reducing vehicle emissions while maintaining its feasibility and traffic flow efficiency. It is intended to visualise and compare the emission results using graphs and tables for the clear indication of the effectiveness of each reduction strategy.

4.8 Recommendations

As part of the emission analysis process, we will identify emission reduction strategies. Based on the effectiveness of the emission reduction plans considered in the previous step, the most effective and practical solutions will be selected for the final reduction plan. A comparative analysis will be conducted based on several factors such as emission reduction performance, traffic flow efficiency, and feasibility of the suggested solution to identify the best solutions. In conclusion, it is expected to extend the emission analysis process to present recommendations that can be implemented to reduce vehicle emissions.

4.9 Tools and Software

The simulation will be implemented using a combination of specialised tools and supporting software in accordance with the objectives of the research and the requirements of the model. The primary tool for traffic simulation is SUMO 1.20.0 (Simulation of Urban Mobility), and HBEFA (Handbook Emission Factors for Road Transport) is used for the emission calculation. The road network can be downloaded through OpenStreetMap and modified using NETEDIT. Python 3.12.6 will be used as the main programming language of this implementation with the support of several libraries such as xml.etree.ElementTree, Pandas, NumPy and Matplotlib. The output emission data will be stored using MongoDB 8.0.3, allowing flexible and real-time querying as needed. Figure 4.3 shows the tools related to each step of the simulation.

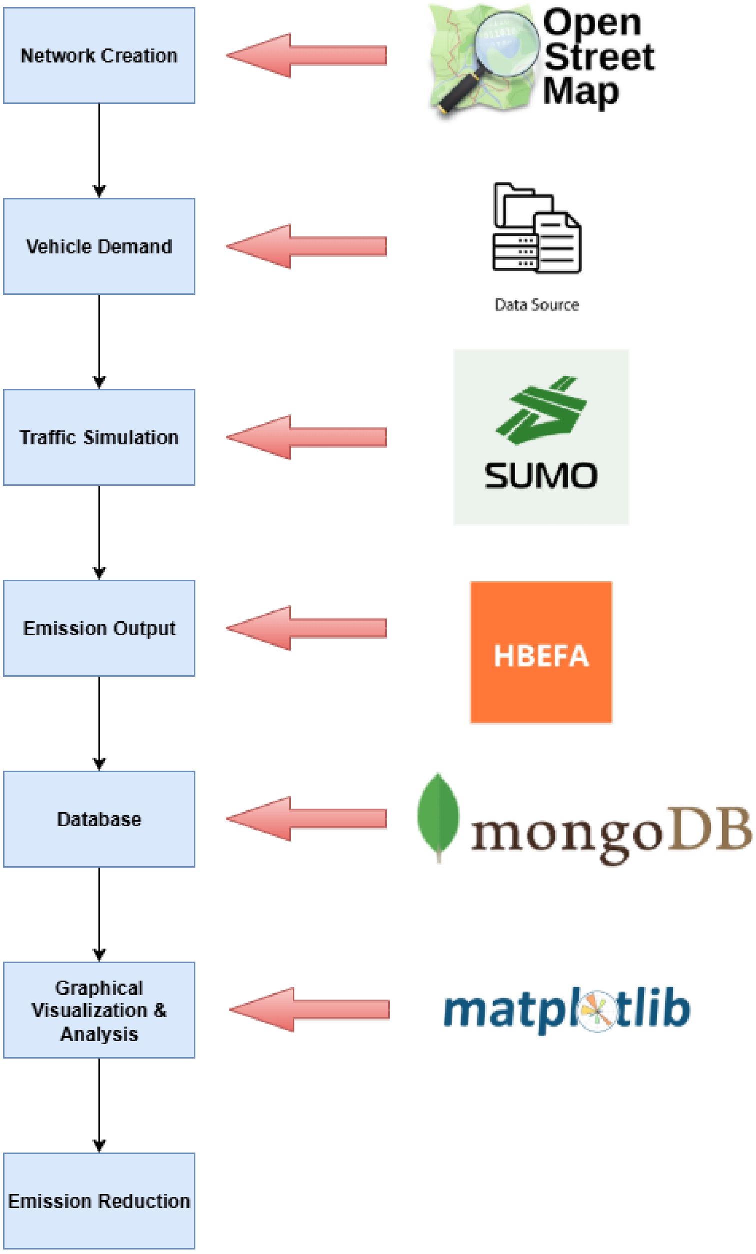

Figure 4.3: Tools and Software used in each step

Chapter 5

Case Study

This chapter presents a case study to investigate vehicle emissions in the Bay of Plenty region, which is one of the fastest-growing regions in New Zealand. Since Tauranga is the main urban city in the Bay of Plenty region, where rapid growth and increased vehicle ownership have raised concerns about transportation-related emissions, we have used Tauranga to illustrate this approach. Utilising real traffic count data, this study simulates current traffic conditions in order to quantify emissions levels and explore practical strategies for reducing the environmental impact of road transport.

5.1 Vehicle Emission in Bay of Plenty

Over the past few decades, the Bay of Plenty region, located on the North Island of New Zealand, has experienced rapid growth in urbanisation and vehicle fleet. Tauranga, the largest city in the Bay of Plenty region, which emerged as a major residential and commercial hub, has faced a rapid increase in private vehicle ownership, leading to high traffic volumes during peak hours [71].

Tauranga City is the fifth largest local authority in New Zealand by population. Between 2018 and 2023, its population increased by 11%, reaching 161,300 in 2024. Tauranga City Council estimates that the population will reach 182,430 by 2033 and 225,410 by 2063, indicating continued urban expansion and corresponding growth in transport demand [64]. In recent years, the city has experienced an increase in traffic volumes and congestion due to this rapid growth of its population, which has placed additional strain on the transportation system, particularly during peak hours [64].

According to statistics, nearly 39% of the households in Tauranga owned two vehicles, while around 31% owned one vehicle. Households without any motor vehicle are equal to 4%. This prevalence of multiple-vehicle households also contributes to the high volumes of daily traffic in Tauranga. According to the Tauranga City Council reports, 60% of those employed in Tauranga drove a private car, truck or van to their workplace and around 13% of the working population of Tauranga had taken a company car, van or truck as their mode of transport to work in 2023. However, only a small percentage (2%) of people used public transport for travelling to work in Tauranga [64].

As demonstrated by the above statistics, Tauranga is heavily dependent on private cars as its primary mode of transportation. According to the feedback undertaken during the Phase of the Cameron Road Stage 2 Detailed Business Case, some respondents stated that public transportation in Tauranga is unreliable and does not reach the areas where they need to commute [10]. The statement from another individual is that public transport does not provide adequate service for many people in Tauranga, since bus stops are not easily accessible, the timetable is irregular, and the cost is prohibitive [10]. Furthermore, private vehicles play an important role in daily life due to their practicality. People in New Zealand have a strong cultural affinity for cars and seek freedom in their travels [10].

There are six territorial authorities in the Bay of Plenty regional area. It includes Tauranga City, the Western Bay of Plenty district, the Whakatane district, the Opotiki district, the Kawerau district, and the Rotorua district. Tauranga represents 24% of the Bay of Plenty's total gross emissions, making it the highest emitting territorial authority in the region. The following largest territorial authorities, Rotorua, Western Bay of Plenty, and Whakatane, represent 23%, 21% and 20% of the Bay of Plenty's total gross emissions. The majority of emissions in Tauranga are due to transportation; however, Rotorua, Western Bay of Plenty, and Whakatane have a significant amount of emissions from agriculture [65].

The total gross emissions in Tauranga in the reporting year 2020/21 (1st July 2020 to 30th June 2021) were 1,345,115 tCO2e [65]. In Tauranga, the largest contributor to emissions is transport, accounting for 74% of total gross emissions [65]. Petrol and diesel consumption account for 36% of Tauranga's total gross emissions, while marine freight contributes 35% [65].

During the period 2015/16 to 2020/21, the total gross emissions of Tauranga increased by 23% (248,961 tCO2e) from 1,096,155 tCO2e to 1,345,115 tCO2e. In the period 2015/16 to 2020/21, the amount of transportation emissions increased by 33% (245,775 tCO2e), primarily due to a 50% increase in marine freight emissions (157,853 tCO2e) and a 21% increase in on-road fuel emissions (75,671 tCO2e) [65].

5.2 Study Area

As mentioned in the previous section, Tauranga contributes the highest proportion of emissions with approximately 24% among the six authorities in the Bay of Plenty region. This significant percentage highlights the city's contribution to regional greenhouse gas (GHG) emissions, with road transport being a primary cause [64].

With such factors, Tauranga would be an ideal case for analysing vehicle emissions using microscopic traffic simulations. When choosing Tauranga for the case study, factors such as increased car ownership, level of traffic congestion, and availability of data were also taken into account.

As the first step, the high-congested roads in the Tauranga area were identified through several reports [8] and the observation of the Google map traffic patterns. Based on the traffic congestion level and the data availability, the following areas were selected for simulation, since it was necessary to simulate multiple sites throughout the Bay of Plenty in order to increase the level of accuracy.

1. Cameron Road - Fifteenth Avenue Intersection
2. Newton Street – Between Aerodrome Road and Tatua Way
3. Turret Road - Between Fifteenth Avenue and Harini Bridge

The three sites that were selected for the simulation are shown in Figure 5.1.

Figure 5.1: Selected Simulation Locations

5.3 Data Collection

Historical data pertinent to traffic counts was obtained from the Tauranga City Council to facilitate the development of a realistic simulation. This data set included vehicle volume for seven days of the week, from 0:00 to 24:00, at 15-minute intervals, to identify patterns in vehicle traffic and emissions. The data reflected different vehicle types, directions of travel, peak and off-peak travel patterns.

In New Zealand, the New Zealand Transport Agency (NZTA) categorised vehicles into 14 classes (CL1 -CL14) to use in the data collection and analysis process [70]. This distinguished vehicles based on weight, axle configuration, and intended use. In this study, these 14 classes were classified into four categories, as shown in the following Table 5.1.

Table 5.1: Vehicle Classification

Simulation Category	**NZ Vehicle Classes**	**Description**
Motor Bike	CL1	Motor bike
Car	CL2 & CL3	Car, Car with 1 axle trailer
Bus	CL4	Bus, Mini Truck
Truck	CL5-CL14	Heavy Truck

5.4 Simulation Setup

The simulation was set up to replicate the traffic volumes of the aforementioned three sites. In order to replicate real-world conditions, the simulation was conducted with 4.8 percent of all cars being electric, as the market share of electric vehicles in the Bay of Plenty region is 4.8 percent in 2025 [21]. Estimation of CO_2, NO_x, and particulate matter emissions was done using emission factors appropriate for New Zealand's fuel requirements. In order to capture daily fluctuations in traffic and emissions, both morning and evening peak hours were included in the simulation.

Chapter 6

Implementation

The purpose of this chapter is to present the detailed implementation of the microscopic traffic simulation undertaken to evaluate vehicle emissions in the Bay of Plenty. This is an integration of a vehicle traffic simulation model with a vehicle emission model, designed to facilitate the vehicle emission analysis process. The implementation includes the road network design, development of traffic demand, emission model integration, simulation and extraction of relevant output data for the subsequent analysis[1].

6.1 Development of Vehicle Traffic Simulation

This phase mainly focused on developing a realistic microscopic traffic simulation model for the selected study area using SUMO (Simulation of Urban MObility). To simulate vehicle traffic, two components were required, namely, the road network and vehicle demand.

6.1.1 Network Preparation

As shown in Figure 6.1, the road network for the study area was extracted from OpenStreetMap (OSM) using the SUMO Python tool OSM Web Wizard.

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[1] See 'https://github.com/Jani-90/SUMO-Simulation' for full implementation details.

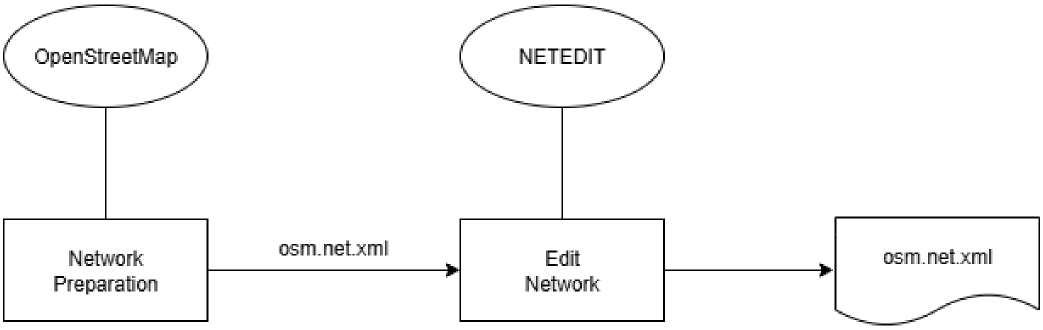
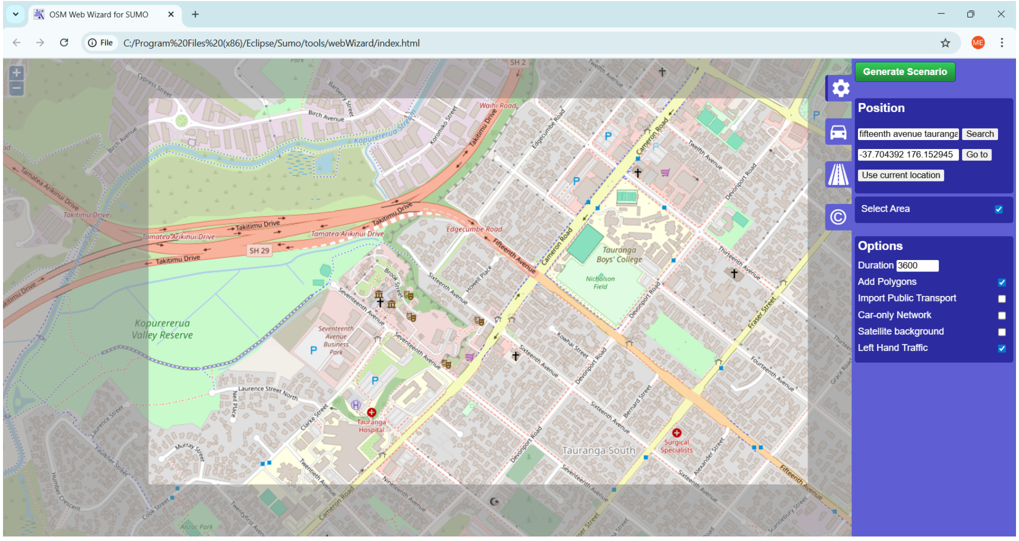


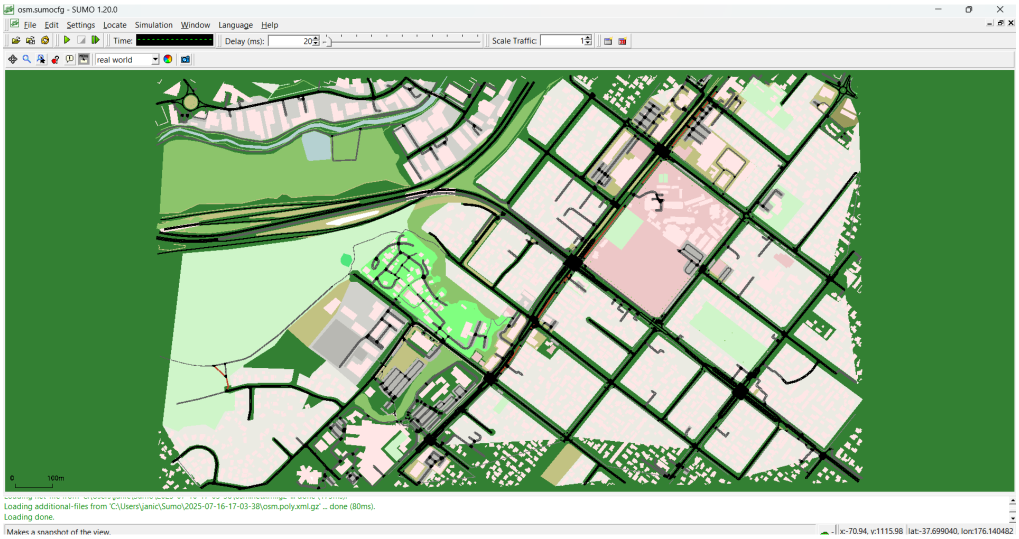
Figure 6.1: Network Preparation Process

The first step was to select and download the study area using the OSM Web Wizard, as shown in Figure 6.2 and Figure 6.3. Once downloaded, it was able to obtain the 'osm.net.xml' file, which was converted into the native network format that SUMO has been designed to use.



Position
fifteenth avenue tauranga
-37.704392 176.152945
Select Area ☑
Options
Duration 3600
Add Polygons ☑
Import Public Transport ☐
Car-only Network ☐
Satellite background ☐
Left Hand Traffic ☑

Figure 6.2: Study Area Selection in OSM Web Wizard



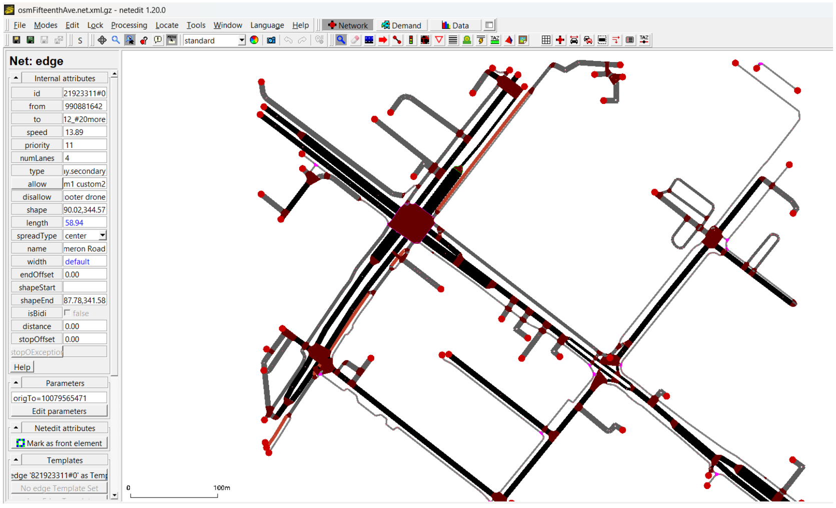
```
Loading additional-files from 'C:\Users\janic\Sumo\2025-07-16-17-03-38\osm.poly.xml.gz' ... done (80ms).
Loading done.
```

Makes a snapshot of the view.

x:-70.94, y:1115.98 lat:-37.699040, lon:176.140482

Figure 6.3: Downloaded Map in SUMO GUI

The downloaded map was then compared with the Google map to ensure that the physical characteristics and traffic control features of the study area were properly reflected in SUMO. A network editing tool, called NETEDIT, was used to correct any discrepancies between the downloaded network and the real world map. With the use of this tool, the edge connections, the number of lanes in each edge, the speed limits, the kinds of vehicles allowed, etc. could be reviewed and modified to conform to real-world conditions. The following Figure 6.4 shows the road network in the NETEDIT tool.



id	21923311#0
from	990881642
to	12_#20more
speed	13.89
priority	11
numLanes	4
type	y.secondary
allow	m1 custom2
disallow	ooter drone
shape	90.02,344.57
length	58.94
spreadType	center
name	meron Road
width	default
endOffset	0.00
shapeStart	
shapeEnd	87.78,341.58
isBidi	☐ false
distance	0.00
stopOffset	0.00
stopOExceptio	

origTo=10079565471

edge '821923311#0' as Temp

Figure 6.4: Road Network in NETEDIT View

Once refinement and validation had been completed, the final network file 'osm.net.xml' was saved to use in simulation. The following Figure 6.5 and 6.6 show the study area captured by the Google map and the corresponding study area after NETEDIT modifications.

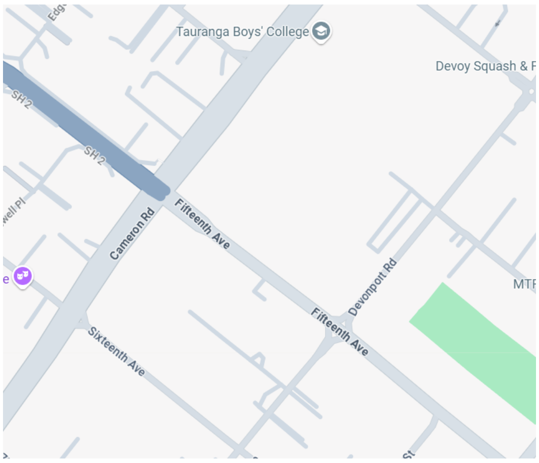


Figure 6.5: Study Area in Google Map

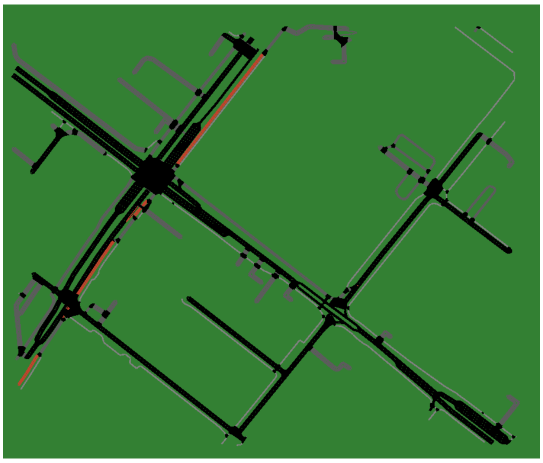


Figure 6.6: Final Network of the Study Area

6.1.2 Demand Modelling

A realistic representation of traffic demand is crucial for an accurate microscopic traffic simulation and subsequent emission assessment. This traffic demand was generated based on the available traffic volume data related to the study area. The demand file generation process can be illustrated as Figure 6.7.

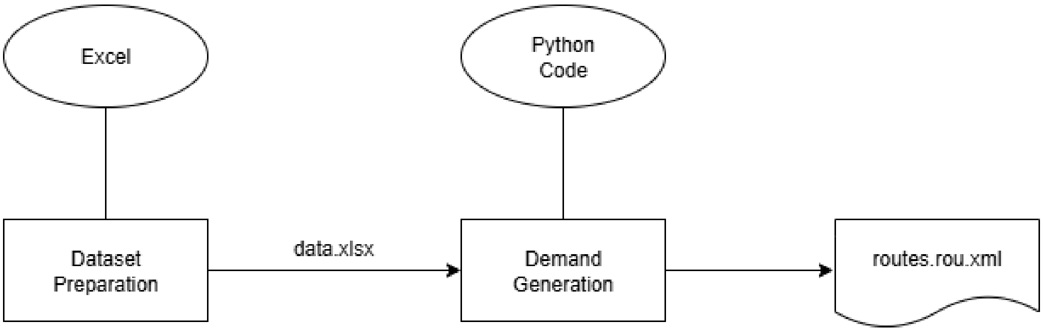


Figure 6.7: Demand Modelling Process

The data set was prepared in a specific spreadsheet format including the data regarding the total vehicle count for both directions of the road in 15 minute intervals, a list of possible routes in the study area for both directions, and vehicle category-specific data counts in each time interval for both directions. This data set included vehicle counts for a complete full day from 00:00 to 24:00 covering a total of 24 hours.

The data sheet was then converted into a dataframe using an open-source Python library called 'Pandas', and then custom Python code was used to generate the route file named 'routes.rou.xml'. This is an XML file that contains vehicle type definitions, as well as the characteristics and routes of each vehicle that needs to be simulated.

6.1.3 Vehicle Simulation

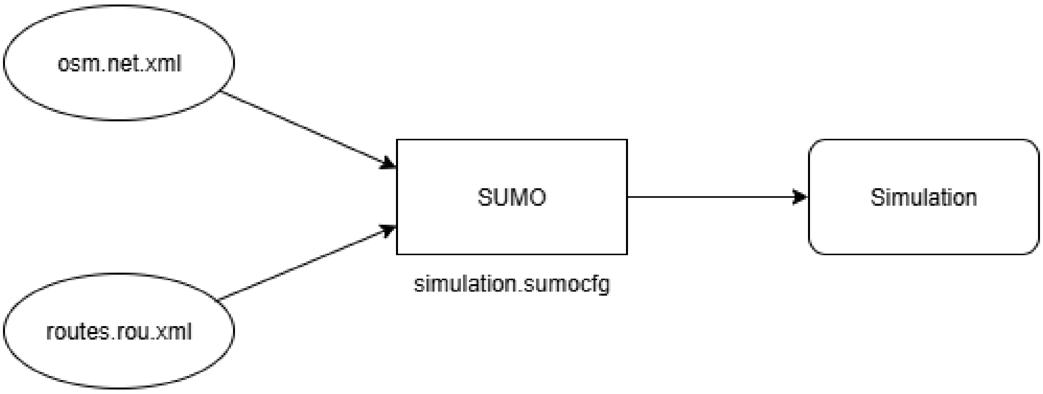
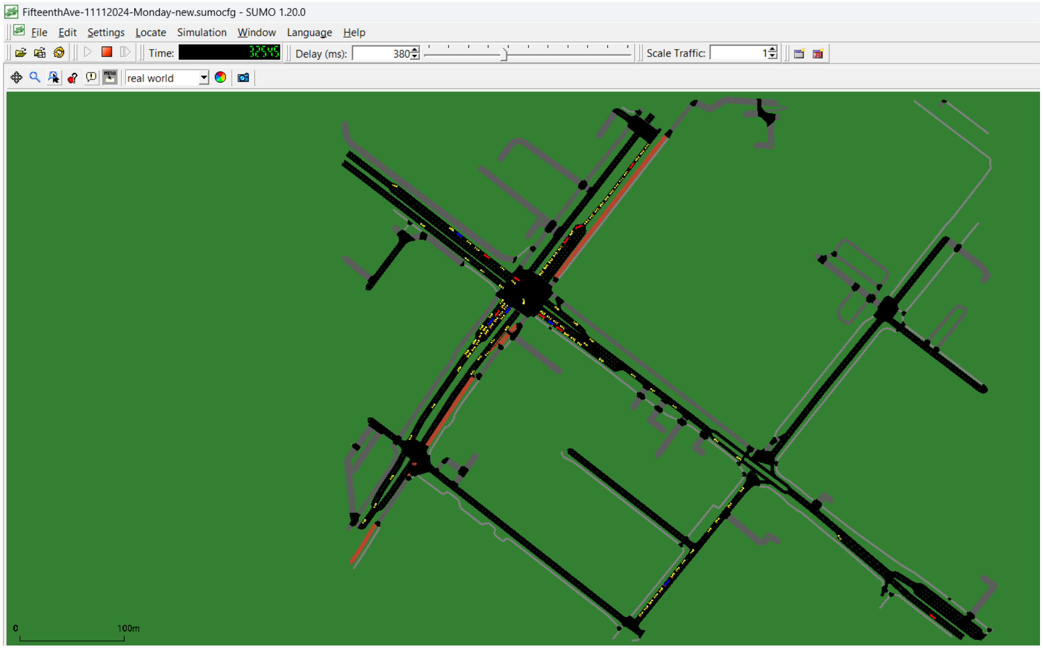


Figure 6.8: Execution of Vehicle Simulation

Following completion of the road network and traffic demand, a SUMO configuration file (.sumocfg) was used to facilitate microscopic traffic simulation.The configuration file consists of the network file, the route file, and all other inputs and parameters needed to run the simulation consistently and reproducibly.

The simulation can be viewed by opening the sumo configuration file and pressing the play button on the main menu. In order to observe the simulation clearly, it is possible to decelerate the simulation by adding a value to the box delay. Figure 6.9 and Figure 6.10 illustrate the SUMO GUI and a sample simulation scenario.



FifteenthAve-11112024-Monday-new.sumocfg - SUMO 1.20.0

Time: 32545

Delay (ms): 380

Scale Traffic: 1

real world

Figure 6.9: Screenshot of SUMO GUI

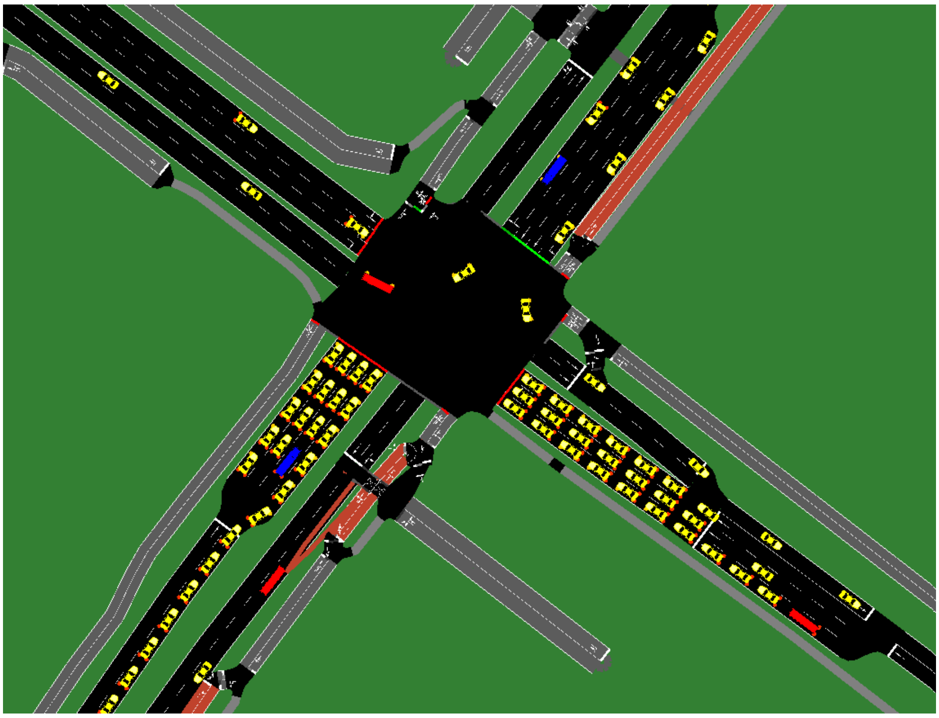


Figure 6.10: Sample Simulation Scenario

6.2 Vehicle Emission Model Integration

The second phase of this implementation involves the integration of the vehicle emission model with the vehicle traffic simulation developed in the previous phase. For realistic estimates of the pollutants emitted by vehicles, it was necessary to incorporate an appropriate vehicle emission model into the SUMO simulation framework.

6.2.1 Vehicle Emission Model

The Handbook Emission Factors for Road Transport (HBEFA) was used as the emission model for this implementation. SUMO is equipped with native support for HBEFA emission factors (version 3.1), which are used to determine the pollutant-specific emission rates for various vehicle classes under different driving conditions, including road gradient, speed, acceleration and speed at which vehicles accelerate.

According to the vehicle categories described in Section 5.3, vehicles were categorised into four categories, namely motorbikes, cars, buses and trucks. Following this, each vehicle type was assigned an HBEFA emission class based on the typical characteristics of the local fleet. Motorbikes were modelled as gasoline vehicles meeting Euro 4 standards (HBEFA3/PC_G_EU4). The HBEFA3/LDV_D_EU4 emission class was used to model the category of buses in the urban fleet, while the HBEFA3/HDV_D_EU4 emission class was used to model the truck category, reflecting the most dominant fuel type among urban fleets.

6.2.2 Emission Output Generation

After emission classes were assigned, the emission output file was generated using the command line. SUMO calculated pollutant emission values of CO_2 (carbon dioxide), CO (carbon monoxide), NO_x (nitrogen oxides), PM_x (particulate matter) for each vehicle in every simulation step and then saved the results in ‘emissions.xml’. Furthermore, this output file included fuel consumption and possibly noise values as well.

6.3 Analysis of Vehicle Emission

This phase outlines the processing, storage and analysis of raw emission data generated by the microscopic traffic simulation to derive significant insights about vehicle emissions within the study area. To efficiently analyse emission output, a NoSQL database (MongoDB) was utilised in conjunction with Python-based data processing and visualisation tools.

6.3.1 Database Management

The library called 'xml.etree.ElementTree' was used to parse the XML output obtained in the previous phase of this implementation. A custom Python script was written to collect pertinent properties, including vehicle ID, vehicle type, CO_2, CO, NO_x, PM_x, and HC values, by iterating over all vehicle entries in each timestep of the XML structure. These values were stored as individual records in a Python data structure and then bulk-inserted into the MongoDB database, as shown in Figure 6.11.

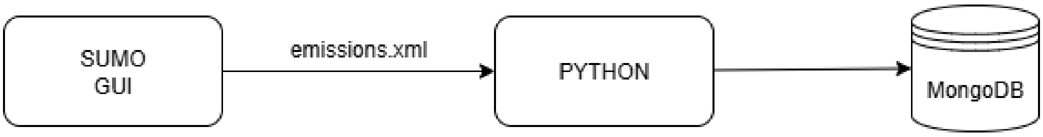


Figure 6.11: Database Management

The Python connection to the MongoDB database was established using the pymongo library. The data were uploaded to the 'emissionData' collection created in the 'SimOutputData' database.

6.3.2 Analyse Emission Data

After storing the data in MongoDB, the next step was to process and analyse the emission data to calculate emissions and compare results using various types of graphs and visualisations. In order to perform the analysis, the Pymongo library was used to connect Python to the MongoDB database, and the Pandas library was used for managing data transformations and aggregations. A number of visualisations, including pie charts, bar charts, and line graphs, were created using Matplotlib and other Python plotting tools for the clear presentation of the emission results. We describe these in more detail in the next chapter.

In addition, the simulation results were utilised to analyse the impact of variations in vehicle density and fuel type selection in light vehicles on total emission levels within the study area. The correlation between increased vehicle density and elevated emissions was visualised using several graphs. In parallel, the study examined the impact of the fuel type composition within the light vehicle fleet on overall emissions.

6.4 Summary

In summary, this chapter outlined the step-by-step development process of the traffic simulation with emission model integration. First, a traffic simulation model was developed using SUMO by modelling the road network model and vehicle demand. Then, HBEFA emission model was integrated with the traffic simulation to generate the emission output. MongoDB was used as the database to store the generated emission output in order to conduct the thorough analysis of the emission results. The results were then visualised for the clear understanding of the emission patterns and trends across different scenarios. The results obtained through this simulation and emission analysis process will be discussed in detailed in the next chapter.

Chapter 7

Results and Evaluation

This chapter presents the results obtained from the traffic simulation and vehicle emission modelling conducted in Tauranga. Our objective was to assess the current state of vehicle emissions within the Tauranga urban road network and to evaluate the potential impact of identified emission reduction strategies. In this study, the real-world scenario was compared with the proposed emission reduction strategies, such as increasing electric vehicle usage, deployment of trackless trams, and promoting carpooling.

7.1 Real-world Scenario: Investigation on Current Emissions

The real-world scenario presented the current state of traffic conditions in Tauranga. As discussed in Section 5.2, the analysis was carried out at the three sites, namely the Cameron Road - Fifteenth Avenue intersection, Newton Street, and Turret Road based on the traffic congestion level and the data availability. According to reports and observations of traffic patterns on Google maps, these areas were identified as having high levels of congestion. Thus, this simulation plays an important role in analysing vehicle emissions at these sites and evaluating the efficiency of possible emission reduction measures. An example of a screen shot from each of the three simulation sites can be found in Figure 7.1, 7.2 and 7.3.

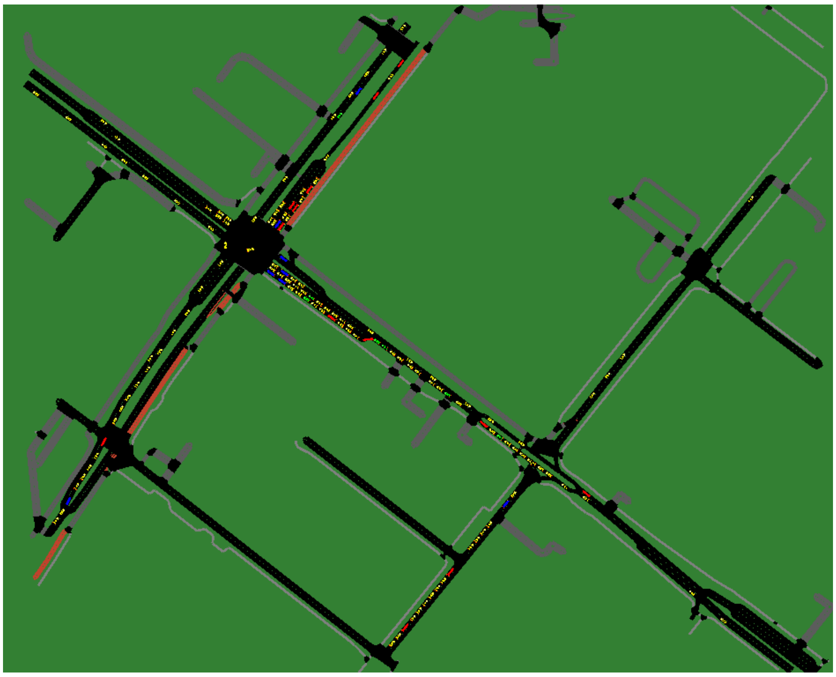


Figure 7.1: Simulation of Cameron Road - Fifteenth Avenue intersection

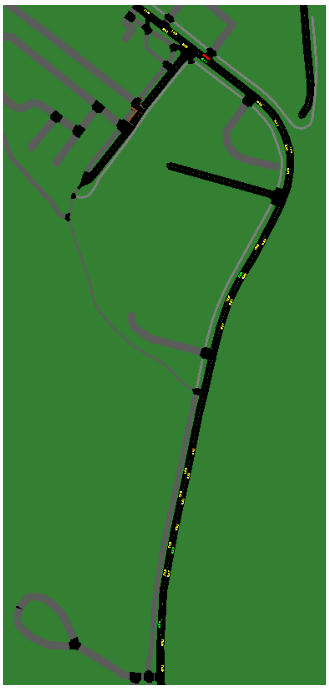


Figure 7.2: Simulation of Turret Road

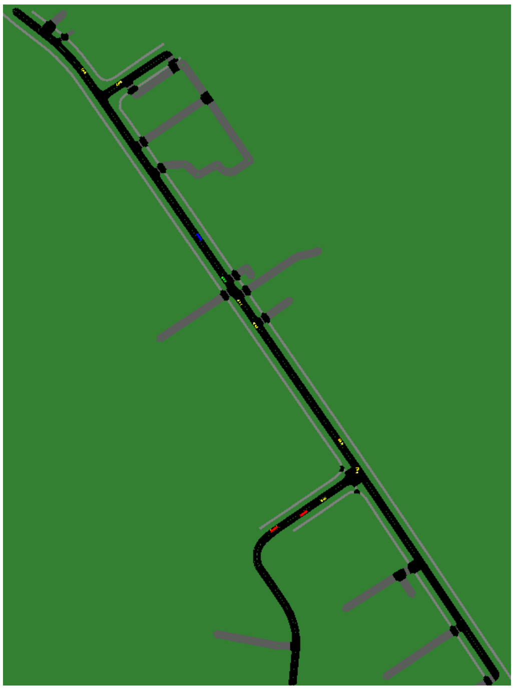


Figure 7.3: Simulation of Newton Street

The yellow, purple, red, and blue colours represent light-duty vehicles, motorbikes, buses or mini trucks, and heavy-duty vehicles, respectively. Green is the colour of electric vehicles, as seen in the following Figure 7.4.

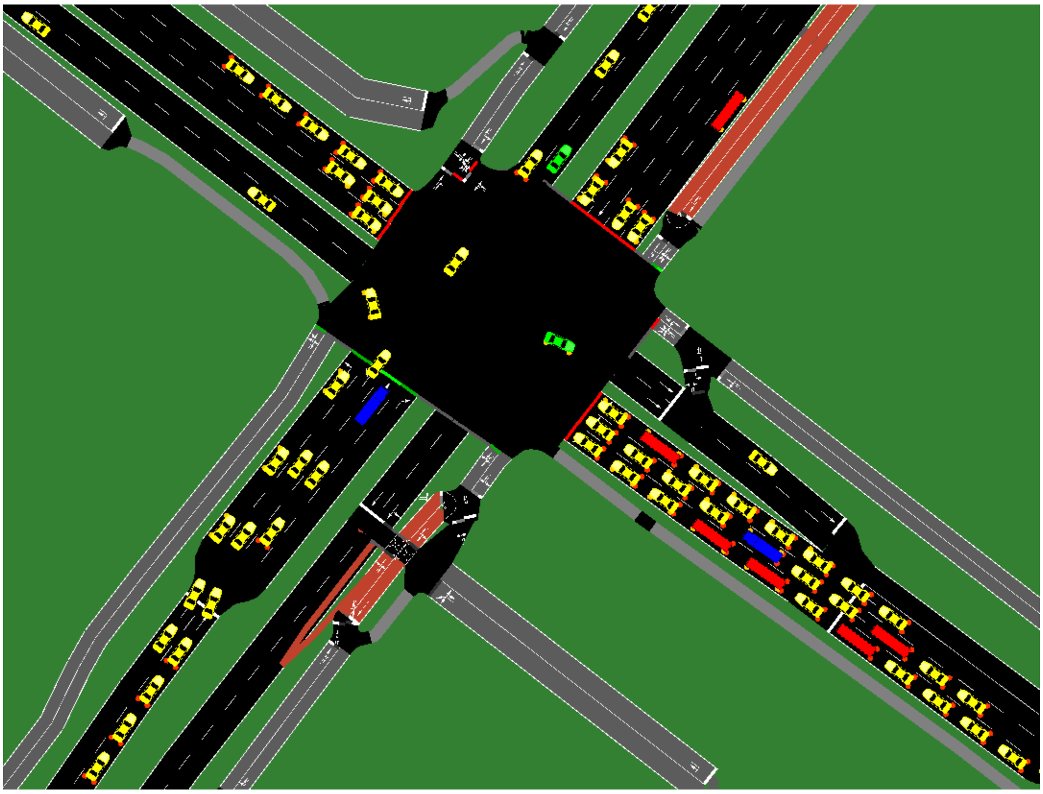


Figure 7.4: Colour Coded Vehicle Categories

Hourly vehicle volumes from 00:00 to 24:00 were simulated for each site and analysed to identify traffic patterns throughout the day, as illustrated in the following figures. In order to gain a better understanding of daily variations, simulations were conducted for seven consecutive days from Monday to Sunday, and the resulting vehicle volumes were plotted to highlight weekly traffic trends.

Figure 7.5 shows the Cameron Road - Fifteenth Avenue intersection illustrating the variation in vehicle volume over the 24-hour period for each consecutive day. The line graph was suitable for visualising variations in vehicle count as discussed in the literature review [44]. In the graph, each point represents the total number of vehicles recorded per hour, which provides insight into daily traffic flow patterns. The graph indicates that, on Monday through Friday, there are usually two distinct peaks: one in the morning, between 7:00 and 10:00, and another in the evening, between 13:00

and 18:00. These peaks align with the typical times people commute to work and school. Traffic volume generally remains moderate between these peaks, with the lowest levels observed in the late night and early morning hours. Weekend traffic volume is typically lower than weekday traffic volume, and the vehicle volume pattern is also different from the weekday pattern, indicating peak hours around 09:00 to 16:00. However, vehicle count during weekends is low compared to weekdays.

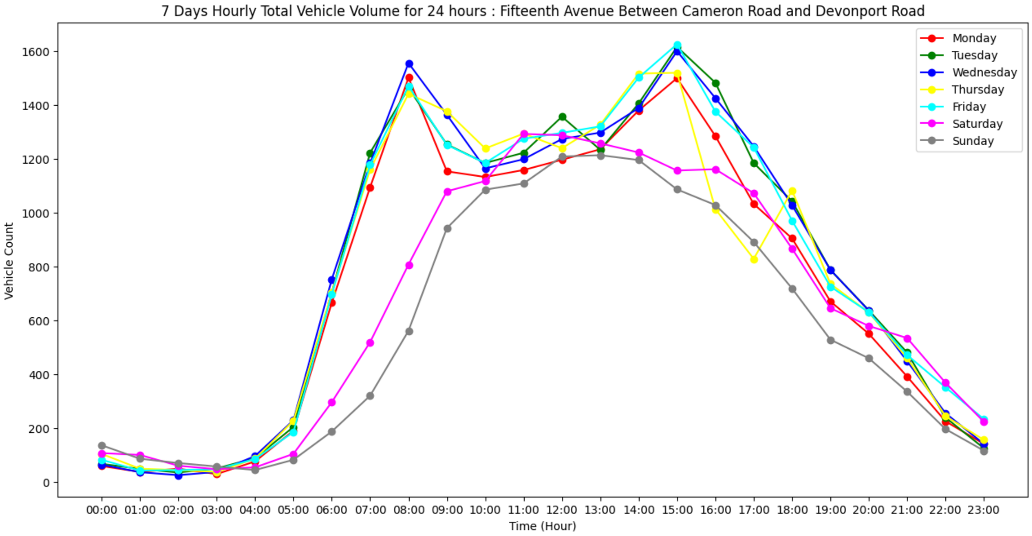


Figure 7.5: Hourly Vehicle Volume - Fifteenth Avenue

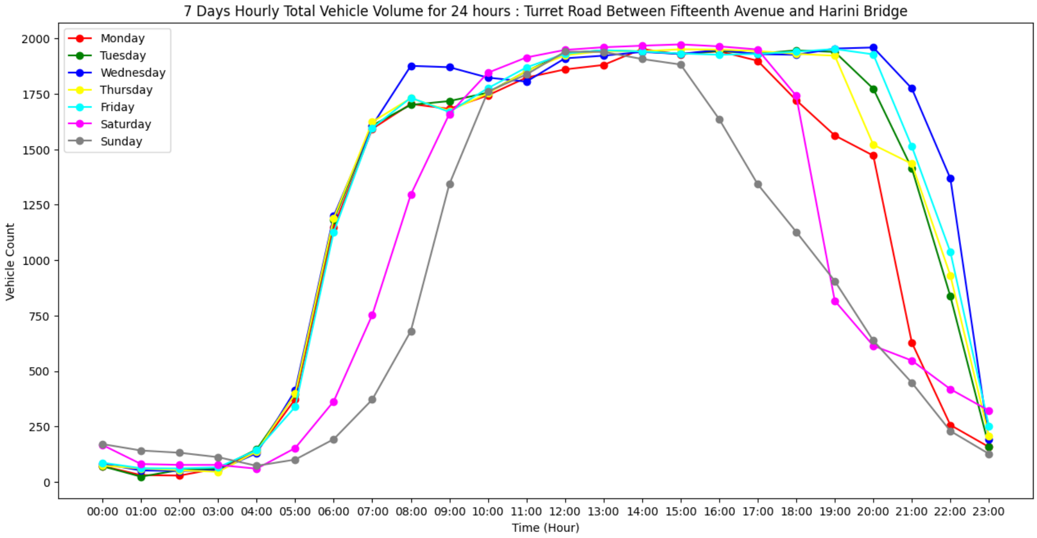


Figure 7.6: Hourly Vehicle Volume - Turret Road

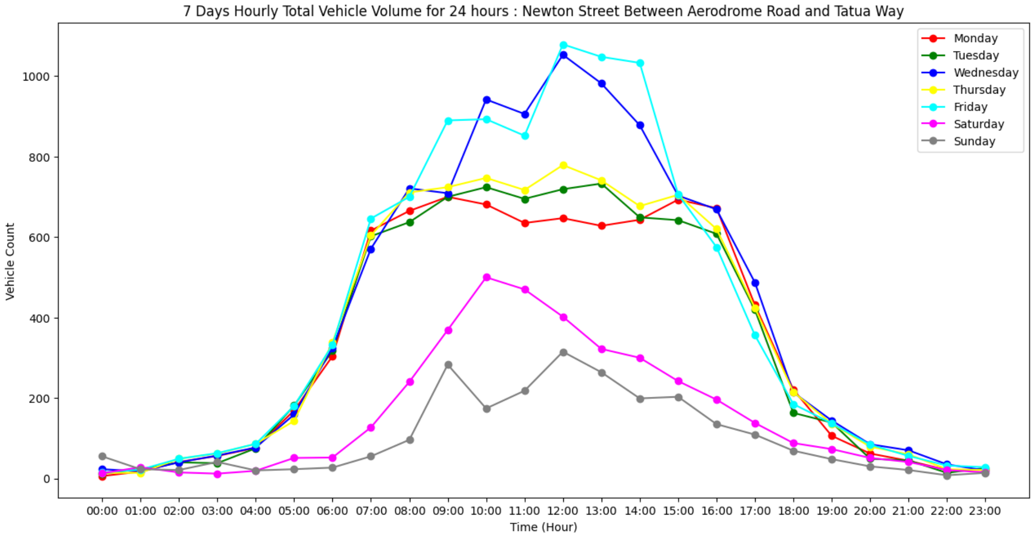
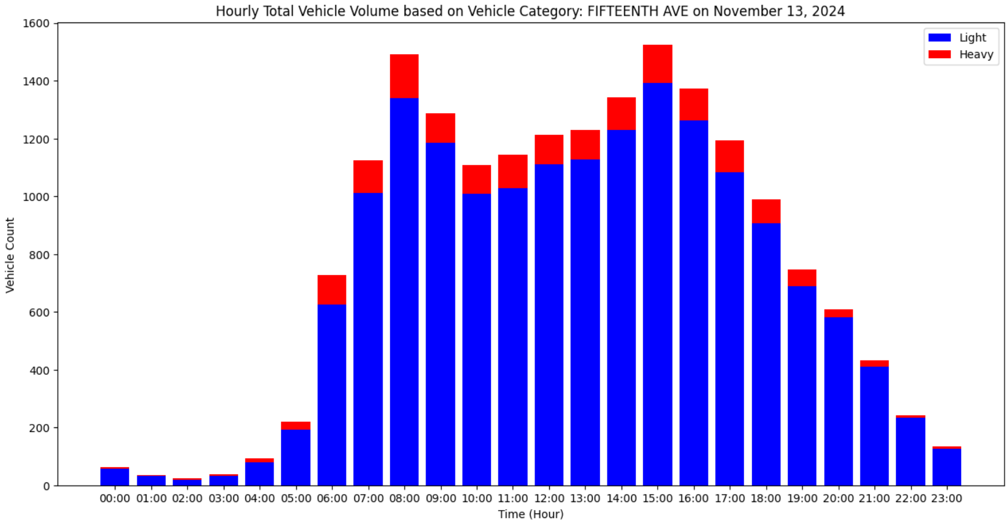


Figure 7.7: Hourly Vehicle Volume - Newton Street

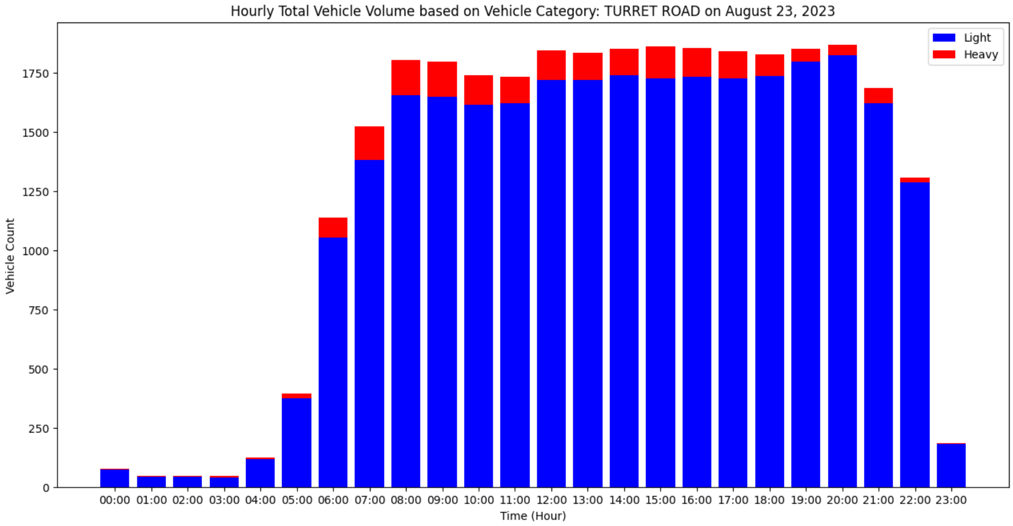
Figure 7.6 above illustrates the daily volume of vehicles travelling along Turret Road on an hourly basis. The vehicle pattern for each consecutive day is colour coded, and the peak volume of vehicles remains the same between 8:00 and 20:00 with the highest peak for weekdays. According to the graph, Wednesday can be identified as the highest vehicle volume with its peak occurring between 8:00 and 21:00. In this area, there is a steady peak in vehicle volume, which is slightly different from the pattern observed at the first site. As part of this site, the Harini Bridge is located, where the speed of the road is limited to 50 km/h. In addition, this road only has one lane in each direction, which limits traffic movement during rush hours. Consequently, this limited capacity worsens the congestion on this road, resulting in a steady peak in traffic.

A graph illustrating the daily traffic volume pattern on Newton Street for each consecutive day is shown in Figure 7.7. Typically, its peak hours begin at 7:00 in the morning and last until about 16:00 in the evening, which corresponds to the movements of vehicles in the industrial area. On Wednesday and Friday, the pattern appears to be similar, however there is a visible difference from the other three weekdays with the highest volume approaching at 12:00. During the weekends, there is a reduction in vehicle traffic, with Sunday showing the lowest traffic volume.

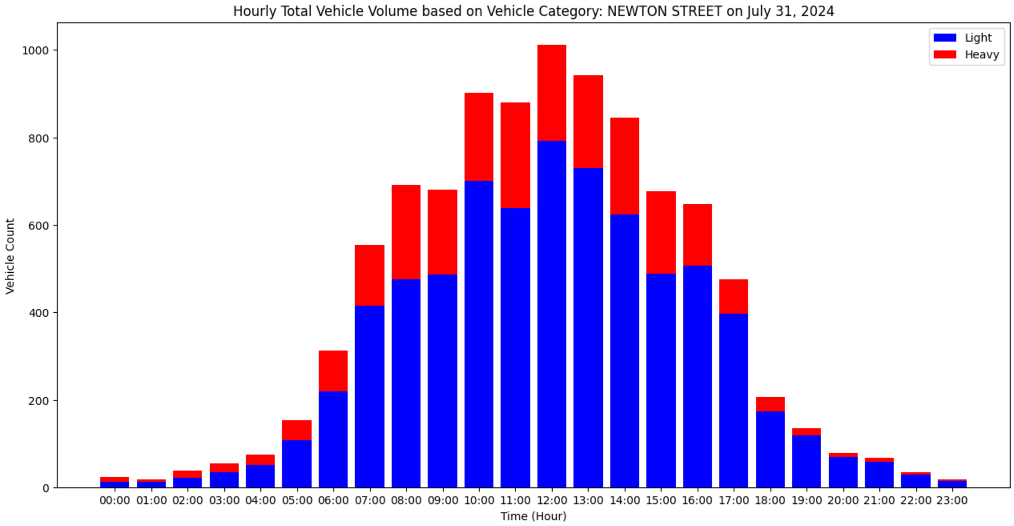
There is a significant difference in the patterns of vehicle volume between the three sites based on road conditions, speed limits, and area-specific variables such as a residential or industrial environment. Considering the vehicle volume patterns shown in the three graphs above, Wednesday was selected as the day for further analysis of vehicle categories, since it is commonly identified as a day with the highest vehicle volume.



(a) Fifteenth Avenue



(b) Turret Road

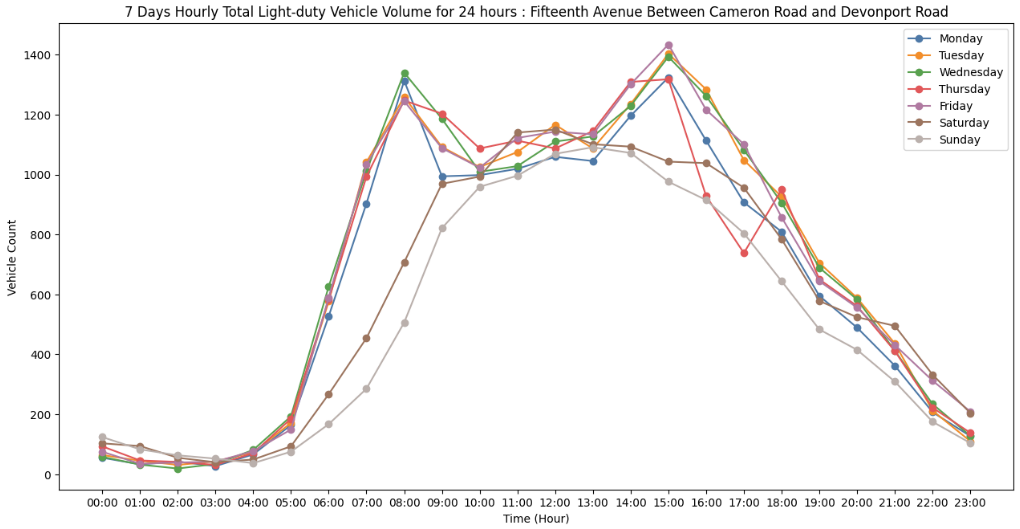


(c) Newton Street

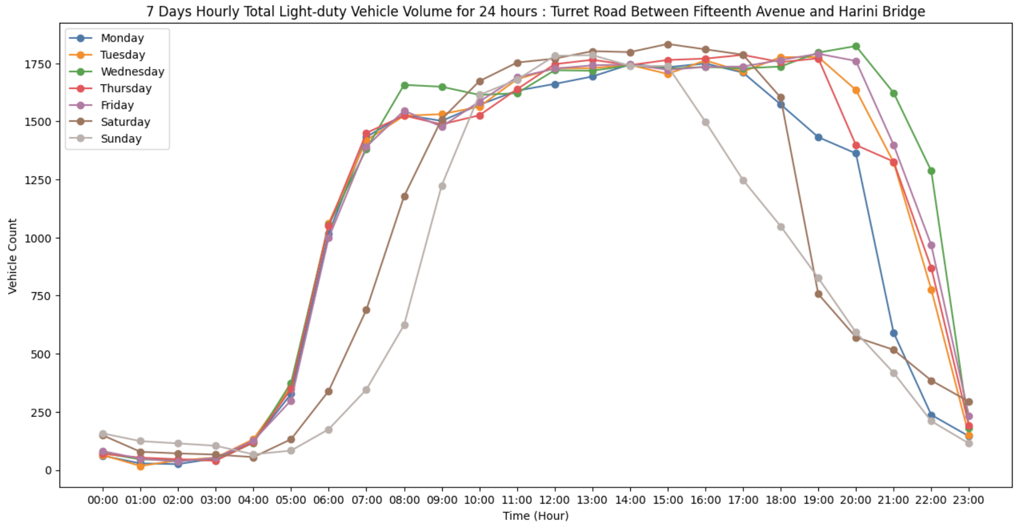
Figure 7.8: Vehicle volume based on Vehicle Category

Figure 7.8 illustrates the volume of light and heavy vehicles recorded on different Wednesdays at each site based on the data availability. These graphs illustrate the hourly distribution of each category, which gives an indication of the composition of traffic throughout the day. According to the graphs, light duty vehicles dominated the vast majority of the total vehicle volume at the three simulated sites. Furthermore, by comparing the three graphs, a high volume of heavy duty vehicles can be observed on Newton Street due to the fact that this area is located within Tauranga's industrial zone.

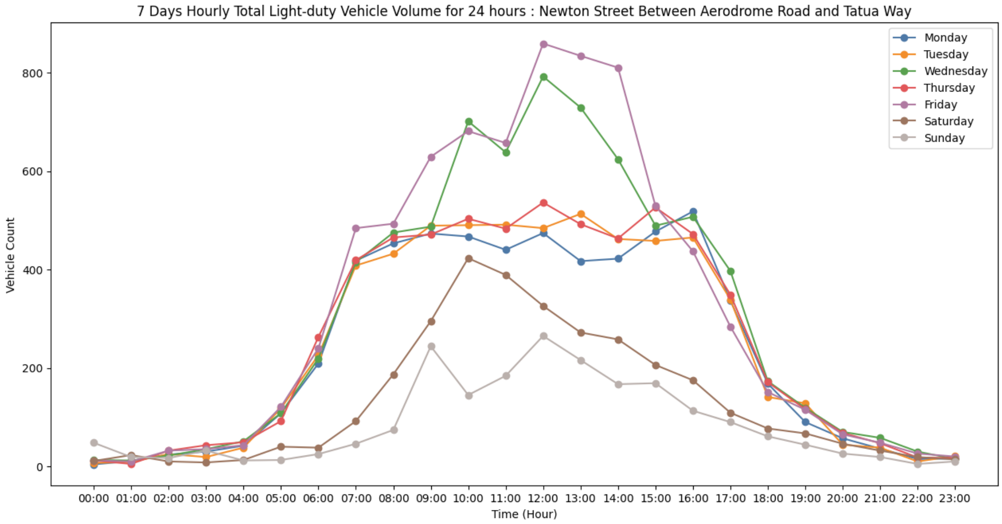
As this research focused on the vehicle emission analysis of light-duty vehicles, the vehicle volume pattern of light-duty vehicles was plotted separately, as shown in Figure 7.9. It illustrates the hourly vehicle volume patterns of light-duty vehicles at each respective site. It is noted that the vehicle volume pattern of light-duty vehicles in each graph is similar to that of the total vehicle volume graphs discussed previously, however, the number of vehicles is slightly reduced.



(a) Fifteenth Avenue



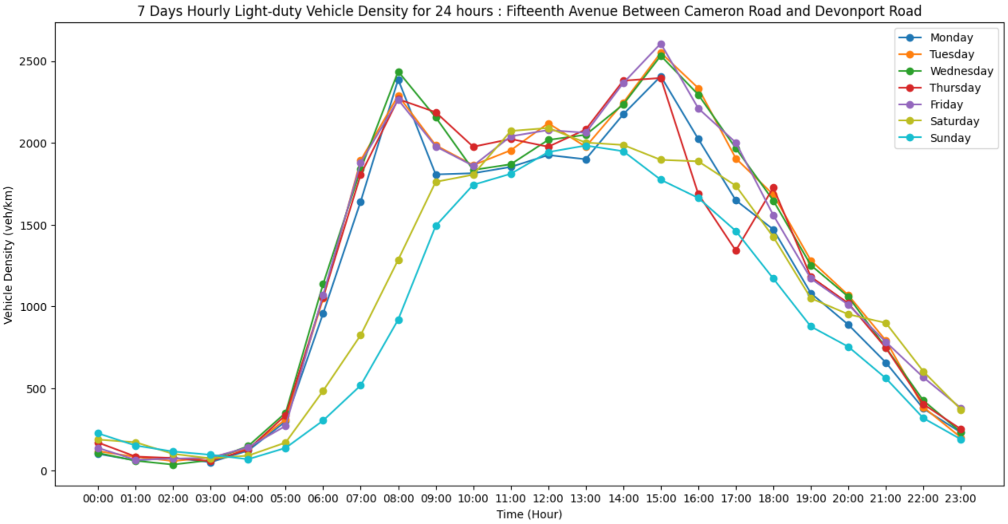
(b) Turret Road



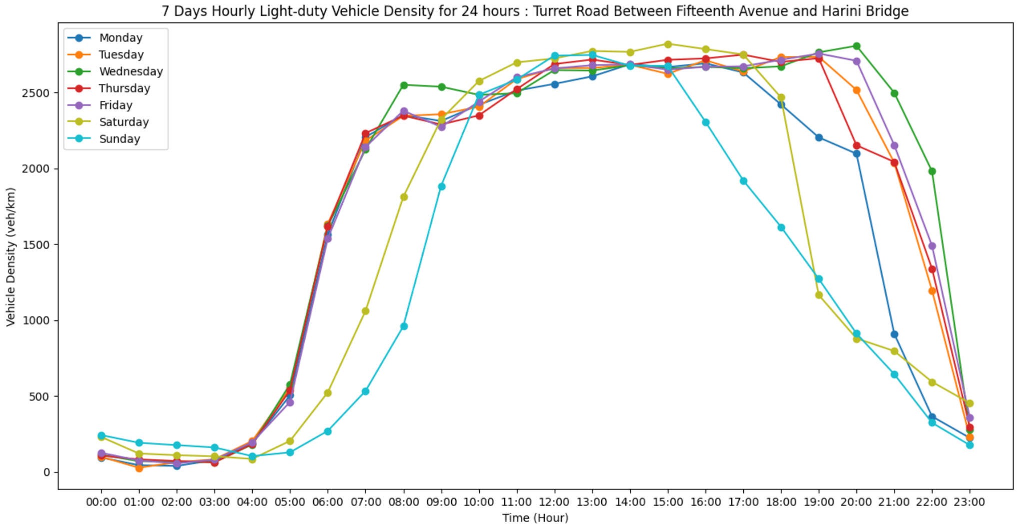
(c) Newton Street

Figure 7.9: Vehicle volume of Light-duty vehicles

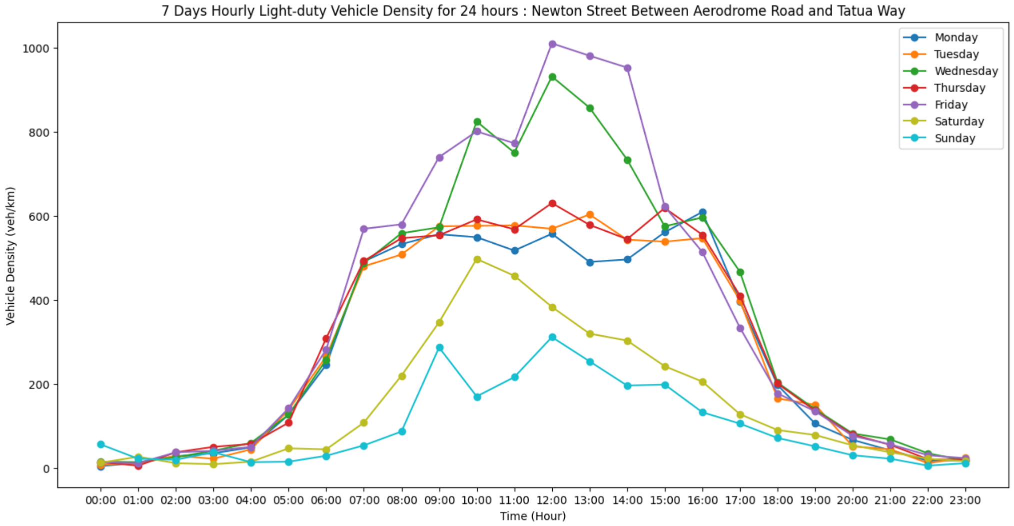
Figure 7.10 demonstrates the hourly vehicle density at each site, providing an indication of the site-specific traffic patterns and their temporal variations throughout the day. This will enable us to present emission reduction strategies based on the traffic patterns of each site.



(a) Fifteenth Avenue



(b) Turret Road



(c) Newton Street

Figure 7.10: Hourly Vehicle Density of Light-duty vehicles

7.1.1 Cameron Road Fifteenth Avenue Intersection

Figure 7.11 illustrates the emission components of light-duty vehicles at the intersection of Cameron Road Fifteenth Avenue. The graph illustrates the fluctuations in carbon dioxide (CO_2) emission recorded throughout the simulated period.

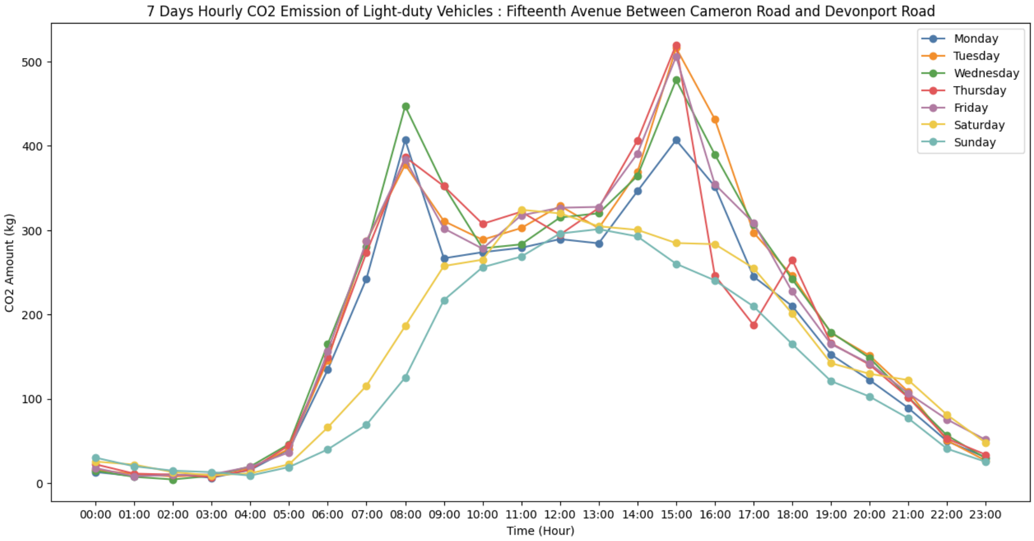


Figure 7.11: Hourly CO_2 Emission - Fifteenth Avenue

The graph shows a high level of emissions during the morning and evening peak hours on working days, as indicated by the graphs 7.11. During the weekend, its peak emissions are around mid-afternoon, which is lower than during the weekdays. Hence, it is important to take precautions to reduce vehicle emissions during these peak periods based on the emission patterns identified.

As can be seen in the above graph, we can observe a similar pattern, showing a close correlation between the volume of vehicles and their emissions, which is to be expected.

A summary of the daily total emission of each pollutant during the simulation can be found in Table 7.1.

Table 7.1: Daily Total Emission by Pollutant - Fifteenth Avenue

Day	**CO_2 (kg)**	**CO (kg)**	**HC (kg)**	**NO_x (kg)**	**PM_x (kg)**
Monday	4274.3585	116.7351	0.6282	1.7740	0.0823
Tuesday	4820.7271	136.7678	0.7322	2.0088	0.0941
Wednesday	4837.5009	137.3866	0.7354	2.0163	0.0946
Thursday	4642.7021	132.0064	0.7061	1.9346	0.0906
Friday	4807.3876	134.4729	0.7216	2.0007	0.0936

Saturday	3789.1127	98.2881	0.5335	1.5654	0.0722
Sunday	3212.0744	81.6944	0.4445	1.3247	0.0609

Based on the results, Wednesday has the highest emissions, equivalent to 4837.5009 kg of carbon dioxide. CO_2 and CO are the two main contributors to vehicle emissions on Fifteenth Avenue. Since the simulated area is approximately 0.25 km^2, the vehicle emission intensity on Wednesday is equal to 19.35 tCO_2-e/km^2/day. This value is high compared to the national average of transport emission in New Zealand, which is equal to 0.34 tCO_2-e/km^2/day [52].

7.1.2 Turret Road

In order to examine different emission patterns for each site, the analysis was repeated for each site separately. Figure 7.12 illustrates the variation of CO_2 emission during the simulation of the Turret Road. The emission pattern of this site is different from the previous site, showing a steady peak similar to the pattern of vehicle volume observed at Turret Road. There is a high level of emissions in this area during working days, from morning until evening, however, during weekends, the emission is high only during the mid-afternoon period.

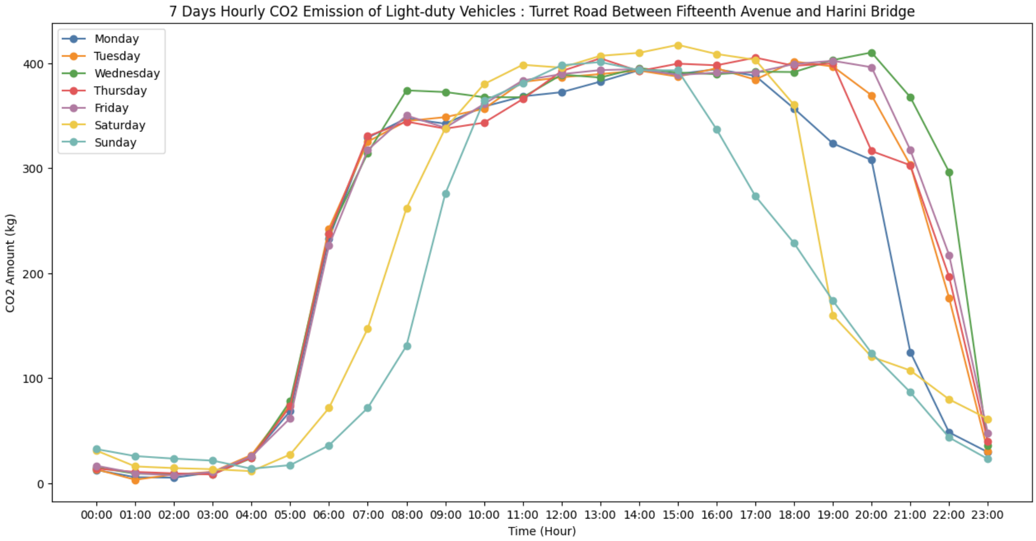


Figure 7.12: Hourly CO_2 Emission - Turret Road

Table 7.2 below outlines the contribution of each pollutant towards the total vehicle emissions on Turret Road. The highest emission volume is recorded on Wednesdays, similar to Fifteenth Avenue, and weekend emission levels are significantly lower than those experienced during the weekdays. Almost all offices and institutes are operating at full capacity in the middle of the week and the majority of employees are commuting to work during this time. Therefore, vehicle emissions are high as a result of the large number of vehicles. Due to the fact that most offices, schools, and other institutes are closed on weekends, there are fewer emissions compared to weekdays.

Table 7.2: Daily Total Emission by Pollutant - Turret Road

Day	**CO_2 (kg)**	**CO (kg)**	**HC (kg)**	**NO_x (kg)**	**PM_x (kg)**
Monday	5616.4408	72.4448	0.4556	2.2095	0.0906
Tuesday	6149.5244	79.5127	0.5000	2.4206	0.0993
Wednesday	6424.1286	83.0019	0.5217	2.5280	0.1033
Thursday	6142.8924	79.2886	0.4988	2.4172	0.0991
Friday	6235.6677	80.5288	0.5065	2.4537	0.1008
Saturday	5040.4591	64.2015	0.4047	1.9778	0.0807
Sunday	4267.8881	53.8356	0.3402	1.6710	0.0681

7.1.3 Newton Street

Figure 7.13 demonstrated the emission patterns of CO_2 recorded during the simulation of the Newton Street area. According to the results, high emission volumes are observed on Wednesday and Friday, whereas moderate emission volumes are observed on Monday, Tuesday, and Thursday. Similar to the other two sites, low emission volumes can be observed on Saturday and Sunday. In terms of the emission pattern, it is slightly different from that of the other two sites; however, it follows the pattern of the vehicle volume of this site, which we have previously discussed. In addition, we observe that the vehicle emission pattern for each of the three sites is similar to that of the vehicle volume.

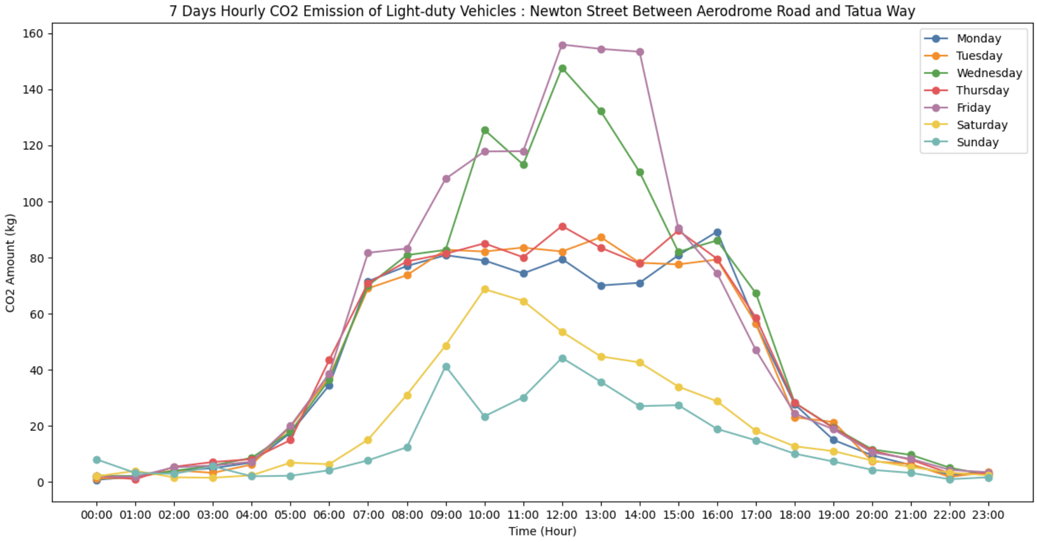


Figure 7.13: Hourly CO_2 Emission - Newton Street

Due to the fact that this research was primarily focused on light-duty vehicles, the figures above illustrate only emissions from light-duty vehicles. The Table 7.3 below summarises the daily total emission volumes based on pollutants.

Table 7.3: Daily Total Emission by Pollutant - Newton Street

Day	**CO_2 (kg)**	**CO (kg)**	**HC (kg)**	**NO_x (kg)**	**PM_x (kg)**
Monday	960.2424	14.1332	0.0856	0.3800	0.0156
Tuesday	985.8181	14.3703	0.0874	0.3899	0.0160
Wednesday	1248.3812	19.8198	0.1183	0.4969	0.0207
Thursday	1027.8858	15.1228	0.0919	0.4069	0.0167
Friday	1331.6033	21.6975	0.1286	0.5308	0.0225
Saturday	513.2400	7.0784	0.0437	0.2019	0.0082
Sunday	334.8102	4.5996	0.0283	0.1319	0.0052

7.1.4 Current Emissions

The results of the study reveal that there are significant amounts of emissions emitted to the environment on a daily basis. Among the five principal pollutants, carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM_x), CO_2 represents the largest proportion of total emissions across all simulated sites. The contribution of CO to total emissions is relatively small, while the contribution of other pollutants is negligible. Wednesday has the highest CO_2 emission in the Fifteenth Avenue and Turret Road area, which is equivalent to 4837.5009 kg and 6424.1286 kg, respectively. In the Newton Street area, the highest daily CO_2 emission is on Friday, which is equal to 1331.6033 kg.

Hence, it is necessary to mitigate the effects of vehicle emissions. In order to determine the appropriate emission reduction strategies, it is essential to perform a detailed analysis of the emission results and the factors that affect vehicle emissions. Figure 7.14 illustrates the relationship between vehicle emissions and vehicle density related to light-duty vehicles. With low densities, the graph appears linear; however, with high densities, CO_2 emissions increase faster than density, creating a polynomial curve of degree three.

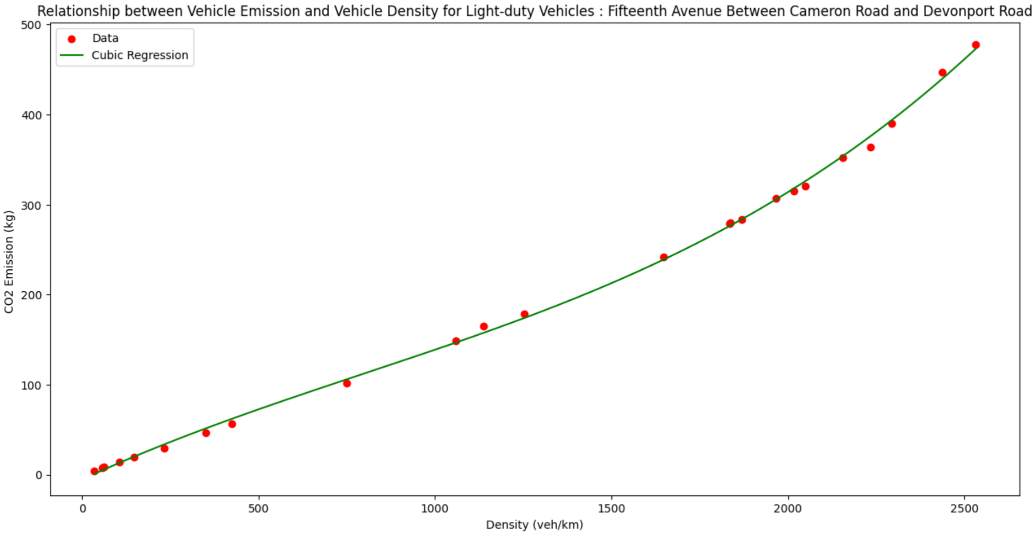


Figure 7.14: Relationship between Vehicle Emission and Vehicle Density for Light-duty Vehicles

Figure 7.15: Vehicle Emission Effects based on Fuel type

Figure 7.15 shows how the fuel type used in vehicles can have an effect on vehicle emissions. In order to simulate this scenario, further 10% of petrol cars in the real-world scenario were replaced with electric cars. As shown in the figure above, there is a significant reduction in vehicle emissions after switching to electric fuel.

Based on the results, it is clear that the vehicle density and the vehicle fuel type are directly correlated with the vehicle emissions. It is therefore necessary to minimise the vehicle density and change the fuel type into a low-emission fuel type in order to reduce the vehicle emissions. Various types of interventions can be implemented to minimise vehicle density, including promoting public transportation, carpooling, and cycling. The reduction in the number of vehicles on the road not only reduces vehicle emissions but also reduces the congestion on the roads. Furthermore, it is possible to greatly mitigate the negative consequences of these emissions by transitioning to alternative low-emission vehicles, such as electric vehicles. It is clear that a reduction in the number of vehicles can reduce the overall demand for fuel, while cleaner fuel ensures a reduction in pollution. The application of appropriate interventions based on these two approaches is therefore crucial in reducing vehicle emissions.

7.2 Emission Reduction Strategies

As part of this study, several practical recommendations were developed for the reduction of transport-related emissions in the Bay of Plenty region based on the analysis of vehicle emissions generated from microscopic traffic simulations. Based on the effectiveness and the feasibility, three specific emission reduction strategies were suggested for the Bay of Plenty region: expanding the use of electric vehicles, introducing trackless trams as an innovative public transport option, and promoting carpooling to reduce the number of single-occupancy vehicles on the road.

7.2.1 Scenario 1: Increasing Electric Vehicle Usage

This scenario involves the replacement of light-duty petrol vehicles with electric vehicles by 20%. This Figure 7.16 shows an example simulation scenario with electric vehicles coloured green. It is important to point out that in this scenario, the number of vehicles remained the same, but the type of fuel has changed.

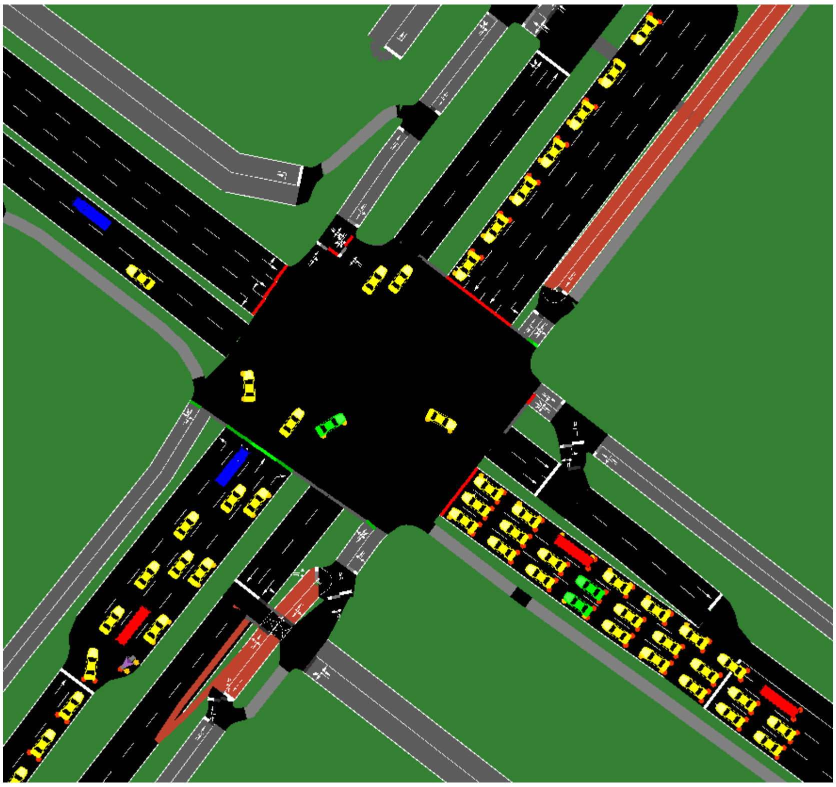


Figure 7.16: Sample Simulation with Electric Vehicles

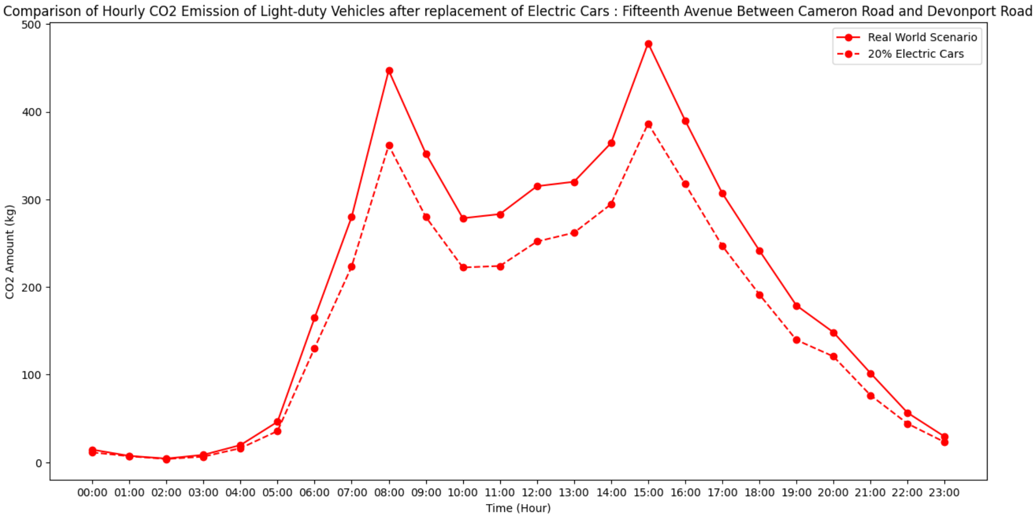


Figure 7.17: Emission Analysis with Electric Vehicles

As shown in Figure 7.17, there is a significant reduction in CO_2 emission after replacing 20% petrol cars with electric cars. This highlights the potential of electric vehicles in terms of mitigating vehicle emissions. Since the number of vehicles in this scenario remains the same, this does not contribute to reducing the level of traffic congestion.

7.2.2 Scenario 2: Deployment of Trackless Trams

Trackless trams were modelled as part of the emission reduction scenarios explored in this research in order to assess their ability to reduce private vehicle usage and associated emissions. A new vehicle category was created in the SUMO demand files to reflect the trackless tram, defining an extended vehicle length, increased passenger capacity, and an electric-powered system with zero emissions to accurately replicate its real-world configuration.

In this scenario, the trackless tram was designed to carry 200 passengers and was assumed to be occupied 50% at a time. Hence, a hundred single passenger cars were replaced with one trackless tram. Two trackless trams were operating every hour in each direction of the road from 7.00 a.m. to 6.00 p.m. A screenshot of the implemented simulation scenario is shown in Figure 7.18.

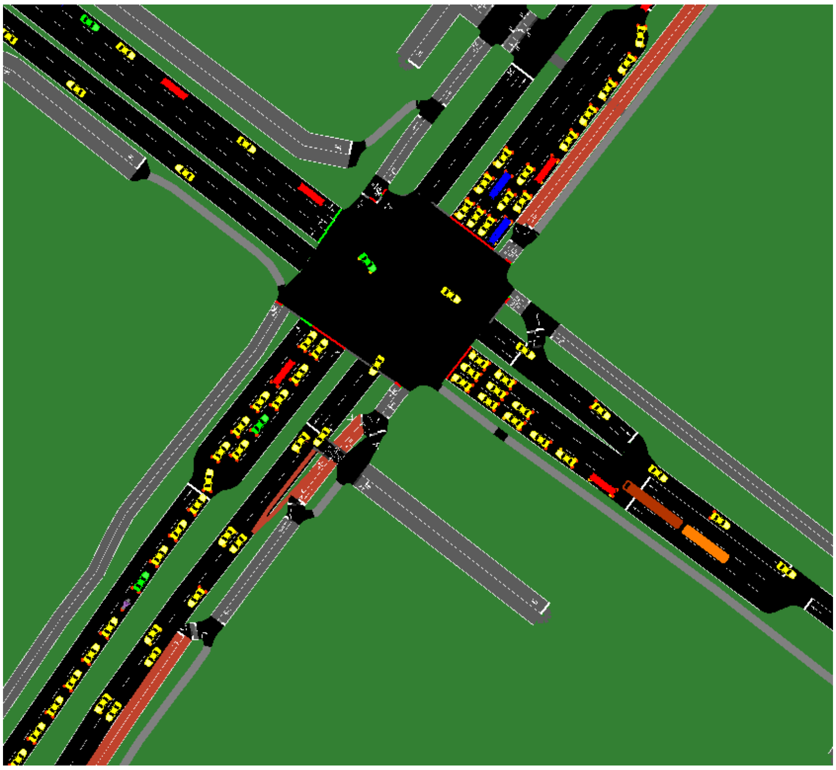


Figure 7.18: Screenshot of Simulation with Trackless Tram

As shown in Figure 7.19, there is a significant reduction in vehicle emissions after introducing trackless trams into the simulation. Therefore, this is an alternative mode of transportation that provides a high-capacity, zero-emission transport option. In addition, its high passenger capacity not only helps to minimise vehicle emissions, but also to reduce traffic congestion in the area by reducing the number of vehicles. Compared to buses, trackless trams have the advantage of carrying more passengers at a time while reducing vehicle volume. In order to make this uptake more realistic, this deployment requires capital investment and government support to succeed in this long-term plan.

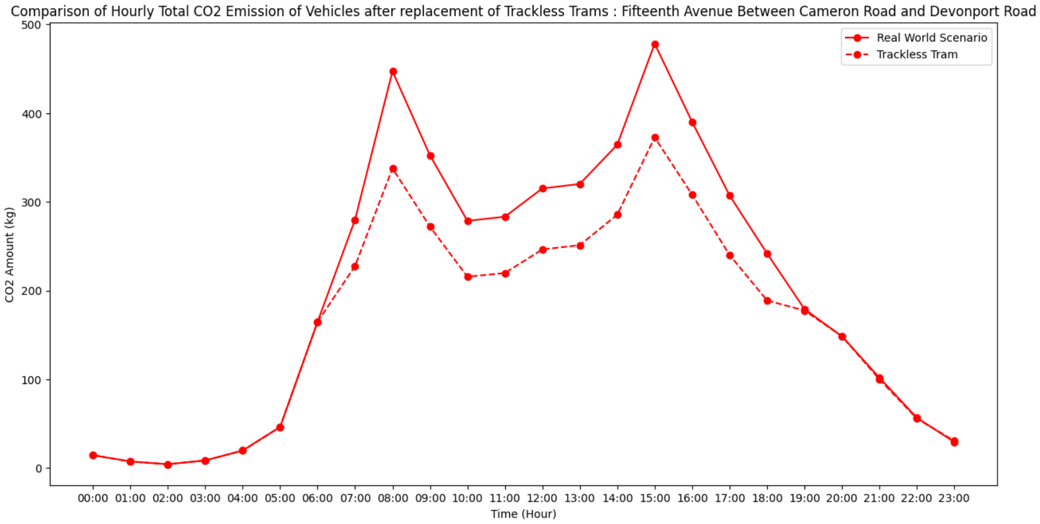


Figure 7.19: Emission Analysis with Trackless Tram

7.2.3 Scenario 3: Promoting Carpooling

A carpooling scenario was created within the SUMO microscopic traffic simulation to evaluate the efficacy of carpooling as an effective approach to minimising vehicle emissions. A carpool car was introduced into the simulation, which could accommodate four passengers at a time.

This scenario was implemented by replacing four single-passenger cars with one carpooling car that covered the same route, and 20% cars in the real-world simulation were replaced by carpooling cars. To implement this scenario in the real world, carpooling apps must be introduced to find riders travelling on similar routes and at similar times. In the following Figure 7.20, a carpooling scenario is presented, and the car pool car is shown in light blue.

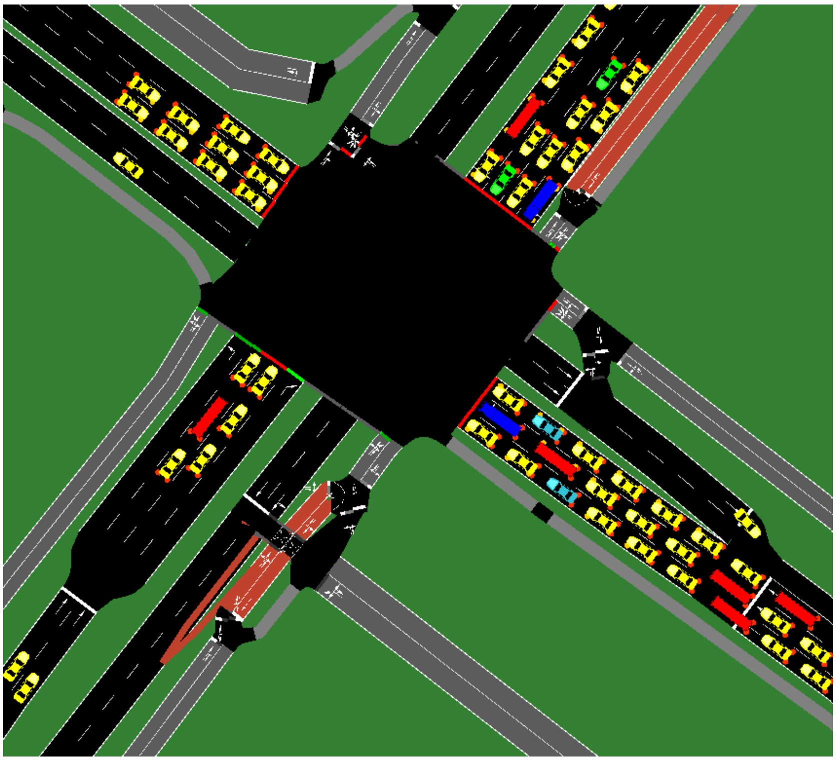


Figure 7.20: Simulation of Carpooling Cars

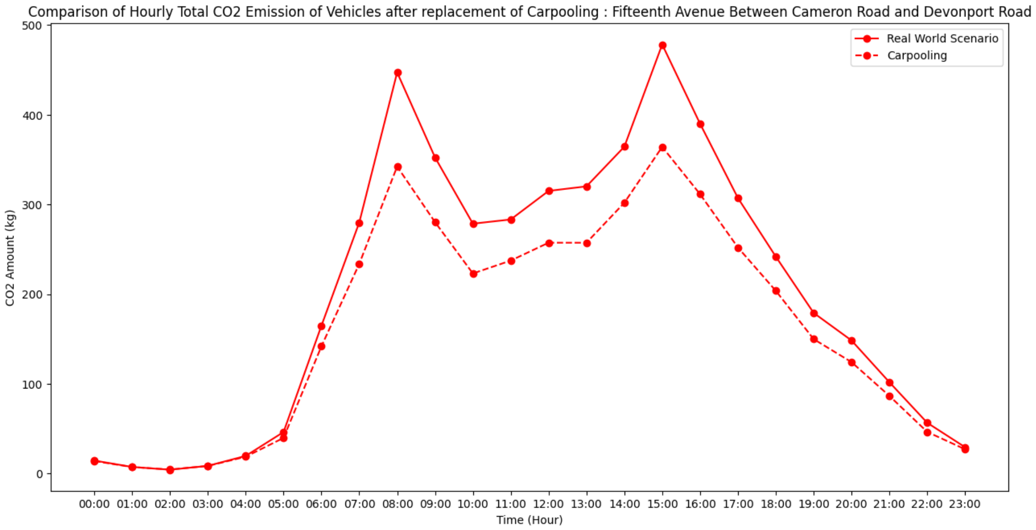


Figure 7.21: Emission Analysis with Carpooling Cars

Figure 7.21 shows the reduction in CO_2 emission level when compared to the baseline scenario. Therefore, this carpooling option is also helpful in mitigating vehicle emissions as well as traffic congestion due to the low vehicle density.

7.3 Comparative Analysis

The emission results for each scenario can be summarised in Table 7.4 to evaluate the effectiveness of each strategy in reducing emissions. We conducted a comparative analysis to quantify the change in total carbon dioxide in comparison with real-world situation without any intervention.

Table 7.4: Comparison of Vehicle Emissions - Fifteenth Avenue

Scenario	**CO_2 (kg)**	**Emission Reduction compared to Real World (kg)**
Real-world	4837.5009	-
20% Electric Cars	3876.8279	960.6730
Trackless Tram	3941.8930	895.6079
Carpooling	3932.0523	905.4486

According to the aforementioned results, the replacement of 20% of conventional cars with electrically powered vehicles was able to achieve the highest level of emission reduction, equivalent to 960.6730 kg of carbon dioxide. In spite of the fact that this option is best for mitigating vehicle emission, it is less effective in reducing traffic congestion because number of vehicles remained unchanged during this transition. However, carpooling and trackless tram options are effective in both emission reduction and traffic efficiency.

7.4 Summary of the Findings

This chapter presented a detailed discussion of the results obtained from the microscopic traffic simulation and subsequent vehicle emission analysis. Through this simulation, it was possible to identify the daily traffic patterns and vehicle types that are specific to each site. The Cameron Road - Fifteenth Avenue intersection area can be identified as a typical city area with high traffic congestion during the morning and evening peak hours on weekdays, which correspond to work and school travel times. On weekdays, the traffic pattern along Turret Road, near Harini Bridge, is quite different, since there is a continuous flow of traffic from morning to evening. Newton Street has a high peak of vehicle volume on Wednesday and Friday, while Monday, Tuesday, and Thursday have moderate traffic volumes. Compared to working days, weekend traffic volumes are low at all three sites.

The traffic patterns of the area depend on the road condition, speed limits, and area-specific factors such as residential or industrial areas. Across all three sites, light-duty vehicles make up the majority of vehicle volumes. However, heavy-duty vehicle volume is higher in Newton Street than in the other two sites, as Newton Street is located near the industrial zone. A similar vehicle pattern can be observed in the light-duty vehicle volume pattern, although the volume of the vehicle is lower than the total vehicle volume. The vehicle density patterns at each site are also similar to the vehicle volume patterns. As a result of this study, CO_2 was the principal pollutant from road transport in Tauranga, and light-duty vehicles account for a majority of the emissions. Currently, traffic congestion contributed significantly to the emission levels in Tauranga, and steps must be taken to reduce the amount of emissions produced by vehicles.

In order to address these vehicle emissions, it is necessary to identify the factors that contribute to high levels of emissions. Vehicle density and the fuel type used in the vehicle are the two main factors that influence vehicle emissions. Based on the observations in this study, the relationship between vehicle density and CO_2 emissions can be modelled as a polynomial curve of degree three. At low densities, the graph appears linear and at high densities, the related emissions of CO_2 increase more rapidly than the density increases. The type of fuel used in a vehicle also affects the amount of CO_2 released into the atmosphere. The substitution of 10% of petrol cars with electric cars led to a substantial reduction in CO_2 emissions. Consequently, the type of fuel used in vehicles is an important factor in determining vehicle emissions.

According to the findings, in order to reduce vehicle emissions, the proposed solutions should focus on reducing vehicle density and moving toward vehicles with zero-emission fuel types. Three strategies were proposed based on the aforementioned factors. The first plan is to increase the electric vehicle usage. Replacement of 20% of light-duty petrol vehicles by electric vehicles led to a reduction of 960.6730 kg of daily carbon dioxide emissions.

The second plan involves the deployment of trackless trams that reduce vehicle density and move toward zero-emission vehicles powered by electricity. It could reduce 100 vehicles by introducing one trackless tram to the site, as it was assumed to be occupied by 100 passengers at a time. This plan could reduce 895.6079 kg of daily CO_2 emissions. The scenario was implemented using two trackless trams that operate every hour from 7:00 am to 6:00 pm in both directions. Further reductions in emissions can be achieved by increasing the number of trackless trams.

The third proposed solution for reducing emissions is to promote carpooling. It is capable of replacing four single-passenger cars with a single carpooling vehicle. In this scenario, petrol carpooling cars were implemented, and the primary focus was on reducing vehicle density in order to reduce vehicle emissions. This could reduce 905.4486 kg of daily CO_2 emission. Further emissions can be reduced by using electric cars rather than petrol carpooling vehicles.

As a result of simulating each scenario, it can be concluded that all three methods result in substantial reductions in vehicle emissions. Apart from reducing emissions, trackless trams and carpooling options also contribute to reducing traffic congestion in the city due to the reduction of vehicle density.

Chapter 8

Discussion

8.1 Simulated vs. Real World

This study presents a SUMO-based traffic simulation environment, serving as a controlled platform for evaluating the effectiveness of emission reduction strategies. Hence, it is possible to gain a thorough understanding of the various interventions before they are implemented. This controlled environment provides the opportunity to isolate specific factors and evaluate their impact on emission levels without interference from external factors. However, the real-world environment introduces significant complications because weather conditions, accidents, and unpredictable driving behaviour have a significant impact on traffic flow, which is not fully incorporated in the simulation.

Several significant insights were gained from the modelling of the three selected interventions: electric vehicles, trackless trams, and carpooling. This study highlights the urgent need to reduce vehicle density and emphasises the importance of transitioning to low-emission transportation modes. The study highlighted that there is a clear reduction in CO_2 emissions in all three interventions. Before applying different interventions to real-world settings, these simulation results provide an evidence-based approach for comparing their potential benefits. Utilising the insights obtained from each scenario, decision makers will be empowered to make more informed decisions concerning transportation and urban development.

The outcomes of this research are closely aligned with the key points identified in the literature review. Several studies have demonstrated that CO_2 is the primary contributor to greenhouse gas emissions and that traffic during peak hours results in higher levels of emissions. This trend was confirmed by the simulation results, which indicated that peak traffic periods with high traffic coincide with the highest emission levels. The researchers explored different types of emission reduction strategies and evaluated their effectiveness. Among these strategies for reducing emissions, electric vehicles, trackless trams, and carpooling were simulated, and the results obtained from the simulation were consistent with the prior studies mentioned in the literature review.

For instance, according to Costa & Seixas [15], as discussed in Section 3.4.1 in the literature review, there was a significant reduction in CO_2 emission after replacing 20% of gasoline-powered vehicles with battery-electric vehicles. Petrović et al. [56] also demonstrated the potential reduction of the CO_2 emission by replacing gasoline-powered fossil fuel vehicles with lighter electric vehicles. Furthermore, Jung & Koo [33] examined the environmental impact on the implementation of the car sharing system, leading to a significant reduction in CO_2 emissions. Overall, the alignment between the findings of this study and the literature review helps to strengthen the validity of this study.

8.2 Recommendations

It has been demonstrated that traffic simulation with emissions modelling can be an effective tool for assisting local governments in making critical decisions. Modelling different interventions can help the council determine which strategies are most effective in reducing vehicle emissions under local conditions before investing in costly infrastructure or policy changes. Furthermore, it is also possible to adapt the methodology developed in this study for use in other cities, allowing them to replicate the process using their own traffic data and to facilitate the use of data-driven decision-making in those cities. The accuracy of the simulation and its associated outcomes depend on the data set used. With the use of a more accurate dataset, the simulation will have a higher level of precision, thereby serving as a more valuable planning tool. This can be adapted by using high-accuracy data collection methods or by integrating real-time data feeds into the simulation.

In addition to the three interventions simulated in this study, this approach is capable of testing a wider range of interventions, including e-scooter systems, hydrogen-powered vehicles, and ferry services. Simulations can be conducted for each of these interventions individually or in combination to determine which combination achieves the best reductions at the lowest cost before implementing them in the real world. A significant advantage of simulation is that these interventions can be studied without the political and financial concerns associated with their rapid incorporation into the real world. Ultimately, this simulation serves as a cost-effective and low-risk decision-making instrument that assists councils in prioritising the most effective treatments before allocating funds.

8.3 Limitations

The study has some limitations and assumptions in simulating vehicle traffic flow and emission factor modelling. It should be noted that the simulation did not fully capture real-world variations such as weather effects, driver behaviour, sudden disruptions, and speed variations. Furthermore, this research has some limitations in terms of data availability. Due to the limited data available, the study was confined to three sites: Fifteenth Avenue, Turret Road, and Newton Street. Additionally, this simulation was conducted on different dates for each site due to differences in data availability. Hence, there may be seasonal variations and different weather conditions that may affect the simulation results.

It is important to note that the traffic patterns, road network design, and vehicle demand used in this simulation are specifically tailored to Tauranga. However, the methodological approach employed in this study is transferable and can also be applied to other cities. It is recommended to import the road network design via OpenStreetMap and feed the simulation with vehicle count data corresponding to the desired city.

In addition, the simulated vehicle classes were categorised into four classes, namely, Motor Bike, Car, Bus, and Truck, without accounting for exact location proportions of engine types, vehicle age, or maintenance conditions. The share of electric vehicles was estimated according to the total electric vehicle share in the Bay of Plenty region, which was 4.8 per cent in 2025. Hence, that may not match the actual fleet in the study area. Furthermore, this simulation was implemented by considering a specific area. Consequently, traffic flow on adjacent roads and junctions may have an impact on the traffic demand in the study area.

Aside from the limitations mentioned above, SUMO also has some limitations, despite being an extremely powerful tool. A car-following model and lane-changing model are employed in SUMO to simulate driver behaviour; however, these models may not fully reflect diverse driving styles, such as sudden braking and aggressive driving. It should be noted that SUMO only provides standard vehicle types, such as cars, buses, trucks, and the like, with adjustable parameters, and is not capable of reflecting specific vehicle models or fleet compositions within a particular geographic area. However, SUMO is an excellent tool for assessing interventions at a low cost and without any risk of failure.

Chapter 9

Conclusion

This study analyses vehicle emissions using a microscopic traffic simulation in SUMO and an integrated emission modelling approach. It examined the current traffic patterns and investigated the relationship between vehicle density and fuel type used in the vehicles with respect to vehicle emissions. Furthermore, three emission reduction strategies, including electric vehicle usage, trackless trams and carpooling, were assessed and evaluated.

9.1 Research Questions

In this study, the following research questions were answered.

1. How can microscopic traffic simulation be applied to council collected data to simulate real-world traffic scenarios?
2. How can we apply traffic interventions and analyse their effectiveness on emission reduction to enable data-driven decision making?

The first research question was addressed from the beginning of Chapter 4. In Chapter 4, the design plan of the simulation was initiated, and the tools and software were selected for the simulation. In Chapter 5, the study area was selected to replicate the real-world traffic scenario and the relevant data was collected. The implementation of the microscopic traffic simulation was carried out as discussed in Chapter 6. Finally, it was able to replicate real-world traffic scenarios using microscopic traffic simulation using the data provided by the Tauranga City Council.

In order to address the second research question, the emission analysis process was designed in Chapter 4 by selecting a suitable emission model. Then, as discussed in Chapter 6, the emission model was integrated into the microscopic traffic simulation, which was addressed in Research Question One. The outcomes of the emission analysis process were then outlined and visualised in Chapter 7.

A real-life scenario was conducted in which 10% of petrol vehicles were replaced with electric vehicles in order to investigate the impact of fuel type on vehicle emission levels. The results show that vehicle density and CO_2 emissions are strongly positively correlated. Emissions increased disproportionately with higher vehicle densities, suggesting that the relationship was non-linear. It could be best described by the polynomial curve of degree three. According to this study, decreasing vehicle density and transitioning to low-emission vehicle technologies are the most effective ways to reduce vehicle emissions.

Based on the findings of this study, three emission reduction plans were proposed: increasing electric vehicle usage, deploying trackless trams, and promoting carpooling. Each proposed plan was simulated and the emission outcomes were analysed. The daily reduction of the CO_2 amount was calculated and compared in order to quantify the effectiveness of each emission reduction plan.

9.2 Future Work and Concluding Remarks

Traffic simulation plays an important role in the analysis of vehicle emissions and the assessment of possible measures to mitigate them. This study demonstrated the significance of traffic simulation in evaluating vehicle emissions and determining the efficacy of transport interventions. Through the application of microscopic traffic simulation and emission modelling, it was possible to quantify how traffic flow patterns, vehicle density, and fuel type used in vehicles influence pollutant levels.

The findings confirm that among the pollutants emitted by light-duty vehicles from urban traffic, CO_2 is the predominant. Furthermore, the study reveals that vehicle emissions are strongly correlated with vehicle density and the type of fuel used in vehicles. The findings demonstrated that vehicle emissions can be reduced by lowering vehicle density and transitioning to a low-emission fuel type. The proposed emission reduction strategies, including increased electric vehicle usage, the deployment of trackless trams, and promoting carpooling, showed a significant reduction in CO_2 emission. This research only analysed the emission impact of the proposed methods; therefore, feasibility and infrastructure cost also need to be addressed before implementing these plans into the real world.

The findings of this research provide a strong foundation for further investigation into emission analysis and traffic simulation, regardless of the limitations of this study. There is a potential to increase accuracy and applicability by addressing these limitations. The dataset could be expanded to include multiple locations and seasonal variations in the future. It is also possible to incorporate real-time data into the simulation for a more accurate model of the system. In addition, modelling several New Zealand cities would enable this simulation framework to be used to develop strategies for the entire country.

The behavioural components of interventions require more investigation, especially the public's willingness to purchase electric cars, switch to trackless trams, or carpool. Furthermore, it is possible to integrate new transport interventions into this simulation in order to evaluate their effectiveness in each method before implementing them in the real world. Further studies could explore the emission impacts of emerging technologies that could change transportation systems in the next decades, such as autonomous vehicles, hydrogen-powered automobiles, and integrated mobility platforms.

In terms of software, the study emphasises the advantages of open-source traffic simulation platforms, each of which comes with special advantages for adaptability, usability, and emission model compatibility. SUMO plays an important role in implementing this research by providing a suitable platform for the simulation of interventions. Choosing the right platform is a crucial engineering choice influenced by project scope, accessible data, and intended use.

In conclusion, this study provides a cost-effective framework for evaluating emission reduction strategies prior to their implementation in real-world settings. Therefore, this provides policymakers and urban planners with a valuable decision-making tool. The findings highlight that there is an urgent need to reduce transport-related emissions and it is essential to take the necessary steps to mitigate these emissions. Ultimately, reducing the emissions associated with transportation is important both for achieving New Zealand's climate commitments and improving public health.

Finally, reflecting on the research questions, this study successfully simulated the real-world traffic scenario using the microscopic traffic simulation model with the help of the data provided by Tauranga City Council. The simulation was applied to different traffic interventions and evaluated the effectiveness of each scenario in terms of reducing emissions. In addition to addressing research questions, this study provides a foundation for future research and policymakers to tackle the issue of transportation-related emissions nationwide.

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Appendix A

Software Selection Procedure

Each criterion was given a coefficient according to its importance, which ranges from 1 (not important at all) to 5 (very mandatory). Table A.1 presents the selection criteria along with the coefficients assigned to each criterion.

Table A.1: Selection Criteria and their Coefficients

Selection Criteria	**Coefficient**
1. Software Category	5
2. Operating System Portability	4
3. Modelling Capability and Customisation	5
4. Visualisation and Output	5
5. Scalability and Performance	4
6. Documentation and the GUI	3

For the evaluation procedure, the traffic simulation software MATSIM, SUMO, AIMSUN, VISSIM, and GAMA were taken into consideration. Subsequently, a mark was assigned on a scale 1-10 based on the capability of the simulator to meet each feature of the criteria. The evaluation findings can be summed up in Tables A.2 through A.7.

$$\text{Mark} = \left(\frac{10}{n_f}\right) \times n_t$$

n_f: Total number of features for each criteria
n_t: Number of ✓ marks for each criteria

The round-off value of the Mark is taken into the final calculation.

Table A.2: Evaluation Results according to the Software Category

Feature	**MATSIM**	**SUMO**	**AIMSUN**	**VISSIM**	**GAMA**
Open-source [17]	✓	✓	✗	✗	✓
Free [17]	✓	✓	✗	✗	✓
Microscopic [17]	✓	✓	✓	✓	✓
Mark	10	10	3	3	10

Table A.3: Evaluation Results according to the Operating System Portability

Feature	**MATSIM**	**SUMO**	**AIMSUN**	**VISSIM**	**GAMA**
Windows [17]	✓	✓	✓	✓	✓
Linux [17]	✓	✓	✓	✗	✓
Mac OS [17]	✓	✓	✓	✗	✓
Mark	10	10	10	3	10

Table A.4: Evaluation Results according to the Modelling Capability and Customisation

Feature	**MATSIM**	**SUMO**	**AIMSUN**	**VISSIM**	**GAMA**
Multimodal Simulation [17][61][72][12]	✓	✓	✓	✓	✓
Visual tool Integration [17]	✗	✓	✓	✓	✗

Network from OSM [17]	✓	✓	✓	✓	✓
Transport Demand [17]	✓	✓	✓	✓	✓
Source-code Access [17]	✓	✓	✗	✗	✓
Emission Modelling Support [46][25]	✓	✓	✓	✓	✗
Mark	8	10	8	8	7

Table A.5: Evaluation Results according to the Visualisation and Output

Feature	**MATSIM**	**SUMO**	**AIMSUN**	**VISSIM**	**GAMA**
2D [17]	✗	✓	✓	✓	✓
3D [17]	✗	✗	✓	✓	✓
Realism [17]	✗	✗	✓	✓	✗
Statistics output [17]	✓	✓	✓	✓	✗
Mark	3	5	10	10	5

Table A.6: Evaluation Results according to the Scalability and Performance

Feature	**MATSIM**	**SUMO**	**AIMSUN**	**VISSIM**	**GAMA**
Low CPU usage [20][73][13]	✓	✓	✓	✗	✗
Low Memory usage [20][73][13]	✓	✓	✗	✗	✗

Ability to cope with large traffic networks [20][32][13]	✓	✓	✓	✓	✓
Mark	10	10	7	3	3

Table A.7: Evaluation Results according to the Documentation and the GUI

Feature	**MATSIM**	**SUMO**	**AIMSUN**	**VISSIM**	**GAMA**
Online [17]	✓	✓	✗	✗	✓
Forum [17]	✓	✓	✓	✓	✓
Conference [17]	✓	✓	✗	✓	✗
Community [17]	✓	✓	✓	✓	✓
GUI [17]	✓	✓	✓	✓	✓
Mark	10	10	6	8	8

Based on the above results, the final score for each simulator was calculated as a weighted average using the following formula.

$$Score = \frac{\sum_{i=1}^{n} mark_i \times coeff_i}{\sum_{i=1}^{n} coeff_i}$$

i: Criteria number
n: Number of criteria
$mark_i$: Mark value of the simulator for each criteria
$coeff_i$: Coefficient of assigned to the criteria

Table A.8: Final Score of each Traffic Simulator

Simulator	**Criteria**						**Score**
	1	**25**	**3**	**4**	**5**	**6**	

MATSIM	10	10	8	3	10	10	8.27
SUMO	10	10	10	5	10	10	9.04
AIMSUN	3	10	8	10	7	6	7.35
VISSIM	3	3	8	10	3	8	5.88
GAMA	10	10	7	5	3	8	7.15