EXAMINING THE IMPACTS OF COVID-19 ON TRANSPORT AND EMISSIONS IN THE HALIFAX REGIONAL MUNICIPALITY

by

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Dalhousie University is located in Mi'kma'ki,
the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

Dedicated To

My Mother, **Salma Akhter**

My Father, **Mosharef Hossain Bhuiyan**

My Sister, **Turaba Tasnim**

And

My Husband, **Hasan Shahrier**

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Abstract

This thesis examines the impact of activity and mobility restrictions on business establishments, traffic, and emissions during the COVID-19 pandemic in the Halifax Regional Municipality. It initially investigates the economic loss of local business establishments in terms of sales using a latent class regression model which incorporates activity patterns from an activity-based travel demand model. Later it develops a modelling framework to estimate the changes in traffic and vehicular emissions during the lockdown and phased reopening scenarios. It develops a finer-grained travel demand model coupled with an emission model. One of the uniqueness of this study is that it considers both passenger cars and commercial vehicles within the modelling framework and estimates multiple types of air pollutants at the local level. The findings will assist transportation professionals in the future to develop transportation systems and policy implications, allowing them to be better prepared for unplanned disruptions like the COVID-19 pandemic.

List of Abbreviations and Symbols Used

AIC	Akaike Information Criterion
APE	Absolute Percentage Error
AQI	Air Quality Index
BAU	Business-as-Usual
BIC	Bayesian Information Criterion
BLB	Best Lower Bound
CDC	Centres for Disease Control
CNY	Chinese Yuan Renminbi
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EMME	Equilibre Multimodal Multimodal Equilibrium
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
GEH	Geoffrey E. Havers, Statistics
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GPS	Global Positioning Systems
HRM	Halifax Regional Municipality
IDW	Inverse Distance Weighted
iTLE	Integrated Transport, Land-use and Energy
LB	Lower Bound
LCM	Latent Class Model

LDS	Longer-term Decisions Simulator
LKR	Sri Lankan Rupee
MAPE	Mean Absolute Percentage Error
MOVES	Motor Vehicle Emission Simulator
MPE	Mean Percentage Error
N_2O	Nitrous Oxide
NAICS	North American Industry Classification System
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
O_3	Ozone
O-D	Origin-Destination
OECD	Organisation for Economic Co-operation and Development
PM_{10}	Particulate Matter ranging from 2.5 to 10 microns
$PM_{2.5}$	Particulate Matter smaller than 2.5 microns
PPB	Parts Per Billion
PPM	Parts Per Million
SARS	Severe Acute Respiratory Syndrome
SDS	Shorter-term Decisions Simulator
SIC	Standard Industry Classification
SO_2	Sulphur Dioxide
TAZ	Traffic Analysis Zone
THC	Total Hydrocarbon
USD	United States Dollar
USEPA	US Environmental Protection Agency

VOC	Volatile Organic Compounds
WHO	World Health Organization

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Chapter 1

Introduction

1.1 Background and Motivation

The COVID-19 pandemic has a significant impact on the public health, world economy and environment *(Bai et al., 2020, Lai et al.,2020)*. The novel coronavirus disease (COVID-19) was first identified in Wuhan, China in December 2019 *(Hui et al., 2020).* In the past, the world faced several major influenza pandemics, namely, the "Spanish Flu" (H1N1 virus) in 1918, the "Asian Flu" (H2N2 virus) in 1957 and the "Hong Kong Flu" (H3N2 virus) in 1968 *(CDC 2020).* The first pandemic of 21st century occurred in 2003 and was caused by a SARS-associated coronavirus (SARS-CoV). Around 8000 people were affected by this virus worldwide whereas 774 died *(CDC 2020)*. The most recent pandemic of 21st century before COVID-19, was the "Swine Flu" (H1N1 virus), which occurred in April 2009 causing death of 12400 people in the United States *(CDC 2020).*

However, COVID-19 is one of the greatest pandemics of this century. This disease is caused by severe acute respiratory syndrome (SARS-CoV-2) *(Baloch et al., 2020).* World Health Organization (WHO) declared COVID-19 as a Public Health Emergency of International Concern on January 30th, 2020, and as a pandemic on March 11th, 2020 *(WHO, 2020)*. Due to its high transmissibility, almost 248 million people in more than 227 countries have been affected resulting in 5 million deaths *(Worldometer, 2021)*. As the virus was primarily spread by close contact between people and through respiratory droplets produced by an infected person or by touching an object or surface with virus on it *(CDC 2019),* WHO strongly recommended physical distancing, frequently washing hand and face, and using face masks as methods to minimize its high transmissibility and reduce death rates *(Kenyon et al., 2020).* A community focused approach named "Flattening the curve" was implemented *(Thunström et al., 2020)* throughout many countries in the world to protect public health.

During the lockdown period, different preventive measures, for instance, social distancing, closure of non-essential business, mobility restrictions were imposed. These controlling measures were somewhat effective in minimizing the spread of the disease.

But these measures affected the economy of the world. An early study by the World Bank predicted that global GDP in 2020 would drop by 5.2% with respect to 2019 *(World Bank, 2020)*. A study by *Coibion et al. (2020)* shows that, the primary lockdown is the main factor for declination of employment in the United States rather than the infections. However, as the restrictions ease during the reopening phases, the economy begins to recover. Similarly, the impact of COVID-19 on the urban travel behaviour, for instance, individual travel pattern, frequency of activities and mode choice, is also very significant. A study shows that out-of-home activities decreased by more that 50% in British Columbia, Canada *(Fatmi, 2020)* during the lockdown period. Similarly in Singapore, during the first week of the stay-at-home order, mobility rate was reduced by 36.4% *(Jiang et al., 2020)*. During lockdown, traffic flow decreased by up to 80% in Spain (*Querol et al., 2021*) and 82% in Italy (*Marinello et al., 2021)*. The change in mode choice is also noticed. In Santander (Spain), public transport users decreased by almost 93% *(Aloi et al., 2020)*. Mass transit ridership dropped to 85% within a week of the pandemic in Boston, USA *(Basu and Ferreira, 2021)*. Moreover, in India, people started to rely on cars much more than before the pandemic *(Thombre and Agarwal, 2020)*.

Though COVID-19 has many negative impacts on health and economy of the world, it has positively affected the air quality by reducing environmental noise, beach, surface, and groundwater pollution *(Mostafa et al.,2021)*. Several studies show that due to mobility restrictions, vehicular emissions got reduced which eventually has a positive impact on air quality. During the lockdown, there was a significant decline in industrial operations, vehicle kilometres travelled, and commercial activity, resulting in a global reduction in emissions *(Tian et al., 2020).* Worldwide, there was a substantial reduction of Carbon Dioxide (CO_2) emissions of 4% to 11%, with a median value of 8% due to the pandemic restrictions *(Dafnomilis et al., 2020)*. In all Western Europe countries, a decrease of 30%-50% in Nitrogen Dioxide (NO_2) concentrations is reported *(Menut et al., 2020)*. Similarly in the United States, a huge decrease in the concentration level of Carbon Monoxide (CO), 27.3% in Orlando and 24.2% in Miami, is observed *(El-Sayed et al. 2021)*. In the "New Normal" phase, we have to consider all these impacts of COVID-19 in the policy making procedure for future. We need to be prepared for future pandemics. Therefore, this thesis develops the tools to estimate the impact of mobility restrictions during a pandemic on the economy, traffic and vehicular emissions. The results of this study will aid policymakers to develop interventions during future pandemics.

1.2 Objectives

The specific objectives of this thesis are:

1. To examine the impacts of COVID-19 pandemic on sales of business establishments by taking an activity-based travel demand modelling approach within the Halifax Regional Municipality (HRM).
2. To develop a transport and emission modelling framework for evaluating the impacts on traffic during the lockdown and reopening scenarios of COVID-19.
3. To examine the impacts of COVID-19 on major pollutants including GHG as CO_2 equivalent, CO, NO_x, SO_2, PM_{10}, $PM_{2.5}$, THC, and VOC during the lockdown and phased reopening scenarios in the Halifax Regional Municipality (HRM).

1.3 Research Significance

The major contribution of this research is to develop an innovative modelling framework to predict the impact of pandemic in the local level. The study will provide a better understanding of the change of sales of local businesses, change in traffic volume and vehicular emissions, especially GHG emission during pandemic scenarios. In this study, the impact of COVID-19 on business establishments, utilizing an activity-based travel demand modelling approach, is estimated during lockdown and phased reopening scenarios. The impact of COVID-19 on the traffic and GHG emission is also estimated in this study. This study will be useful for policy makers to be better prepared for any pandemic in the future.

1.4 Organization of the Thesis

The thesis is organized into **six** chapters. The **first** chapter specifies the background, motivation, objectives and organization of the thesis. In the **second** chapter, a thorough literature review on the impact of COVID-19 is conducted. The **third** chapter illustrates the economic impact analysis of COVID-19 during lockdown and phased reopening scenarios. This chapter includes an extensive analysis of the business establishments and the estimations of sales during pandemic scenarios by utilizing the Latent Class Regression

Model. The **fourth** chapter includes the comparative analysis of traffic network model and vehicular emissions during the lockdown phase of COVID-19. The extensive analysis of traffic network model and vehicular emissions during the phased reopening scenarios of COVID-19 is illustrated in chapter **five**. The **sixth** chapter demonstrates the major findings, contributions, limitations, and future recommendations of the research.

Chapter 2

Literature Review

2.1 Impact of COVID-19 on Economy

Worldwide, there has been significant amount of research works on the consequences of COVID-19 since the outbreak of the pandemic. Table 2-1 summarizes major research works on the economic impact of COVID-19 due to lockdown in many countries such as, United States, United Kingdom, Canada, Germany, Spain, China, France, Australia, India, Bangladesh, Korea, Colombia, and Egypt. The economies of these countries were negatively affected by the COVID-19. Due to the lockdown, many people lost their jobs and the employment rate dropped suddenly in many countries. In United Kingdom, 4% of the workers lost their jobs and 18% of people were laid off *(Aum et al., 2021)*. In California (United States), the number of active business owners decreased by 22% during the lockdown period *(Fairlie and Fossen, 2021).* Similarly, in Canada, 15% of working people lost their jobs during lockdown *(Lemieux et al., 2020).* Laying of people from their jobs directed to huge economic loss in many countries. For instance, in France, 5% loss of GDP is reported *(Malliet et al. 2020),* while Indian economy is estimated to face 10-31% decrease of GDP during COVID-19 pandemic *(Kanitkar, 2020).* Moreover, an average business sales faced loss of 17% in California, USA *(Fairlie and Fossen, 2021)*. Another survey in Pakistan, collecting data from 184 Pakistani micro, small, and medium-sized enterprises, reported that three-fourths of the businesses expected a 60% decline in sales during 2020 *(Shafi et al., 2020).* The following table includes information of the authors, study area, objectives, and major findings of major research works.

Table 2-1 Literatures on COVID-19 and Economy

Authors	Study Area	Objectives	Major Findings
Fairlie and Fossen, 2021	California, United States of America	To provide an analysis of sales volume reduction during COVID-19 and some policies to mitigate the loss for any future pandemic situation.	• Number of active business owners dropped by 22% from February to April 2020, which were affected by mandatory lockdowns such as 91% accommodations lost, whereas online sales grew by 180%. • Overall business sales dropped by 17% during COVID-19
Hu, 2020	United Kingdom	Investigate the impact of COVID-19 on people's economic well-being in the UK, with a focus on interlocking ethnic and native–migrant inequality.	• 4% people lost their job and 18% were laid off. • According to survey, 41% of household believe that their household income is reduced due to COVID-19 pandemic
Lemieux et al., 2020	Canada	To examine the early effects of the coronavirus disease 2019 (COVID-19) pandemic on the Canadian labour market	• Between February and April 2020, the weekly work hours were reduced by 32%. • 15% of workers of age group 20 years - 64 years lost their employment.
Moehring et al., 2021	Germany	Evaluating the inequalities in	• Lower educational degrees and in low-wage employment were

		employment trajectories during the first COVID-19 pandemic lockdown in Germany.	more affected by continuous furlough and job loss. • Women have a higher chance of being continuously furloughed because they are overrepresented in low-wage sector.
Chamorro-Petronacci et al., 2020	Region of Galicia, Spain	To determine the economic and health-care impact of COVID-19 on dentists.	• The respondents' economic losses were mostly (27%) between 1000–4999 EUROs, followed by 5000–9999 EUROs (25.5%). • Of the male respondents, 33.1% suffered losses more than 15,000 EUROs compared to 19.4% of female respondents.
You et al., 2020	Wuhan, China	Investigation of the linkages between epidemic preventive and control methods and economic-social development by assessing health and meso-economic loss from a human-centered approach.	• The direct economic losses in the transportation, logistics and warehousing, postal service, food, and beverage service industries total 21.61 billion CNY. • During the lockdown, total monthly economic losses amount to 177.0413 billion CNY.

Malliet et al., 2020	France	To provide a quantitative evaluation of the economic and environmental implications using a computable General Equilibrium model.	• The lockdown has resulted in a huge drop in economic production of 5% of GDP.
Romano, 2020	Australia	To understand the severity and longevity of the current COVID-19 pandemic on Australian economy.	• Australia's private consumption might fall by up to 20% from 2019 levels (totaling $1.1 trillion), resulting in a $220 billion loss to GDP. • A government program of $300 billion is required to overcome this economic shock.
Kanitkar, 2020	India	Utilise a linear Input-Output (IO) model to evaluate the economic losses caused by COVID-19 in India.	• Indian economy is likely to face a loss of about 10 to 31% of its GDP. • In power sector, the daily supply from coal-based plant reduced by 26%.
Mottaleb et al., 2020	Bangladesh	Estimation of the daily economic loss during COVID-19 lockdown.	• Nearly 35% of 61 million employed work force gets paid daily. • A one-day total lockdown results in a $64.2 million USD equivalent economic loss.

Aum et al., 2021	Daegu-Gyeongbuk-DG, Korea	Evaluate the causal effect of the outbreak on the labour market.	• A one per thousand increases in infections causes 2.68% drop in employment. • In terms of gender, male workers lost more jobs than female. • Services, real estate, small business, transportation/storage, and education are hit hardest by the epidemic.
Bonet-Morón et al., 2020	Colombia	Assessing the regional economic impact of the lockdown measures ordered by the national government to prevent the spread of COVID-19	• Monthly economic losses that represent between 0.5% and 6.1% of national GDP. • The most affected industries include accommodation and food services, real estate, administrative services, construction, and trade.
Allam et al., 2020	Egypt	To explore the role of the Coronavirus on the trading behaviour of individual and institutional investors on the Egyptian Stock Exchange.	• For Egyptian and Arab investors, the "Daily Deaths" variable was more effective and sensitive for individuals and institutions. • The "Daily Cases" variable was more sensitive to Arab individual investors' trading activity.

Most of the studies mainly focused on the economic loss during lockdown. There is a clear research gap about this impact of mobility restrictions during phased reopening scenarios at the local level specifically traffic analysis zones (TAZs) level. Therefore, this thesis aims to estimate the sales of business establishments during lockdown and phased reopening scenarios of Halifax Regional Municipality utilizing activity-based travel demand model.

2.2 Impact of COVID-19 on Traffic and Emission

Table 2-2 summarizes major research works on the impact of COVID-19 on travel behaviour, traffic volume and emission. According to *Fatmi (2020)*, in British Columbia, Canada, almost 50% of out-of-home activities were reduced during COVID-19 restrictions. Similarly, in Budapest (Hungary), the number of daily trips dropped from 10.1 to 4.3 million *(Bucsky, 2020)* and 50% reduction of total trips is reported in Italy *(Pepe et al., 2020)*. The change in modal choice is also noticed. For instance, a study of Sweden demonstrates a 40-60% drop of public transport usage *(Jenelius and Cebecauer, 2020)* and people started to replace public transport by private means and walking *(Abdullah et al., 2020)*. In China, a noticeable decrease in taxi trips is reported *(Nian, 2020)* whereas a significant increase of walking trips by 50% is observed in Greece *(Politis et al., 2021)*. Moreover, the dependency on car usage increased in many countries such as Germany *(Eisenmann et al.,2021)*, Spain *(Aloi et al., 2020)*, Netherlands *(de Haas et al., 2020)*, and UK *(Harrington and Hadjiconstantinou, 2020)*. A case study of Egypt indicates a strong link between the COVID-19 lockdown and the reduction in environmental noise, beach, surface, and groundwater pollution, along with a 15 to 33% decrease in NO_2, a 5% decrease in CO and a 4% decrease in GHG emissions *(Mostafa et al.,2021)*. The lockdown due to COVID-19 has affected the air quality positively. However, most of the studies have focused on the emission at national level. The following table illustrates some insights about the impact of COVID-19 on travel behaviour, traffic volume and emissions.

Table 2-2 Literatures on Impact of COVID-19 on Travel Behaviour, Traffic Volume and Emissions

Author	Study Area	Objectives	Major Findings
Fatmi., 2020	British Columbia, Canada	To examine the change in daily out-of-home travel activities, in-home activities, and long-distance travel during the restrictions of COVID-19	• Out-of-home activities got reduced by 50%. • Teleworking seems to be more acceptable by the higher income households. • Private car was the main mode of travel for long-distance
Tanzer-Gruener et al., 2020	Pennsylvania, United States of America	To experiment on the extent to which reductions in traffic-related emissions can aid in meeting more strict regulations.	• In both high traffic and commute traffic region, the CO and NO_2 reduced by approximately 50%. • In 2019, the concentration of $PM_{2.5}$ was 9 $\mu g/m^3$ and during lockdown, it is reduced by 29%.
El-Sayed et al., 2021	Florida, United States of America	Provide insights into the impacts of the COVID-19 pandemic on vehicular emissions in Florida, US.	• During lockdown, Florida experienced 25.2 (+/- 9.2%) declination in NO_2. • The largest decreases in CO concentrations were observed in central and southern Florida in Orlando (27.3%) and Miami (24.2%), while the decreases in northern Florida were less than 15%

			• A significant decrease of SO_2 was observed in Jacksonville and Tallahassee (44.1% and 52%, respectively) in northern Florida.
Adams, 2020	Ontario, Canada	To identify the connection between the major air pollutant and state of emergency declared in Ontario, Canada.	• In comparison with the mean value of past five years, NO_2, NO_x, O_3 got reduced by 2ppb, 2ppb and 1ppb respectively. • Fine particulate matter did not show any significant reductions during the five weeks of state of emergency
Turner et al., 2020	San Francisco, United States of America	To quantify the changes in urban CO_2 emissions from different sectors in response to COVID-19 mobility restrictions in San Francisco.	• 5-50 ppm decrease in midweek CO_2 concentrations with the most change on Monday to Thursday morning rush hour. • A large reduction in CO_2 emissions but meteorology needs to be coupled with emissions to device a more concrete conclusion.
Lian et al., 2020	Wuhan, China	Evaluating the impact of city lockdown on air quality through spatial distribution	• Average air quality index (AQI) for Wuhan city was 59.7 which was 33.9% lower during lockdown. • NO_2 and CO got reduced by 53.3% and 22.7% respectively. • $PM_{2.5}$ decreased by 36.9% but O_3 increased by 116%.

Liu et al., 2021	Hangzhou, China	To analyse the reduction of vehicular emission during COVID-19	• PM_{10} and $PM_{2.5}$ reduced by 50% • CO and SO_2 got decreased by 24% and 18% respectively. • Major reduction is happened to NO_x (77%)
Shi and Brasseur, 2020	China	To investigate changes in surface emissions of air pollutants during lockdown measure in China.	• The substantial reduction in NO and PM as observed during the lockdown may not have been significant enough to avoid ozone damage.
Arimura et al., 2020	Sapporo, Japan	To analyse the change in population density during emergency period	• Population density decreased up to 90% in the crowded areas. • During emergency declaration, almost 70%-80% contact reduced among people.
Bucsky, 2020	Budapest, Hungary	To understand the urban modal share developments during COVID-19 pandemic	• Mobility got significantly reduced in a range of 51% - 64%. • The number of daily trips got dropped from 10.1 to 4.3 million.
Dantas et al., 2020	Three locations of Rio de Janeiro, Brazil	To discuss the impact of COVID-19 pandemic on the air quality	• Maximum reduction (33.3%) of PM_{10} happened in the region Tijuca, Rio de Janeiro. • Another study area, Iraja experienced highest proportion of NO_x reduction (53.4%). • In all three locations exhibits more than 40% decrease of CO.

Marinello et al. (2021)	Reggio Emilia, Italy	Report an assessment of the change in vehicle flows and in air quality of a specific study area in the north of Italy.	• Vehicular movement in the traffic network is reduced up to 82%. • NO$_2$ and CO reduced over 30% and 22% in the study area respectively. • Particulate material (PM) grew over 30% and O$_3$ increased by nearly 13%.
Querol et al., 2021	11 Metropolitan Areas of Spain	To understand the COVID-19 lockdown effects on the air quality of Spain.	• Traffic flow decreased by up to 80% during the lockdown. • Major study areas experienced 61% to 72% decrease of NO. • During lockdown, the concentration of CO dropped to 100-428µg/m^3 from 267-563µg/m^3
Kutralam-Muniasamy et al., 2021	Mexico City, Mexico	To assess air quality and to estimate changes observed in air pollutants (CO, NO$_2$, O$_3$, SO$_2$, PM$_{10}$ and PM2.5) during lockdown.	• Concentrations of NO$_2$ (− 29%), SO$_2$ (− 55%) and PM$_{10}$ (− 11%) declined. • The contents of CO (+ 1.1%), PM$_{2.5}$ (+ 19%) and O$_3$ (+ 63%) increased during the lockdown
Mahato et al., 2020	Delhi, India	To compare the atmospheric pollutant concentrations in Delhi during the pre and during lockdown periods	• The concentrations of PM$_{10}$ and PM$_{2.5}$ have been reduced by the greatest amount (50%) as compared to the pre-lockdown phase. • NO$_2$ and CO level have reduced by 52.68% and 30.35%

			respectively during-lockdown phase. • Air quality of various part of Delhi is improved by 40%-50%.
Broomandi et al., 2020	Tehran, Iran	To examine the potential effects of the COVID-19 lockdown on air quality	• Reduction of vehicular emission during COVID-19 lockdown puts a positive impact on air quality of Tehran city. • In Tehran, CO, NO_2, SO_2 and PM_{10} got reduced by 13%, 13%, 12.5% and 11.33% respectively.
Mostafa et al., 2021	Egypt	To examine pandemic air pollution levels of particulates and GHG emissions as it relates to COVID-19 measures.	• A strong link was observed between COVID-19 lockdown and the reduction in environmental noise, beaches, surface, and groundwater pollution. • It was also found that the Absorbing Aerosol Index decreased by about 30%, the NO_2 decreased by 15 to 33%, and CO decreased by about 5%. GHG emissions in Egypt were reduced by at least 4% during lockdown.

However, the research on COVID-19 is still emerging. There are still some gaps in the existing literatures. At first, very few studies have analysed sales volume changes of businesses during the pandemic scenarios. Most importantly, how activity restrictions affected the local businesses is unclear. Secondly, the unobserved heterogeneity across the Traffic Analysis Zones (TAZs) is not considered yet. Moreover, a comprehensive modelling framework to estimate the emissions during pandemic scenarios is necessary. Because most of the studies have analysed the changes of emission due to COVID-19 from top-down approaches from satellite observed data. Also, there is gap on evaluating the impact of COVID 19 on finer detailed level like traffic analysis zones.

Therefore, this study will offer to estimate the impact of activity and mobility restrictions on sales of local business establishments during the pandemic scenarios. The pandemic scenarios are developed within the activity-based travel demand model. The study also contributes to capture the unobserved heterogeneity across the Traffic Analysis Zones (TAZs) by utilizing a Latent Class regression modelling approach. Moreover, the study will offer a novel approach to integrate an activity-based travel demand model with the multiclass traffic network model and an emission modelling framework. The model will examine the impacts of the pandemic on the traffic volume and vehicular emissions within the Halifax Regional Municipality (HRM), Nova Scotia, Canada.

Chapter 3

Economic Impact of COVID-19[1]

3.1 Introduction

The COVID-19 pandemic has a significant impact on the economic sector. During lockdown period, shutdown of many businesses and imposed restrictions on travel and mobility *(OECD, 2020)* have resulted in affecting the global economy significantly as the world is not prepared to handle COVID-19 pandemic yet (*Yu and Aviso, 2020*). A recent study by OECD reveals that the global GDP growth could decrease by 4-6% points than estimated if the lockdown continued until August 2020 *(OECD, 2020).* Additionally, the Conference Board of Canada estimated 1.1% decrease in GDP of Canada in 2020 due to this pandemic *(Antunes and Stewart, 2019).*

The COVID-19 has affected the economy of many countries worldwide. For instance, in Wuhan (China), where the first case of COVID-19 was detected, total monthly economic loss was 177.0413 billion CNY during lockdown period *(You et al. 2020)*. In California (USA), active business owners decreased by 22% within February to April 2020 *(Fairlie and Fossen, 2021)*. Many European countries experienced a significant increase in COVID-19 cases, leading to overcrowded hospitals. The increased number of COVID-19 cases also affected the economy. In United Kingdom (UK), almost 4% people lost their job *(Hu, 2020).* Similarly in Germany, people of lower educational degrees and low-waged employed people were mostly affected *(Moehring et al. 2021)*. Likewise, the economic production faced a loss of 5% of GDP during lockdown period in France *(Malliet et al. 2020)*.

The pandemic affected the labour market of Canada significantly. Canada's first case of COVID-19 was confirmed on January 27th, 2020, in Toronto *(Government of*

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[1] This chapter is adapted from:
Hossain F., and Habib M.A., "Estimating Economic Impacts of COVID-19 Pandemic at the Municipal Level: A Latent Class Regression Modelling Approach", *Presented at 100th Annual Meeting of Transportation Research Board. A Virtual Event, January 25-29, 2021.*

Canada, 2019). By the first week of April, during the first wave of COVID-19 in Canada, almost 1 million people lost their jobs, increasing the unemployment rate to 7.8% *(Renner, 2019a)*. An additional 2 million people lost their jobs in the month of April, which rose the unemployment rate to 13% *(Renner, 2019b)* and eventually the unemployment rate reached its peak at 13.7% by the end of May, the highest unemployment rate since 1982 (13.1%) *(Trading Economics, 2019)*. However, in the month of June, the labour market started to recover by increasing employment by about 1 million and the unemployment rate dropped to 12.3%. In the province of Nova Scotia, 50% of people returned to their jobs and employment rate increased by 3.5% from May to June *(Statistics Canada, 2020)*. Some studies also focused on the impact of this pandemic on local businesses. For instance, to explore the impact of COVID-19, a survey of more than 5,800 US-based small businesses, was conducted. This survey shows that only one-half of the firms had the ability to pay for their business expenses between one and two months *(Bartik et al., 2020).*

Although many studies are examining economic losses at the international and national levels, the economic impact due to this pandemic on the regional level is largely unknown. Most importantly, the effect of mobility restrictions and lockdown on the sales of local businesses is unclear. Therefore, this chapter proposes to develop an innovative modelling approach by utilizing activity patterns from an activity-based travel demand model *(Khan and Habib, 2021a)* and an economic model to estimate the impact of the COVID-19 pandemic on sales of local business establishments during the lockdown and phased reopening scenarios for the Halifax Regional Municipality (HRM).

3.2 Literature Review

The economic impact of a pandemic is a major issue of interest around the world since COVID-19 lockdown. Various studies have attempted to better understand the relationship of the world's economy and pandemic. Most of the previous studies examined global or national economic losses in terms of GDP. For instance, the World Bank predicts a reduction of GDP by 5% because of a severe pandemic as 1918 influenza *(Jonas, 2020 and Burns and Timmer, 2006)*. In another study, *Mckibbin et al. (2006)* estimated that extreme severe case of influenza pandemic would lead to 12.6% loss in global GDP including 50% losses in developing countries.

A recent study of policy responses published by OECD identified that the largest impacts of COVID-19 pandemic is in retail, wholesale trade and professional and real estate services *(OECD, 2020)*. However, the economic impact will vary from one country to another depending on the duration of shutdown, severity of pandemic *(Patterson et al., 2020)* and their economic sector compositions *(OECD, 2020)*. Therefore, Vanguard's approach is used to assess the impact of COVID-19 on various countries and region's GDPs to estimate the probable loss due to pandemic which shows that GDP of the U.S. is not expected to regain its pre-pandemic level until the end of 2021 *(Patterson et al., 2020)*. An economic model *(Smith et al., 2009)* estimated 5.9-9.6% decrease in GDP due to 10% case fatality rate of an influenza pandemic in the UK. Another study reveals that Australia could face a total loss of $280 billion due to the COVID-19 pandemic according to a transmission mechanism, containing various steps including reduction in labour market, household consumptions and discretionary spending *(Romano, 2020)*.

Additionally, to better understand the economic impact of pandemic, many researchers attempted to combine epidemiological models with economic models. For example, recently the RAND corporation developed a tool to provide information about the time frame of relaxing the nonpharmaceutical interventions of COVID-19 in the United States *(Vardavas et al., 2020)*. An epidemiological model estimates the impacts on health whereas an economic model estimates the economy of each state as well as regional and national impacts of policy changes. Aggregate percentage income losses by state for portfolio level 1 (only school closes) to level 5 (non-essential business closure and shelter-in-place order) were identified using this model which mainly reflects the possible short-term economic impact of social distancing *(Vardavas et al., 2020)*. Similar study was conducted by *Thunström et al. (2020)* to measure the benefits of social distancing by the number of lives saved without considering its impact on economy and analyzing the benefits and costs of relevant individual and neighborhood attributes. Another study identified 10% decrease in GDP from the Spanish Flu (1918-1920) and estimated a 6% decrease for COVID-19 pandemic using data from 48 countries *(Barro et al., 2020)*. Researchers argue that urgent analysis of economic impact of this pandemic is required to examine the balance between the public health and economy *(Clement, 2020)*. Some studies explore the economic impact at the state level. For instance, an individual based simulation model, which developed seven intervention strategies, was applied to explore the economic impact of a flu-like pandemic in the New River Valley of Virginia in the year 2011 *(Barrett et al., 2011)*. Some studies also explored the impacts of COVID-19 on business establishment classified by various types. For instance, a study by Office for National Statistics of Government of United Kingdom reveals that during lockdown period in April 2020, in-store retail sales got decreased by 88% and entertainment sector sales reduced by 97% *(ONS.gov.UK)*. Similarly in Canada, sales volume decreased by more than 65% of the retail trade *(CTV News, 2021).* However, there are limited studies on the impacts caused by a pandemic on sales of local business establishments including industry, retail, service, wholesale, and transportation businesses.

Therefore, this study proposes an innovative modelling framework by utilizing an operational activity-based travel demand model *(Khan and Habib, 2021a)* to develop an economic model for estimating the impact of activity and mobility restrictions due to COVID-19 pandemic on sales of the business establishments within the HRM. The activity-based travel demand model is an effective tool to evaluate activity and mobility restrictions and eventually to estimate the impacts of sales volume at the regional level. The considered pandemic scenarios are (1) Lockdown Scenario, (2) Conservative Reopening Scenario, and (3) Aggressive Reopening Scenario. As travel and activity restriction is a key part of slowing and stopping COVID-19 pandemic, the existing operational activity-based travel microsimulation model *(Khan and Habib, 2021a)* will offer an effective tool to evaluate the alternative scenarios of pandemics within transportation modelling and economic assessment paradigm.

3.3 Study Area

The area considered for this study is the Halifax Regional Municipality (HRM), the capital of Nova Scotia. The urban area (34.23 km^2) comprises of downtown Halifax and Dartmouth, which has a mix of land uses, such as commercial, industrial, and residential *(Province of NS, 2020).* The urban area is surrounded by suburban areas (470.24 km^2), which contain mostly residential use and few industrial and commercial uses. Finally, the suburban area is surrounded by rural area of 5349.82 km^2. Figure 3-1 shows the study area containing 219 Traffic Analysis Zones (TAZs), where 95 TAZs are in the urban area, 92

TAZs are in the suburban area and 32 TAZs are in the rural area. To examine the sales volume of local business establishments 219 TAZs are considered whereas additional three external zones are considered to represent the commercial vehicle movements to examine the impact of COVID-19 on traffic volume and emission (Chapter 4 and Chapter 5).

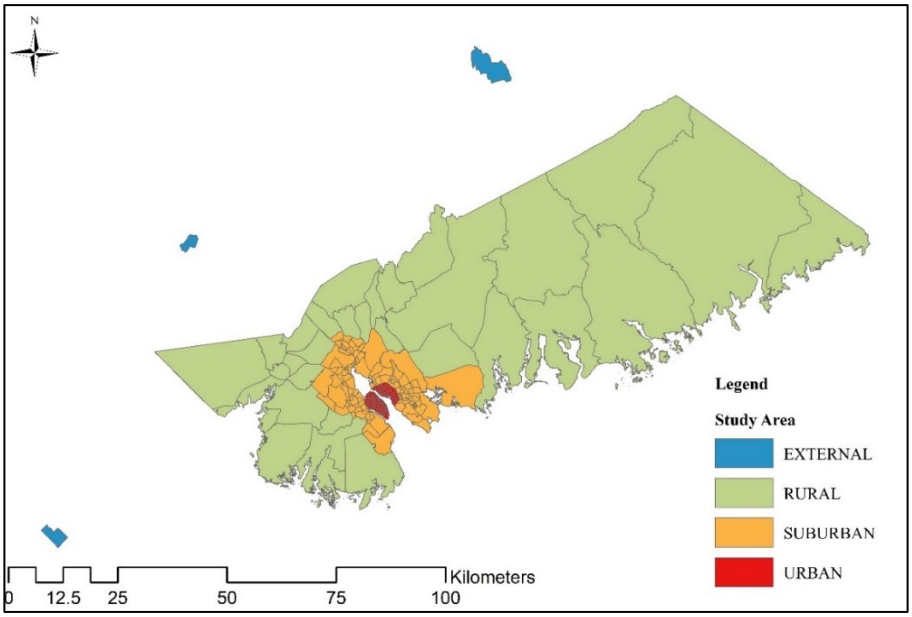


Figure 3-1 Study Area and Urban Core of Halifax

3.4 Methodology

This study develops a Latent Class Model (LCM) to investigate the sales volume of 219 TAZs of the Halifax Regional Municipality (HRM) in terms of business, mobility and built environment attributes. The study integrates an activity-based travel demand model and latent class model to estimate the sales volume of business establishments during the lockdown and phased reopening scenarios for the HRM. The following Figure 3-2 illustrates the modelling framework of this chapter.

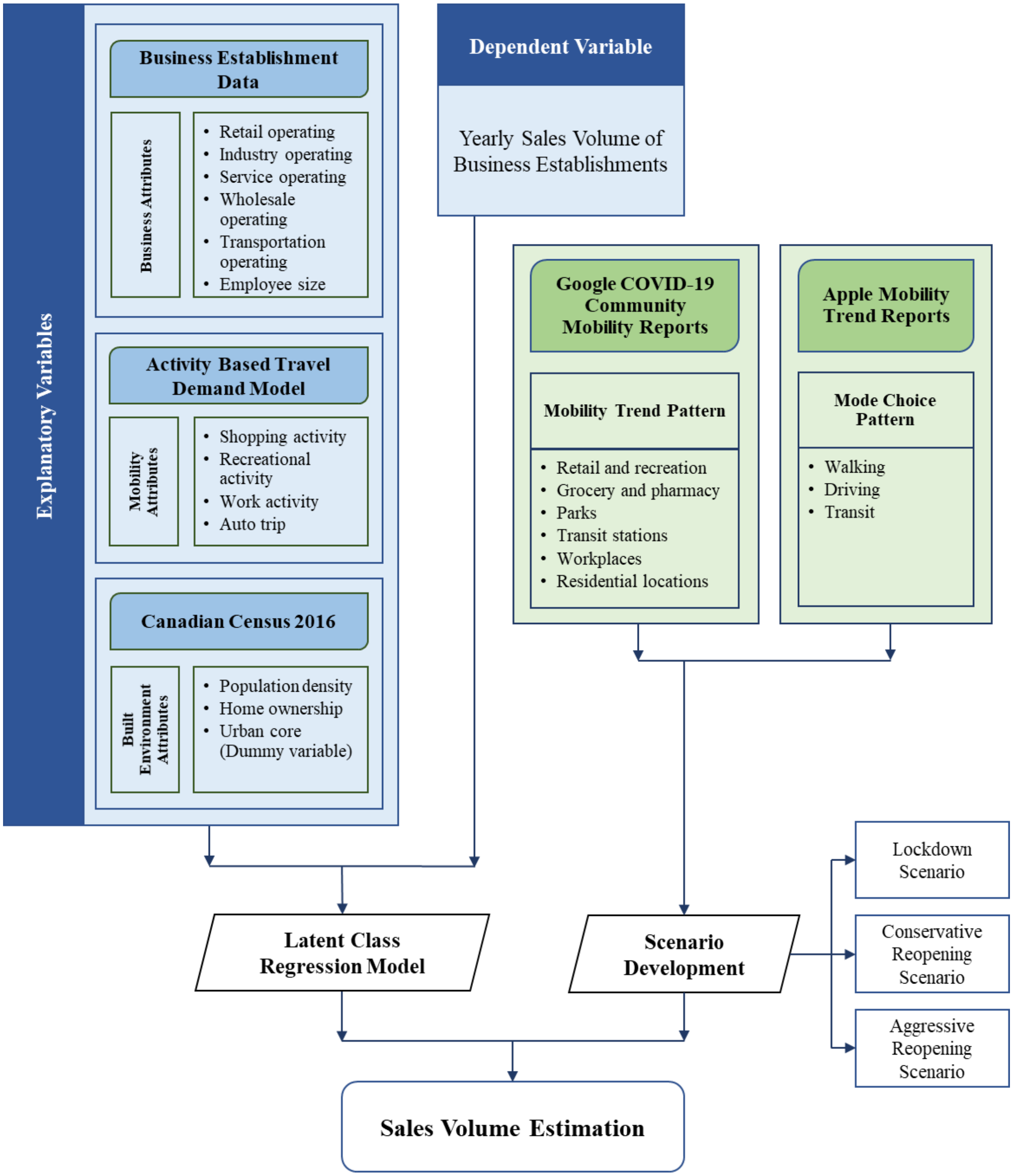


Figure 3-2 Framework of Economic Model

3.4.1 Activity-Based Travel Demand Model

The activity-based travel demand model is developed within an agent based discrete-time simulation platform, known as integrated Transport, Land-use and Energy (iTLE) platform, for daily travel in the Halifax Regional Municipality. One of the crucial parts of iTLE is the Shorter-term Decisions Simulator (SDS) which takes input from the Longer-term Decisions Simulator (LDS). Activity generation, activity scheduling and mobility assignment are three major components of SDS *(Khan and Habib, 2021a)*. The activity generation sub-module generates daily activity patterns for individuals using a Markov Chain process which includes activity type along with activity start time and end time *(Khan and Habib, 2021a)*. This model categorizes tours into seven different types: (1) Work, (2) School, (3) Escort, (4) Personal business, (5) Shopping, (6) Eating out and (7) Recreation. The activity type is also classified into four groups: (1) Work, (2) School, (3) Maintenance, and (4) Discretionary. The activity scheduling sub-model provides the activity agenda, destination location choice and travel time of individuals *(Khan and Habib, 2021a)*. The third sub-module, mobility assignment, generates mode choice decisions of individuals for the four modes available within the model: (1) Auto, (2) Transit, (3) Walk, and (4) Bike *(Khan and Habib, 2021a)*. The following Figure 3-3 shows the modelling framework of the activity-based travel demand model.

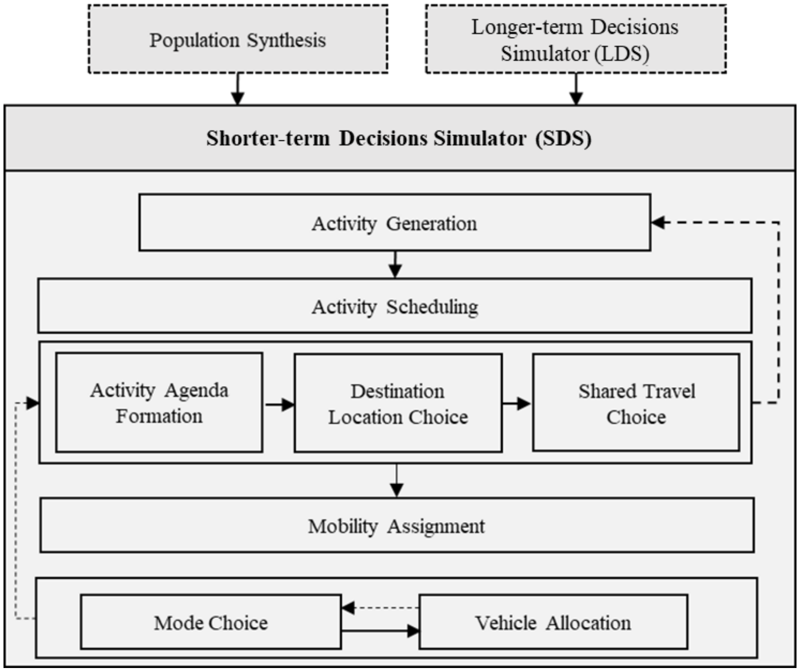


Figure 3-3 Framework of Activity-Based Travel Demand Model

This study utilizes outputs of the activity-based travel demand model including tours classified by activity types, and mode choices. The "mobility attributes" of this model, for instance, the dataset of shopping activity, recreational activity, work activity and auto trip are collected from the output of this activity-based travel demand model.

3.4.2 Activity Mobility Estimation

In this study, three pandemic scenarios, (1) Lockdown scenario, (2) Conservative Reopening Scenario, and (3) Aggressive Reopening Scenario, are developed within the Activity-Based Travel Demand Model based on the directions of government of Nova Scotia supported by multiple available data sources. To build the pandemic scenarios, this study utilizes two available mobility data sources - Google COVID-19 Community Mobility Reports *(Google, 2020)* and Apple Mobility Trend Reports *(Apple Inc., 2020)* for change in activity patterns and modal share respectively.

The daily updated "Apple Mobility Trend Reports" contain the relative volume of directions requests compared to a baseline volume on January 13th, 2020. This dataset comprises the trend reports of the change in mobility patterns of driving, walking, and biking of 63 countries as well as 596 sub-regions and 295 cities. For Canada, data is available for all provinces and territories and 7 cities *(Apple Inc., 2020)*. However, in reality, the mobility pattern could be different as this dataset does not provide the information of actual travel.

The Google COVID-19 Community Mobility Reports provide the trends of mobility pattern for 135 countries around the world including the regional trends of 94 countries. This report assumed the median value of a 5-week period (January 3rd, 2020, to February 6th, 2020) as the baseline day value and provides the mobility trend pattern for retail and recreation, grocery and pharmacy, parks, transit stations, workplaces, and residential locations. This report contains the trends of movements of all provinces and territories of Canada *(Google, 2020)*. The percentage change of activity for Nova Scotia obtained from this report is used in this study.

3.4.3 Business Establishment Dataset Analysis

The Business Establishment data set for the year of 2018, obtained from Info Canada, is a rich dataset containing 11432 detailing business establishment records of the Halifax Regional Municipality (HRM), including 7-digit North American Industry Classification

System (NAICS) codes. The dataset is used in this study to analyse the business establishment distribution in Traffic Analysis Zones (TAZs) for five categories of establishments (Industry, Retail, Service, Transportation and Wholesale). This large dataset provides the detailed information of establishment names, establishment addresses, latitude and longitude, primary SIC description, actual sales volume, actual employee size, NAICS code and NAICS description. There are 95 sub sectors of establishments in total which are clustered into 24 sectors and finally re-grouped into five types of establishments, including industry, retail, service, transportation, and wholesale according to NAICS codes. The Business Establishment Data, 2018 is classified according to NAICS codes and descriptions for HRM. The following Table 3-1 illustrates the type of business establishments throughout the HRM.

Table 3-1 Distribution of Business Establishments by NAICS Categories

Establishment Types	NAICS Sector	Number of Establishments	Total
Industry	11 Agriculture, forestry, fishing, and hunting	16	**1397**
	21 Mining, quarrying, and oil and gas extraction	28	
	23 Construction	931	
	31-33 Manufacturing	422	
Retail	44-45 Retail Trade	1810	**1810**
Service	22 Utilities	6	**7243**
	51 Information & Cultural Industries	203	
	52 Finance & Insurance	635	
	53 Real State and Rental and Leasing	523	
	54 Professional, Scientific and Technical Services	1054	
	55 Management of Companies & Enterprises	2	
	56 Administrative and support, waste management and remediation services	430	
	61 Educational services	352	
	62 Health care and social assistance	1063	
	71 Arts, entertainment, and recreation	279	
	72 Accommodation and food services	972	
	81 Other services (except public administration)	1561	
	91 Public administration	163	
Transportation	48-49 Transportation & Warehousing	285	**285**
Wholesale	41 Wholesale Trade	617	**617**
Unclassified	99 Unclassified	80	**80**
	Total Business Establishments in HRM		**11432**

However, some business establishments provided their global employee size and yearly sales (for example, Stantec or Emera Inc.) which can result in overestimating these values for HRM. Therefore, the employee size and sales of these business establishments are adjusted for HRM. And finally, utilizing the exact latitude and longitude, the business establishments are geocoded and then spatially joined with attributes of Halifax to determine the sales of each TAZ in the HRM. Finally, the activity-based travel demand model is calibrated using different k-factors for urban, suburban, and rural areas.

3.4.4 Development of Latent Class Regression Model

This study utilizes a regression modelling framework for estimating the impact of activity and mobility restrictions on sales volume of local businesses. To capture the unobserved heterogeneity of the variables across TAZs the Latent Class Regression Model coded within *NLOGIT 6* platform, is utilized by assigning them to different latent classes. A linear regression function for TAZ i belonging to class c can be written as,

$$f\left(y_i \middle| x_{ij}\right) = f\left(y_i, \beta_c^{'} x_{ij}\right) = \varphi(i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Here, the index j denotes sales volume whereas x_{ij} is the observed characteristics of TAZ i. The distribution is assumed to be normal with mean of $\beta_c^{'} x_{ij}$ and variance of σ^2. The density is assumed to be affected by the unobserved heterogeneity of the distribution of y_i. The model is modified for a latent sorting of y_i into c classes with a model which allows for heterogeneity. The probability of observing y_i given that regime j applies is,

$$\varphi(i|c) = \varphi\left(y_i \middle| x_{ij}, c\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

But it is unknown that in which class TAZ i is allocated, and class membership must be estimated. Therefore, a simple form of the class variation is considered, where only the constant term varies across the classes. The model can be expressed as:

$$\varphi(i|c) = \varphi\left[y_i, \beta_c^{'} x_{ij} + \delta_{ic}\right], Prob[class = c] = F_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This model can be formulated more generally as,

$$\varphi(i|c) = \varphi\left[y_{ij}, \beta_c^{'} x_{ij} + \delta'_{ic}\ x_{ij}\right], F_c = \frac{e^{\theta_c}}{\sum_c e^{\theta_c}}\ , \qquad with\ \theta_c = \ 0\ \ldots\ldots\ldots\ldots\ldots.\ldots\ldots(4)$$

In this formulation, each class has its own parameter vector $\beta_c^{'}$, although the variables that enter the mean are assumed to be the same. In sum, the model is:

$$f\ (y_i|class = c)\ =\ N\left[\ \beta_c^{'} x_{ij}, \sigma_j^2\right], Prob\ (class = c) = F_c =\ \frac{e^{\theta_c}}{\sum_c e^{\theta_c}} \ldots\ldots\ldots\ldots\ldots\ldots.(5)$$

Thus, the within class model is the linear regression model with normally distributed disturbances. The fit of Latent Class Model is estimated by considering log-likelihood, AIC, and BIC values. For this model, the logarithmic value of yearly sales is considered as the dependent variable. The model has several explanatory variables classified into business attributes, mobility attributes, and built-environment attributes. Business attributes cover the characteristics of business establishments such as operating industries, retails, services, wholesale and transportation type businesses and employee size. On the other hand, mobility attributes mainly focus on the activity patterns and mode choice including shopping activity, recreational activity, work activity and total number of autos, transit, bike and walk trips. The number of auto drivers and auto passengers are also considered in mobility attributes. The Canadian Census, 2016 is utilized to gather information about the built environment characteristics of each TAZ. Built environment attributes represent the neighborhood characteristics, which consist of population density, dwelling density, number of houses by type (single detached, semi-detached, apartment and row), percentage of ownership and rental houses, full-time and part-time employment, people in the labour force and not in the labour force, total employed and non-employed people, employment rate, activities destined to per business establishments, and land use type (urban, suburban and rural).

3.4.5 Estimation of Sales during Pandemic Scenarios

To estimate the sales volume changes during COVID-19 pandemic scenarios including lockdown and phased reopening stages of Nova Scotia, this study utilizes regression modelling. To develop the pandemic scenarios, along with Google COVID-19 Community Mobility Reports *(Google, 2020)* and Apple Mobility Trend Reports *(Apple Inc., 2020)*, a dataset from Statistics Canada is also utilized to calculate the percentage change in employee size for Nova Scotia during pandemic *(Statistics Canada, 2020)*.

Due to the unavailability of operational business establishments data during the phases of pandemic situation of Nova Scotia, this study estimates the percentage change of businesses operating by incorporating the restrictions implemented by the Nova Scotia Government and the classified Info Canada Data according to NAICS codes. Although there is a decrease in all types of operational business establishments, service and wholesale type firms were operating at almost the same capacity during the entire period predominantly in virtual settings. Therefore, wholesale and service are assumed to be 95% and 90% operational respectively throughout the whole pandemic. Similar assumption is made about participation in work activity as most people were working from home throughout the whole pandemic, which is 90% of business-as-usual scenario. 10% reduction in work activity is assumed to consider the laying off due to shut down of businesses.

3.4.5.1 Business as Usual Scenario

Business-as-usual scenario represents the pre-COVID scenario which is developed utilizing the output from activity-based travel demand model *(Khan and Habib, 2021a)*, Info Canada Data, 2018 and Canadian Census, 2016.

3.4.5.2 Lockdown Scenario

In Nova Scotia, after reporting the first three presumptive cases on March 15th, 2020, a provincial state of emergency was declared by the government on March 22nd and to minimize the spread of the disease, social gathering of more than five people was prohibited *(Province of NS, 2020)*. Certain restrictions were imposed on travelling outside the province. To remain open during lockdown, non-essential workplaces and business establishments had to strictly follow social distancing measures. Even, provincial parks, park beaches and tourist attractions were closed. People were asked to stay home unless any requirement of essential items or services. Childcare, schools, and universities were shifted to online classes and most people started working from home. The lockdown period lasted till April 30th.

During lockdown, in Nova Scotia, auto trip decreased by almost 50% *(Apple Inc., 2020)*. Even 26% decrease in shopping activity (reported as grocery and pharmacy activity in Google COVID-19 Community Mobility Reports), 50% decrease in recreational activity and 54% decrease in work activity from baseline were noticed *(Google, 2020)*. These percentages are implemented to develop the lockdown scenario in the modelling process except participation of work activity.

3.4.5.3 Conservative Reopening Scenario

On May 1st, some restrictions were mitigated including reopening of parks, trails, and fishing *(Province of NS, 2020)* to improve people's mental health. The government started allowing people to visit community garden, nurseries, small businesses, and their own cottages. Drive-in religious services were allowed while maintaining proper physical distancing between cars and people *(Province of NS, 2020)*. On May 15th, golf, paddling, boating, and tennis were resumed and public beaches were reopened *(Province of NS, 2020)*. Family bubble concept was introduced by allowing two immediate family households to gather without physical distancing *(Province of NS, 2020)*. Limit of gathering of people was increased to 10 persons from May 29th and to restart the economy, from June 5th, various business establishments including restaurants (dine out service), bars, personal services and fitness facilities were allowed to open *(Province of NS, 2020)*.

In this model, the period in between May 1st to June 14th is considered as "Conservative Reopening Scenario". Apple Mobility Trend Reports indicate that auto trip increased by around 38% during this period from lockdown scenario *(Apple Inc., 2020)*. Similar pattern is reported by Google COVID-19 Community Mobility Reports regarding people's participation on different types of activities *(Google, 2020)*. For instance, shopping activity increased to 93% of business-as-usual scenario. Recreational activity also increased by 26% from lockdown phase.

3.4.5.4 Aggressive Reopening Scenario

As the situation improves, the provincial government allowed more flexibility in terms of outdoor restrictions, if 6 feet of social distancing is maintained *(Province of NS, 2020)*. From June 15th, licensed childcare centers were allowed to restart operating at minimum 50% capacity and people were allowed to visit long-term care facilities ensuring proper physical distancing measures *(Province of NS, 2020)*. Due to the low rates of COVID-19, government increased the gathering limit of people from June 18th to 50 people with physical distancing and 10 people without physical distancing. But small businesses which are unable to ensure physical distancing were still limited to 10 people *(Province of NS, 2020)*. To boost the business and tourism sector of Nova Scotia, from July 3rd, travel within the Atlantic bubble (Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland and Labrador) without the requirement of self-isolation was permitted due to the low cases of the Atlantic provinces *(Province of NS, 2020)*.

This study considers the time frame from June 15th to July 31st as the "Aggressive Reopening Scenario" stage. For Nova Scotia, the Apple Mobility Trend Report illustrates a 31% increase in auto trip *(Apple Inc., 2020)* while Google COVID-19 Community Mobility Report *(Google, 2020)* also shows 3% increase in shopping activity than business as usual scenario till July 22nd. The percentage of work and recreational activity also increased in aggressive reopening scenario *(Google, 2020)*. As the increase in auto trip and shopping activity during aggressive scenario seem to be overestimated these percentages were adjusted to 90% and 95% respectively. After building the scenarios, latent class regression analysis is used to estimate the probable loss at municipal level.

3.5 Results

3.5.1 Hotspot Analysis of Business Establishments through Halifax Regional Municipality (HRM)

This study demonstrates the hotspot analysis of the business establishments throughout Halifax Regional Municipality (HRM). The percentage of yearly sales and business establishments operating by industry type is summarized in Table 3-2.

Table 3-2 Percentage of Yearly Sales for Each Establishment Types

Business Establishment Types		Industry	Retail	Service	Transportation	Wholesale	All Establishments
Percentage of Yearly Sales	Urban	29%	31%	**72%**	6%	13%	42%
	Suburban	**56%**	**62%**	24%	**79%**	**80%**	**50%**
	Rural	14%	7%	4%	15%	7%	8%
	All TAZs	17%	23%	39%	7%	15%	100%
Percentage of Business Establishments	Urban	19%	39%	45%	24%	20%	39%
	Suburban	57%	50%	43%	59%	70%	48%
	Rural	24%	11%	12%	18%	11%	13%
	All TAZs	12%	16%	**63%**	2%	5%	100%

While considering all TAZs, almost 63% business establishments fall in the category "Service". Similarly, in the urban areas, "Service" produces the highest sales volumes of 72%. However, for all other business establishments, their sales are higher in suburban areas. This is likely a result of there being a higher percentage of the industry, retail, transportation, and wholesale type business establishments in suburban areas over urban areas.

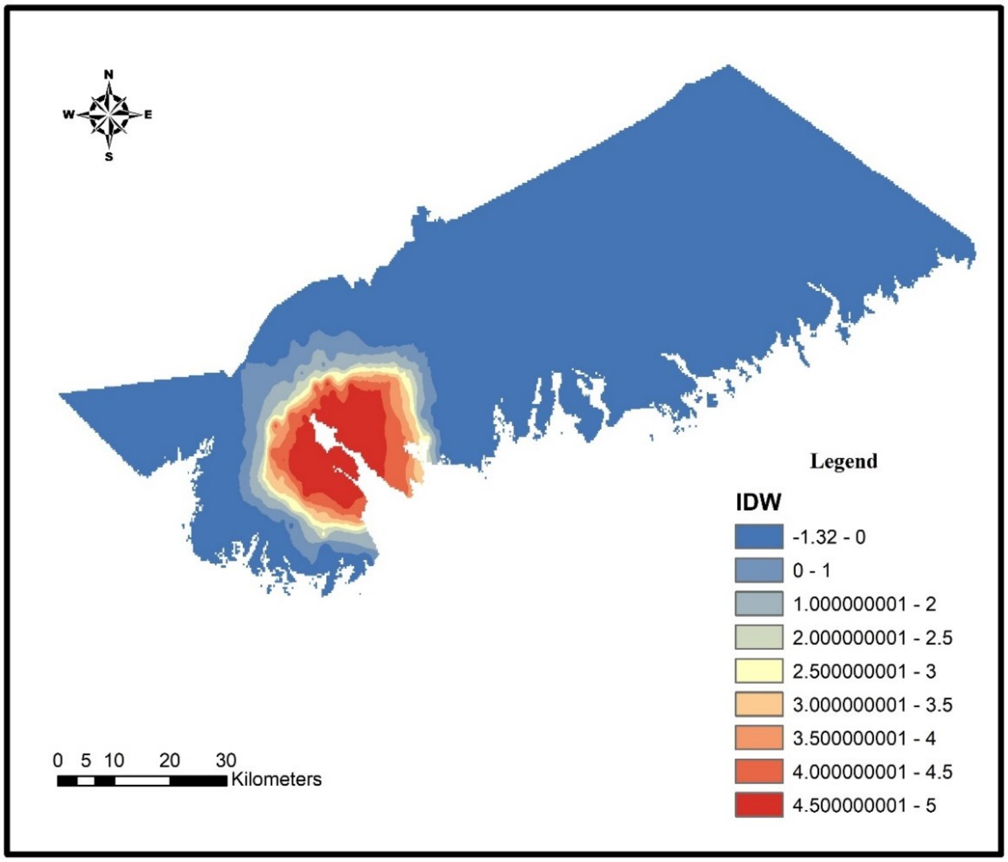
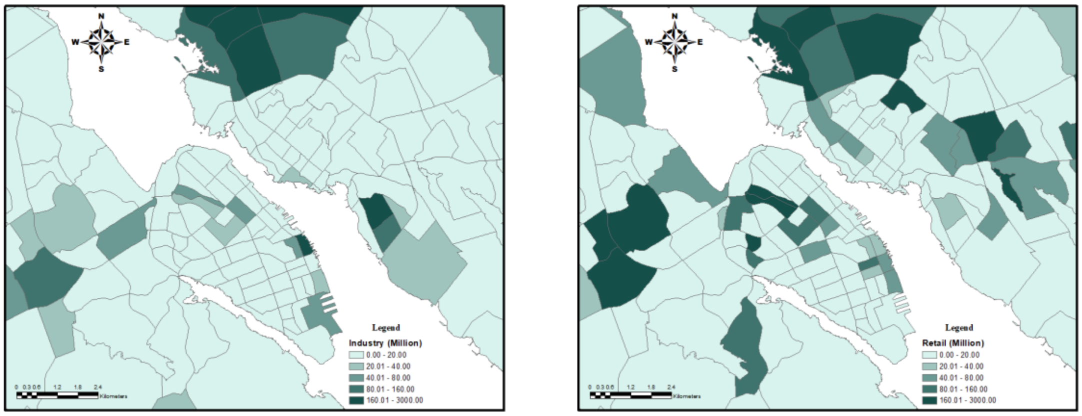
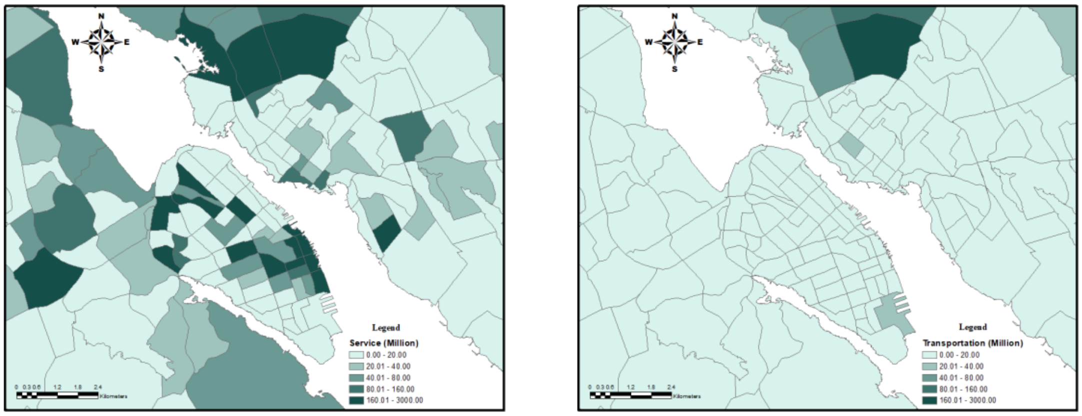


Figure 3-4 Hotspot Analysis of Business Establishment Density throughout HRM

A hotspot analysis is used to understand the distributions and characters of the business establishment distribution throughout HRM. The values shown in the Figure 3-4 demonstrate the Inverse Distance Weighted (IDW) values of TAZs. It is clearly visible that the density of business establishments is highest in the urban core of HRM and decreases gradually in the suburban and rural community.



(a) Industry (b) Retail



(c) Service (d) Transportation

(e) Wholesale (f) All Establishments

Figure 3-5 Yearly Sales (in Million) Distribution throughout Urban Core of HRM by Establishment Types

Total yearly sales for each establishment are spatially joined with the results from the activity-based travel demand model. The spatial distribution shown in Figure 3-5 illustrates sales distribution throughout the urban core of HRM for the five types of business establishments. The yearly sales of "transportation" and "wholesale" is below 20 million for most of the TAZs in the urban core. This distribution clearly indicates a low density of "Transportation" and "Wholesale" type businesses in the urban core of Halifax (Table 3-2). However, for these two types of businesses, sales volume within the range of 160 million - 3000 million indicates the density of business establishments in the "Burnside Industrial Park" area. "Industry" shows a similar pattern of distribution. However, the sales of "Retail" and "Service" indicates different distribution than the rest of the business establishment types. For instance, "Service" type business establishment shows a major concentration in downtown Halifax. Specially, the core downtown Halifax and Halifax waterfront area fall into the maximum range of sales volume. On the other hand, "retail" sales volume is distributed in various TAZs which represent Burnside Industrial Park, Clayton Park, and some areas of Halifax downtown. The retail and service establishments account for a major portion of sales in the urban core. A summary of data collected from business establishment data is enclosed in Appendix A.

3.5.2 Latent Class Model Results

The following Table 3-3 illustrates the summary statistics of the explanatory variables that retained in the final model.

Table 3-3 Summary of Explanatory Variables

	Variables	Description	Mean/ Proportion	Standard Deviation
Business attributes	Retail Operating	Operational retail firms in the zone	10.523	12.862
	Industry Operating	Operational industrial firms in the zone	7.932	10.759
	Service Operating	Operational services in the zone	35.505	40.326
	Wholesale Operating	Operational wholesale firms in the zone	4.407	8.912
	Transportation Operating	Operational transportation firms in the zone	2.794	3.555
	Employee Size	Total employee size	896.041	1719.852
Mobility attributes	Shopping Activity	Total number of shopping activity	568.550	534.350
	Recreational Activity	Total number of recreational activities	933.128	869.880
	Work Activity	Total number of work activity	1862.580	1758.019
	Auto Trip	Total number of auto trips	3555.822	3334.925
Built environment attributes	Population Density	Population density of the neighborhood	1899.364	2172.879
	Home Ownership	Percentage of own home	57.880	28.934
	Urban Core	Dummy, if TAZ is in urban zone = 1, 0 otherwise	42.01%	--

The LCM model of two classes provides log likelihood function of -24.42 along with AIC value of 110.8 and BIC value of 114.36. The model is estimated for two classes, consists of 23.65% TAZs in class one and 76.35% in class two. The model results are presented in Table 3-4.

Table 3-4 Parameter Estimation

Variables		Least Square Regression		Latent Class Model			
				Class 1		Class 2	
		Co-efficient	z	Co-efficient	z	Co-efficient	z
Constant		18.0772	37.36	18.3283	45.75	17.3803	34.49
Business attributes	Retail Operating	0.03872	3.38	0.02936	4.46	0.06252	4.44
	Industry Operating	0.03005	2	0.03352	2.83	0.02715	1.72
	Service Operating	-0.00257	-0.52	0.01045	2.77	0.00907	1.62
	Wholesale Operating	-0.02787	-1.38	-0.08869	-4.41	-0.05221	-2.39
	Transportation Operating	0.05	1.4	0.23903	3.09	0.15259	7.28
	Employee Size	0.00021	2.77	.72090D-04	0.42	-.75884D-04	-0.57
Mobility attributes	Shopping Activity	0.00069	0.8	-0.00203	-3.55	0.00024	0.38
	Recreational Activity	0.00039	0.61	-0.00525	-5.31	0.00027	0.66
	Work Activity	-0.00091	-1.95	-0.00064	-2.3	-0.00096	-2.65
	Auto Trip	0.00029	0.83	0.00166	6.2	0.00046	1.72
Built environment attributes	Population Density	-.68633D-04	-1.09	-.86226D-04	-3.25	-0.00022	-3.55
	Home Ownership	-0.00748	-1.42	0.00842	1.73	-0.00853	-1.71
	Urban Core	0.21987	0.71	2.9806	9.64	0.50944	2.59

Note: | z value | ≥ 1.645 indicates significance level of at least 10%

| z value | ≥ 1.96 indicates significance level of at least 5%

| z value | ≥ 2.576 indicates significance level of at least 1%

For both classes, the number of retail operating, industry operating, service operating, and transportation operating demonstrate a positive relationship with sales whereas wholesale operating indicates negative relationship. Positive relationship of retail operating with sales indicates that as the number of retail increases, the sales volume increases. Similarly, growth in sales volume is noticed with the increase in number of services, industries and transportations operating. The operating wholesale exhibits a negative relationship with sales because the maximum percentage of wholesale business establishments are located further away from the urban core of Halifax. However, TAZs with fewer employees have a higher probability of increased sales volume in the case of class one. In comparison, TAZs in class two reveal a negative relationship.

Interestingly, both shopping activity and recreational activity illustrate heterogeneous behaviour across the two classes. TAZs that attract higher shopping activity as well as recreational activity have greater odds of increased sales volume in class two. On the other hand, these variables show a negative relationship in class one. Except that, work activity maintains a negative relationship in both classes. Because not necessarily every work activity generates sales of business establishments. For example, work trips to hospitals, schools, parks, or churches do not generate any sales of these establishments which can affect the overall relationship of work activity with sales. However, auto trip and population density reflect no heterogeneity across the two classes. Positive relationship of auto trip in both classes indicates that it can be considered as a catalyst in sales volume increase. But population density shows a negative relationship. The higher effect of population density in class two reflects a higher probability of TAZs containing residential houses in class one. Meanwhile, home ownership exhibits a heterogenous behaviour across the two classes. TAZs that belong to class one, have a positive relationship with household ownership and are more likely to have higher sales volume, while TAZs of class two reveal a negative relationship.

3.5.3 Sales Volume Estimation Results

This study estimates the sales volume of 219 TAZs in the HRM utilizing the Latent class regression model for pandemic scenarios including lockdown and phased reopening scenarios of Nova Scotia. In this study, the loss of sales volume is reported by the percentage of sales during the business-as-usual scenario.

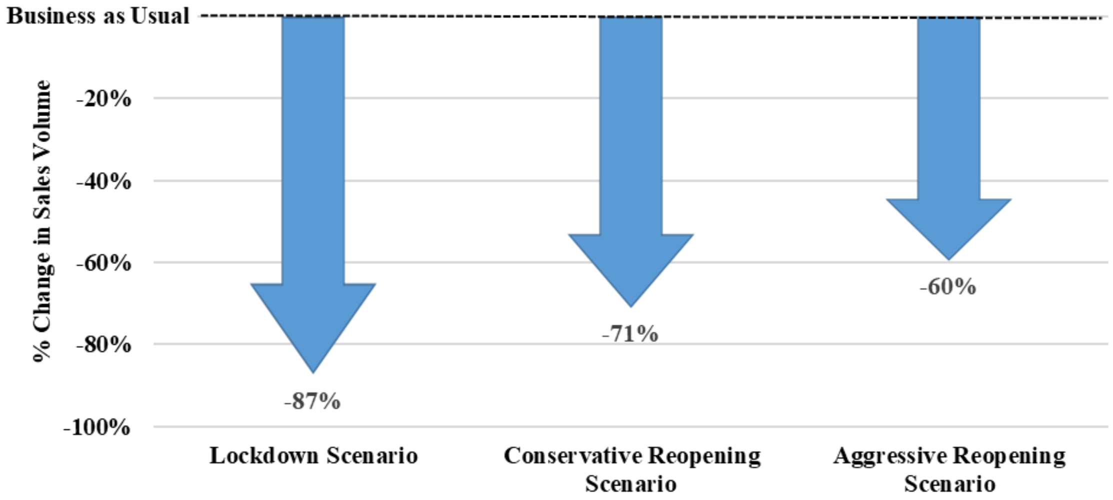
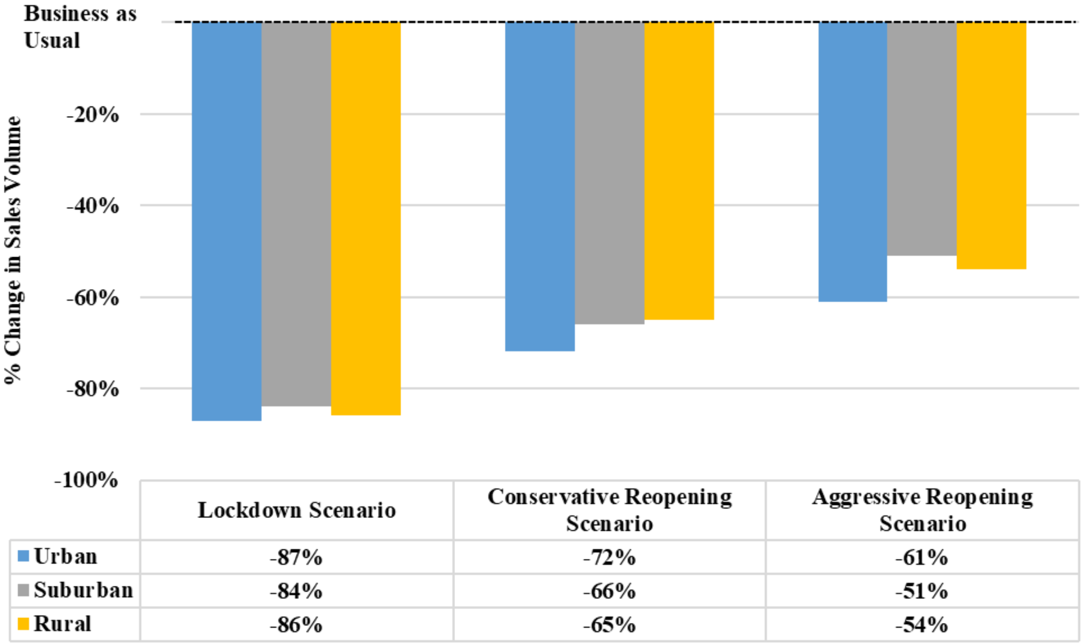


Figure 3-6 Overall Percentage Change in Sales Volume in Three Phases

The results from LCM, shown in Figure 3-6, demonstrates that the sales volume of HRM is highly affected by the pandemic situation. The estimated maximum decrease in sales volume is 87% during the lockdown period. Eventually sales volume begins to increase as the pandemic restrictions begin to ease. The model predicts that during the conservative reopening scenario, the sales volume is 71% of the business-as-usual scenario, which ultimately increased by 11% in the aggressive reopening scenario. The remaining restrictions and laying off labour force reflect the 60% reduction in sales during the aggressive reopening scenario in comparison to the business-as-usual scenario.



	Lockdown Scenario	Conservative Reopening Scenario	Aggressive Reopening Scenario
■ Urban	-87%	-72%	-61%
■ Suburban	-84%	-66%	-51%
■ Rural	-86%	-65%	-54%

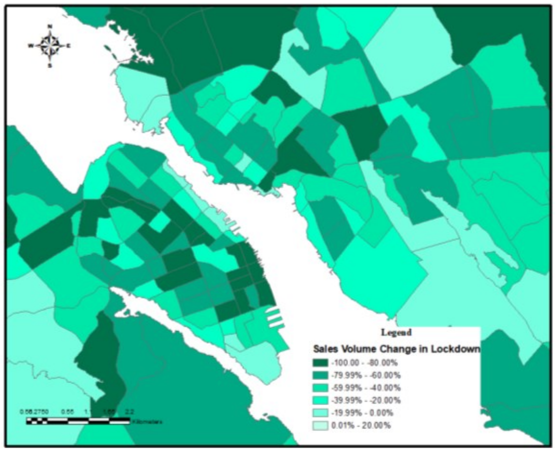
Figure 3-7 Percentage Change in Sales Volume by Area Types in Three Phases

Figure 3-7 depicts the percentage change in sales volume by spatial structure type by using regression modelling. The model results predict that during lockdown, the probable decrease in sales volume is highest in the urban core which is 87%. However, for all land use types, the sales volume is increased from lockdown to aggressive reopening scenario.

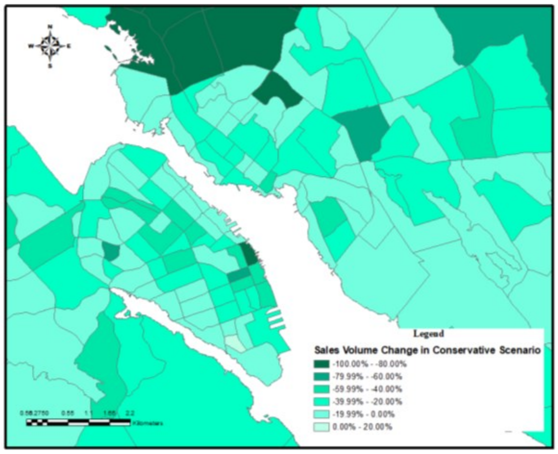
Table 3-5 presents the summary of zonal sales volume loss during pandemic scenarios. The zonal average losses of sales classified by land use type are also reported here. These results reveal that urban zone experiences the highest average zonal loss of 57% during lockdown scenario. Also, the percentage decrease in sales volume from business as usual is divided into six divisions. During lockdown, sales volume changes in all TAZs. The distribution of TAZs indicates that the percentage change in sales volume is somewhat equally distributed over the whole range. However, the model also predicts that the economy started getting better during the conservative scenario, by estimating less than 20% decrease in sales through half of TAZs. The spatial distribution of these results is shown in Figure 3-8.

Table 3-5 Overall Result of Estimated Sales of 219 TAZs of HRM

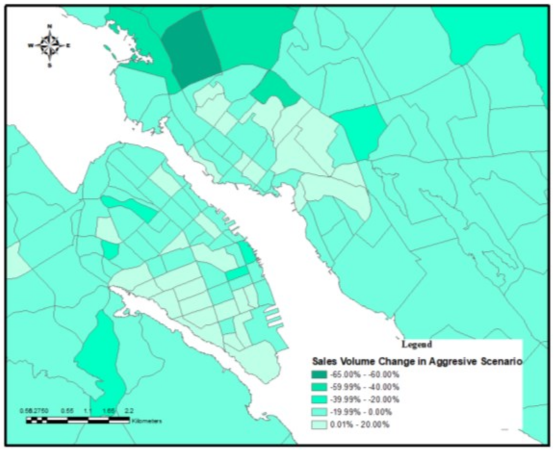
Pandemic Scenarios		**Lockdown Scenario**			**Conservative Reopening Scenario**			**Aggressive Reopening Scenario**		
Land Use Type		**Urban**	**Suburban**	**Rural**	**Urban**	**Suburban**	**Rural**	**Urban**	**Suburban**	**Rural**
		Statistical Summary of Decrease in Sales								
Statistical Criteria	**Mean**	57%	52%	54%	24%	29%	31%	3%	11%	10%
	75 Percentile	78%	75%	85%	31%	45%	52%	5%	16%	18%
	Range	100%	99%	96%	87%	93%	73%	2%	63%	33%
	Maximum	100%	99%	96%	87%	93%	73%	41%	62%	33%
	Minimum	0%	0%	0%	0%	0%	0%	-12%	-2%	0%
		Number of Traffic Analysis Zone (TAZ) Belonging to Each Category								
Percentage Decrease in Sales	**Less than 0%**	0	0	0	0	0	1	1	2	33
	0%-20%	6	17	7	12	40	48	26	76	54
	20%-40%	6	13	20	7	28	27	5	10	4
	40%-60%	5	22	19	10	16	12	0	6	1
	60%-80%	3	23	25	3	4	2	0	1	0
	80%-100%	12	20	21	0	7	2	0	0	0



(a) Lockdown Scenario



(b) Conservative Reopening Scenario



(c) Aggressive Reopening Scenario

Figure 3-8 Spatial Distribution of Percentage Change in Sales Volume during Pandemic Scenarios

From the Figure 3-8, we can see that the traffic analysis zones representing the downtown Halifax and the waterfront area, were affected most during lockdown which also recovered with the reopening stages. These results clearly imply that, as the restrictions on activities and business establishments ease, most of the TAZs are predicted to retrieve their respective sales volume as seen in the business-as-usual scenario. However, the loss during the pandemic situation will represent a great impact on the total economic activities of the business establishments considered.

3.6 Conclusion

This study develops an economic modelling tool aided by an activity-based travel demand forecasting model to estimate economic loss due to restrictions implemented during the lockdown and phased reopening scenarios for COVID-19 in HRM. A novel approach of LCM framework is proposed by utilizing individual business establishment level data. Although it is challenging to ascertain economic losses in exact terms at the Traffic Analysis Zonal level due to data unavailability and methodological inconsistencies in transport and economic modelling, this study offers a first-cut approach for quicker, reasonable estimate of business losses. Particularly two reopening scenarios, can at least offer lower (conservative scenario) and upper (aggressive scenario) bound of losses that businesses incurred.

The latent class model (LCM) explores the effect of business attributes, mobility attributes and built environment attributes. A significant heterogeneity within the two classes of LCM is indicated by the model results. The regression model results exhibit that the municipality faced an average economic loss of 87% during the lockdown period in comparison to the business-as-usual scenario. Through the multistage reopening of the business establishments and activities, the sales volume started to increase. In the aggressive scenario, there is still a 60% reduction in sales volume in the municipality, which reflects the remaining restrictions and laid off labour force. But more than half of the TAZs face only a 20% economic loss indicating the diversity of factors that affect the economy of each zone. Results also reveal variation across land use types. For all land use types, the sales volume is increased from lockdown to aggressive reopening scenario. There are some limitations of this study. Use of multisource data for building alternative reopening scenarios is one of the main limitations which lead to certain assumptions. This study assumes the same percentage change in the variables throughout 219 TAZs of HRM due to insufficiency of data. Availability of the reduction of travel activity and operational business establishments at the zonal level will improve the prediction of economic loss utilizing this tool. Additionally, adding more disaggregated travel activity types as an explanatory variable of this model could help to better understand the relationship of the economy with the travel activity patterns of individuals. Even though online shopping was an option during lockdown, it is not considered in this model. Future study could focus on combining an epidemiological model by implementing health impact parameters within the economic model framework to interpret the pandemic scenarios in the case of future waves. Moreover, real time data of change in travel behaviour and operating business establishments during pandemic in more disaggregate level are needed for further improvement of this model. Nevertheless, this model can be used by the policy makers to estimate the economic impacts of future waves of pandemics to implement different zonal level policies.

Chapter 4

Impact of COVID-19 on Traffic and Emissions during Lockdown

4.1 Introduction

Vehicular emission and associated challenge of climate crisis is a major threat to the world in the 21st century *(US Press Release, 2021)* which has a significant negative impact on the environment and human health. Within urban transportation networks, emissions from passenger cars and commercial vehicles are an ever-present component. Greenhouse gas (GHG) emissions are a significant cause of concern for both personal health and the environment *(Sivanandan et al., 2008).* The most common environmental pollutants are Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Sulfur Dioxide (SO_2), Particulate Matter ($PM_{2.5}$ and PM_{10}) *(Bel and Holst, 2018),* Total Hydrocarbon (THC) and Volatile Organic Compounds (VOC) *(Farzaneh and Zietsman, 2012).* In North American cities, air quality degradation is of particular concern *(Abou-Senna and Radwan, 2012)*. For instance, in Canada, GHG emissions from the transportation sector grew by 31% from 1990 to 2005, making this sector the second-largest contributor of Greenhouse Gas (GHG) emissions *(Bela and Habib, 2020).* It is also reported that vehicular traffic emissions account for 25% of total emissions in Canada *(Ayres, 2010).* However, emission sources from road transport are different depending on geography. For instance, in suburban areas, freight transportation is the primary source of pollution, whereas in urban areas, private vehicles are attributed as a leading source of emission *(Bel and Holst, 2018).* Furthermore, a study by the US Environmental Protection Agency *(US Environment, 2003)* shows that commercial vehicles can contribute up to 38% of transportation's net GHG emissions in the USA. In a port city like Halifax, freight transport is a major concern to the air quality degradation, which causes serious public health concerns and increases the severity of related illnesses *(Künzli et al., 2000).* Within its downtown core, Halifax features two container terminals and one intermodal terminal, which experience a high daily truck traffic flow, especially during the peak hours *(MariNova Consulting Ltd., 2006)*. It is known that this large truck flow for good movements significantly contributes to the local traffic congestion and environmental pollution of the city *(Natural Resources Canada, 2020)*.

Undoubtedly, the outbreak of COVID-19 has an enduring impact on the global economy, environment, and health *(Bai et al., 2020 and Lai et al., 2020)*. A significant impact of COVID-19 on travel behaviour has been reported due to the implemented lockdown and social distancing measures *(Abdullah et al., 2020)*. A study by *De Vos (2020)*, illustrated that people would like to reduce their travel and use active transportation system of private cars over public transit due to the COVID-19 pandemic. The active transportation system will allow people to enjoy the exposure of environment and scenic beauty *(Mokhtarian and Salomon, 2001)*. During the lockdown, there was a significant decline in industrial operations, vehicle kilometres travelled, and commercial activity, resulting in a global reduction in emissions *(Tian et al., 2020)*. Worldwide, there was a substantial reduction of CO_2 emissions of 4% to 11%, with a median value of 8% due to the pandemic restrictions *(Dafnomilis et al., 2020)*. In the Pennsylvania state of United States of America, Carbon Monoxide (CO) and Nitrogen Dioxide (NO_2) got reduced by around 50% *(Tanzer-Gruener et al., 2020)*. Similarly, in Florida, declination of CO_2, SO_2 and NO_2 is reported *(El-Sayed et al., 2021)*. Moreover, In Wuhan, China, average air quality index (AQI) was 59.7 during lockdown which was 33.9% lower than pre pandemic period *(Lian et al., 2020)*.

Though various researchers have examined the impact of COVID-19 restrictions on global and national emissions, very few have analysed the impact on vehicular emissions at the regional and local levels, considering all vehicle types in urban network. Therefore, this chapter considers commercial vehicles and transit, along with passenger cars, to analyse the emissions of regional transport within the Halifax Regional Municipality (HRM), Nova Scotia, Canada. In addition, this chapter proposes an innovative modelling approach by integrating an activity-based travel demand model with the multiclass traffic network model developed within the Equilibre Multimodal Multimodal Equilibrium (EMME) platform, with an emission modelling framework based on the Motor Vehicle Emission Simulator (MOVES) developed by the US Environmental

Protection Agency (USEPA). This chapter assists to provide a comparative analysis of traffic volume and vehicular emissions during the lockdown phase of COVID-19 within the proposed modelling framework at the regional and local levels.

4.2 Literature Review

The COVID-19 pandemic has had a considerable impact on the public health, economy, and environment *(Bai et al., 2020 and Lai et al., 2020)*. By November 1, 2021, around 248 million people have been affected by the coronavirus, including 5 million deaths globally *(Worldometer, 2021).* Lockdown measures were adapted all over the world to minimize the spread of the virus. The imposed lockdown due to the COVID-19 pandemic has affected the global economy of the entire world *(Rajput et al., 2021)*. In contrast, the pandemic has a positive impact on air quality in urban environment. Many studies suggested that the air quality improved during lockdown in various regions *(Zambrano-Monserrate et al., 2021 and Bao et al., 2020).* The underlying reason behind the reduction of air pollutants is the decline in travel demand due to imposed restrictions on mobility. Globally, an 8.8% reduction in CO_2 emissions in the first half of 2020 is reported *(Liu et al., 2020).* A study by *Kumari et al. (2020)* indicates a positive impact of lockdown on air quality throughout the world, including European, American, as well as Asian countries, while experiencing public health measures due to the pandemic. For instance, a study in India shows improvement in air quality in 22 cities due to reductions in emission levels of $PM_{2.5}$, PM_{10}, CO and NO_2 *(Sharma et al., 2020).* Similarly, a decrease of 7.80% of the air quality index (AQI) was reported along with 6.76%, 5.93%, 13.66%, 24.67%, and 4.58% decreases of five major air pollutants: SO_2, $PM_{2.5}$, PM_{10}, NO_2, and CO respectively, for 44 cities of northern China *(Bao et al., 2020).* Moreover, a 36% decrease of $PM_{2.5}$ and a 51% decrease of NO_2 concentration were observed shortly after lockdown in New York City, USA *(Zangari et al.,2020)*.

Lockdown measures have a similar consequence in Canada as well. Given the impact of COVID-19, the GHG emissions of the Canadian transportation sector for 2020 are estimated to be 93 metric tons of CO_2 equivalents, a significant reduction in the past two decades *(Abu-Rayash and Dincer, 2020). Tian et al. (2021)* examined the air pollutant emission of eight representative Canadian cities and found a significant drop of

CO_2 emissions from 7303.73 million kg in March to 4593.01 million kg in April 2020 due to the lockdown, along with decreases in the concentration of NO_2 and CO in different provinces. An average 31% - 34% decrease of NO_2 concentrations and a 6-7% decrease of $PM_{2.5}$ is predicted in four metropolitan areas of Canada: Toronto, Montreal, Vancouver, and Calgary *(Mashayekhi et al., 2021).* Even in Toronto and Mississauga, an average 40% decrease in NO_2 emissions was reported due to the lockdowns *(Griffin et al., 2020).*

However, there are limited research on the impact of COVID-19 at local level considering multiclass transport network model. Therefore, the main objectives of this chapter are: 1) to examine the influence of COVID-19 restrictions on the traffic volume considering multiclass transport network model; and 2) to evaluate the significant reductions of major pollutants during the lockdown situation in the Halifax Regional Municipality (HRM). This study contributes to the existing literature in two ways: 1) by developing a comprehensive modelling framework for the Halifax Regional Municipality (HRM) to examine the impact of COVID-19 on traffic volume and transportation emissions produced by multiple types of vehicles, including delivery trucks and long-haul trucks; and 2) by comparing the emissions of major pollutants for multiple scenarios during the morning and evening peak periods. In addition, this study adds a new dimension to the literature by integrating an activity-based travel demand model with transport network and emission models to predict the change in vehicular movement on traffic networks and vehicular emissions during the COVID-19 pandemic.

4.3 Study Area

A detailed description of the study area considered is illustrated under section **3.3 Study Area**. To represent the commercial vehicle movements, three external zones: Truro, Windsor, and Bridgewater, are considered. Figure 4-1 shows the study area containing 219 Traffic Analysis Zones (TAZs), including 92 urban TAZs, 95 suburban TAZs, 32 rural TAZs and 3 external TAZs coded within EMME/4 platform.

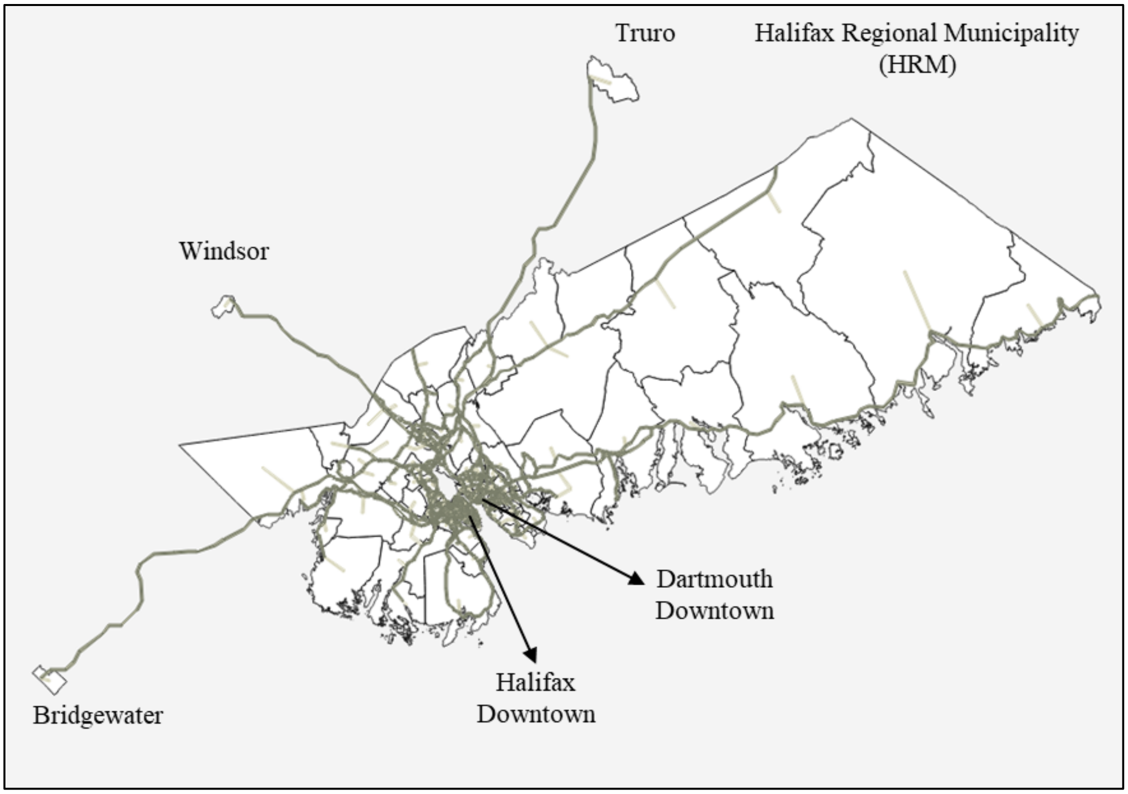
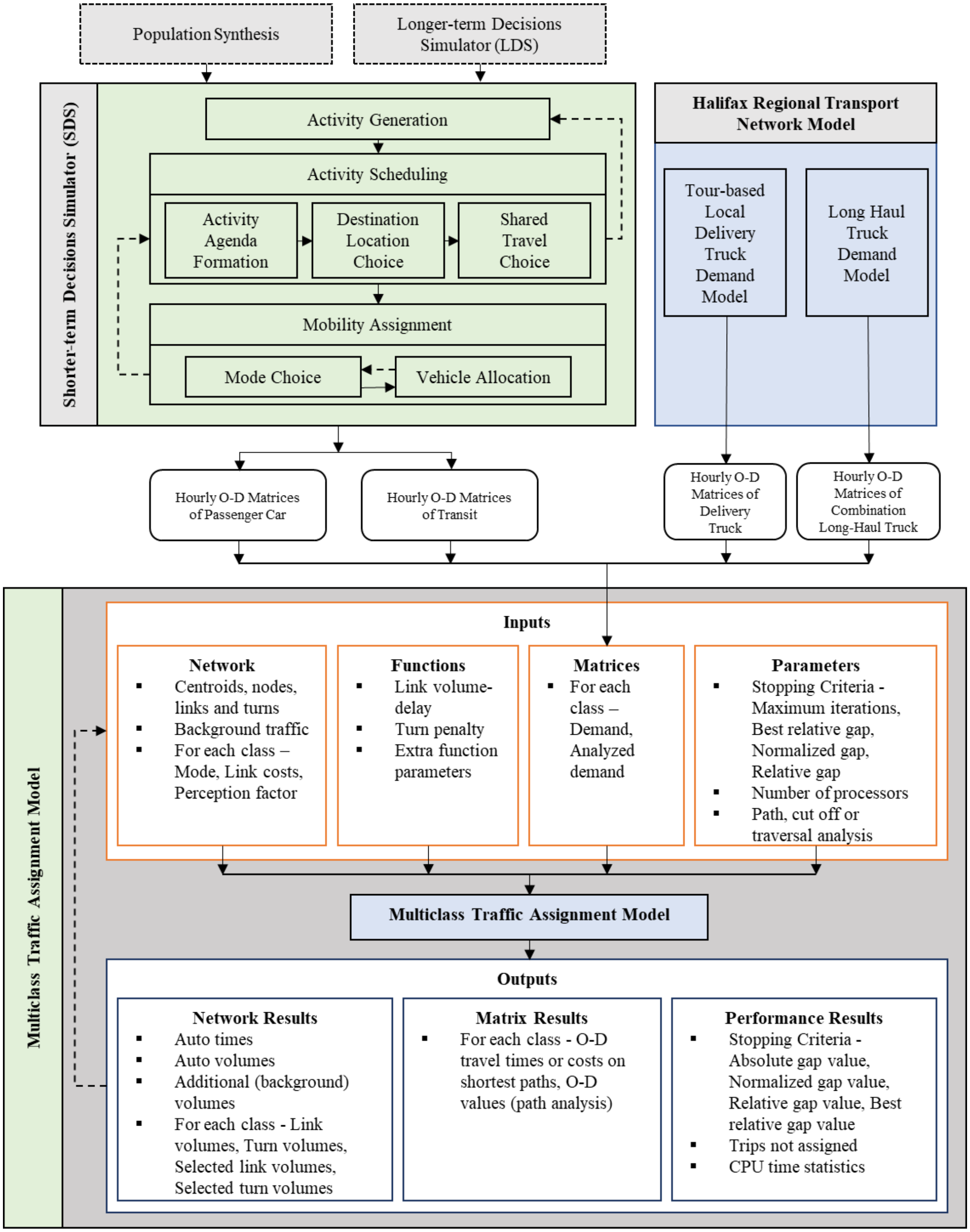


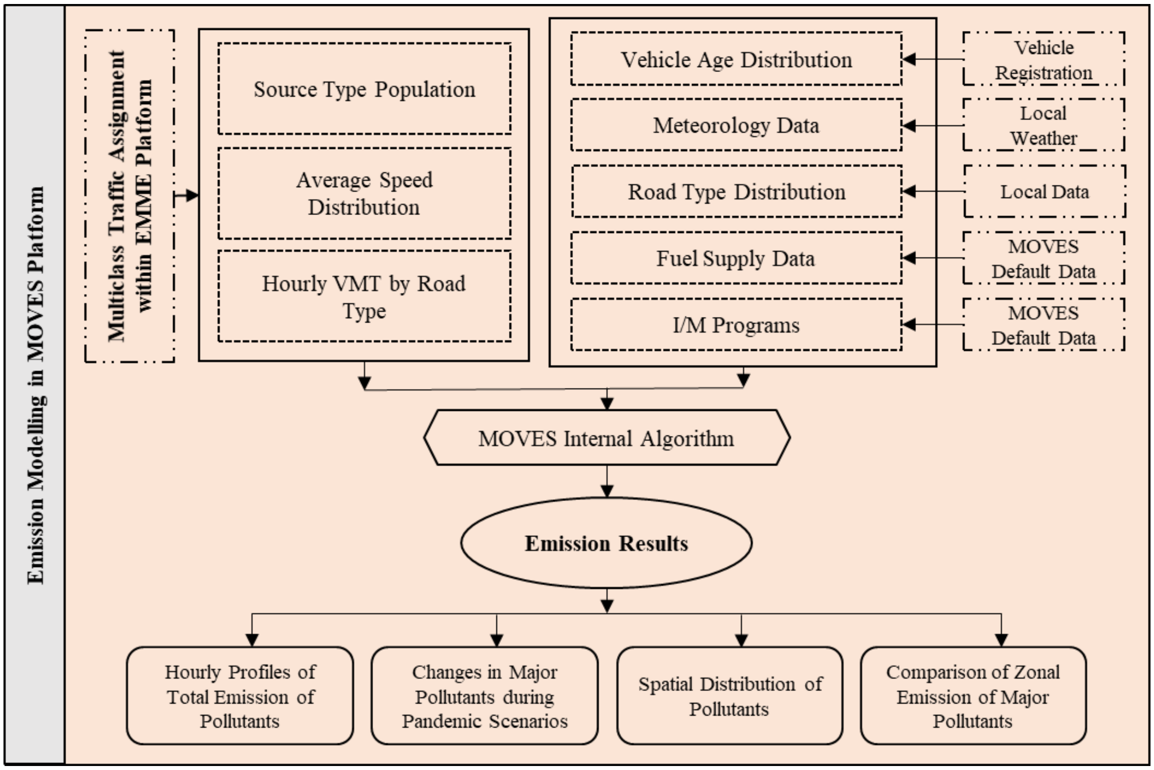
Figure 4-1 Regional Transport Network Model for Halifax Regional Municipality (HRM) along with Three External Zones

4.4 Modelling Approach

This study integrates an activity-based travel demand model *(Khan and Habib, 2021a)*, a Halifax regional transport network model, and an emissions model for the study area to estimate the vehicular emissions of major air pollutants during both business-as-usual and lockdown scenarios. Figure 4-2 portrays an overview of the conceptual modelling framework that is utilized in this study.



a) Integration of Activity-Based Travel Demand Model and Multiclass Traffic Assignment Model



b) Emission Modelling Framework

Figure 4-2 Overview of Conceptual Modelling Framework

4.4.1 Activity-Based Travel Demand Model

The activity-based travel demand model is developed within an agent based discrete-time simulation platform, known as integrated Transport Land Use and Energy (iTLE) platform, for daily travel in the Halifax Regional Municipality. One of the crucial parts of iTLE is the Shorter-term Decisions Simulator (SDS) which takes input from the Longer-term Decisions Simulator (LDS). Shorter-term Decisions Simulator (SDS) is a validated activity-based travel demand model, and a comprehensive validation for the base year and forecasting years is reported by Khan et al. *(Khan et al., 2021b)*. The SDS validation results demonstrate that it has a strong ability to predict travel behaviour for any emergency, such as the COVID-19 pandemic. The pandemic scenarios are developed within this model, and hourly O-D matrices for passenger cars and transit are extracted from SDS output, for instance, the number of activities and mode choices of individuals. The detailed description of activity-based travel demand model will be found under the section **3.4.1 Activity-Based Travel Demand Model**.

4.4.2 Development of Pandemic Scenarios within Activity-Based Travel Demand Model

The pandemic scenarios are developed within the Activity-Based Travel Demand Model. The model considers four available modes – passenger car, delivery truck, combination long-haul truck, and public transit. The changes in volume of passenger car and public transit are predicted from two available mobility data sources - Google COVID-19 Community Mobility Reports *(Google, 2021)* and Apple Mobility Trend Reports *(Apple Inc., 2021).* The reports provide the change in activity patterns and modal share due to the pandemic, respectively. The section **3.4.2 Activity Mobility Estimation** demonstrates the description of Google COVID-19 Community Mobility Reports and Apple Mobility Trend Reports. And for the change in delivery truck and combination long-haul truck volume, Mobility Trends in Calgary Report is used *(Mobility Trends in Calgary, 2020)*. According to Mobility Trends in Calgary report, during the month of April 2020, volume of delivery truck and combination long haul truck were 55% and 62% respectively compared to the business-as-usual scenario. These assumptions are considered to develop model for lockdown scenario.

4.4.2.1 Business-as-Usual Scenario

The business-as-usual scenario represents the pre-COVID timeline developed within the SDS framework of iTLE utilizing the 2016-2017 NovaTRAC (Nova Scotia Travel Activity) Survey data.

4.4.2.2 Lockdown Scenario

The timeline of March 22nd, 2020 - April 30th, 2020, is considered as lockdown scenario in Nova Scotia. During this time, the restrictions on mobility and activities were imposed by the government to minimize the spread of the disease. During this time auto trips got decreased by almost 50% *(Apple Inc., 2021)*. 26% decrease in shopping activity (reported as grocery and pharmacy activity in Google COVID-19 Community Mobility Reports), 50% decrease in recreational activity and 54% decrease in work activity from baseline were noticed *(Google, 2020)*. These observations are used to develop the lockdown scenario in the modelling process. In addition, activities such as school, escort (drop-off and pick-up passengers), personal business (including work and household-related errands, healthcare, civic/religious activities), dine out and recreation (including visiting friends/relatives and entertainment) activities are restricted within activity-based travel model according to the data obtained. In this model, transit mode was assumed to be limited during the lockdown scenario in Nova Scotia.

4.4.3 Halifax Regional Transport Network Model

The study utilized the previously developed Halifax regional transport network model within the Equilibre Multimodal Multimodal Equilibrium (EMME/4) platform *(Bela and Habib, 2020)*. The model includes 222 Traffic Analysis Zones, 222 zonal centroids, 2459 link nodes, and 5272 links. This model considers four modes: passenger car, delivery truck, combination long-haul truck, and public transit.

4.4.3.1 Passenger Car Demand Forecasting Model

The passenger car demand forecasting model of Halifax Regional Transport Network model is modified considering the pandemic scenarios. The model focuses on two peak periods (morning peak and evening peak) to demonstrate differences in network flows during COVID-19 restrictions. The hourly origin destination (O-D) matrices of passenger cars for two peak periods were extracted from the output of the activity-based travel demand model and then a multiclass traffic assignment model was run to estimate the vehicular flows. The activity and mobility restrictions, changes in activity patterns and modal share during pandemic scenarios are incorporated within this model to represent the pandemic scenarios.

4.4.3.2 Tour-based Local Delivery Truck Demand Model

The delivery truck tour model is developed by utilizing Info Canada Business Establishment data set for 2018. This dataset contains 11432 entries detailing business establishment records for the Halifax Regional Municipality (HRM), including 7-digit North American Industry Classification System (NAICS) codes. *Bela and Habib (2020)* developed the delivery truck tour formation and distribution using a Monte Carlo simulation technique. For this study, the origin-destination (O-D) matrices for delivery trucks are modified according to the restriction assumptions during the pandemic scenarios.

4.4.3.3 Long Haul Truck Demand Model

The SHAW GPS tracking information data is used to extract long-haul truck movement information *(Gingerich et al., 2016)* for the business-as-usual scenario. As this dataset includes a record of approximately 56000 Canada-owned trucks, the Halifax-related data was clipped. This model considers three locations outside of HRM at Truro, Windsor, and Bridgewater to represent the long-haul truck movements.

4.4.4 Multiclass Traffic Assignment Model

After the preparation of the hourly O-D matrices for passenger cars, transit, delivery truck, and combination long-haul trucks, a multiclass traffic assignment model is performed by utilizing a user equilibrium assignment principle within the developed transport network model. To solve the user equilibrium multiclass traffic assignment principle, a standard method is used which aims to minimize the overall travel time along the congested road links. In this method, given that there exist alternative options, the congested link discourages more travelers from using it. Thus, this method solves for the link flow and cost to establish a user-equilibrium conditions in the network by iteration.

4.4.4.1 Mathematical Formulation

The traffic assignment implemented in EMME/4 is based on Wardop's user optimal principle. This implementation is mainly a static deterministic user equilibrium model. In the multiclass traffic assignment model, it is assumed that the different classes are subjected to the same congestion level based on the total traffic volume of the link. But each traffic class perceives a different constant bias b_l^m. The cost of the link l perceived by a traffic class can be written as:

$$s_l^m(v_l) = s_l\,(v_l) + b_l^m \qquad l \in L, m \in M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The traffic assignment model implemented in EMME thus computes the equilibrium flows and travel time by solving the following objective function:

$$Min\ f\ (v) = \sum_{l\epsilon L} \int_{0}^{v_l} s_l\ (v + \overline{v_l}) dv + \sum_{l\epsilon L} \sum_{m\epsilon M} b_l^m\ v_l^m + \sum_{n\in N} \sum_{l_1 \in L_n^-} \sum_{l_2 \in L_n^+} \int_{0}^{v_{l_1 l_2}} p_{l_1 l_2}\big(v + \overline{v_{l_1 l_2}}\big) dv \ldots\ldots\ldots. (2)$$

Subject to:

$$v_l = \sum_{r\in R} \delta_{lr} h_r \qquad l \in L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$v_{l_1 l_2} = \sum_{r\in R} \delta_{l_1 l_2 r} h_r \qquad l_1 \in L_n^-, l_2 \in L_n^+, n \in \overline{N} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$\sum_{r\in R_{pq}^m} h_r = g_{pq}^m \qquad p \in P, q \in Q, m \in M \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$h_r \geq 0 \qquad r \in R_{pq}^m, p \in P, q \in Q, m \in M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Here,

Indices and Sets:

$m \in M$	Vehicle classes
$p \in P$	Origin zones
$q \in Q$	Destination zones
$r \in R_{pq}^m$	Directed paths linking p and q for class m
$r \in R$	All directed paths
$n \in N$	Nodes of road network
$n \in \overline{N}$	Nodes corresponding to intersections with turn penalties
$l \in L$	Links of road network

$l \in L_n^-$	Links "ending" at node n
$l \in L_n^+$	Links "starting" at node n

Constants:

g_{pq}^m	Traffic demand from p to q for class m
$\overline{v_l}$	Additional volume on link l
$\overline{v_{l_1 l_2}}$	Additional volume on turn $l_1 l_2$
b_l^m	Fixed link cost on link l for class m
δ_{lr}	1 if link l belongs to route r, 0 otherwise

Functions:

$s_l(v_l)$	Volume-delay function on link l

Variables:

v_l	Traffic volume on link l
$v_{l_1 l_2}$	Traffic volume on turn $l_1 l_2$
h_r	Path flow on route r

4.4.4.2 Convergence Measures

The multiclass user equilibrium assignment method implemented in EMME considers several traffic classes by using different subnetworks and perceiving different fixed link costs in addition to the link travel times. It also considers fixed background volumes and turn penalties at intersection nodes. Therefore, this method is complex and refined than the generic method.

At each iteration of the second-order linear approximation method, EMME determines the solution of the sub problem providing a lower bound, LB, for the optimal value of the objective function $f(v^*)$:

$$LB = f(v) + \sum_{l \epsilon L} s_l(v_l + \overline{v_l})(y_l - v_l) + \sum_{l \epsilon L} \sum_{m \epsilon M} b_l^m \,(y_l^m - v_l^m) + \sum_{d \in D} \sum_{l_1 \in L_d^+} \sum_{l_2 \in L_d^+} \int_0^{v_{l_1 l_2}} p_{l_1 l_2}(v_{l_1 l_2} + \overline{v_{l_1 l_2}})(y_{l_1 l_2} - v_{l_1 l_2}) \ldots\ldots\ldots\ldots (7)$$

Here, $f\ (v)$ is the current value of the objective function.

The best current lower bound, BLB is referred to the largest value of LB obtained up to the current iteration. After that, the 'best relative gap', is determined, which is a measure of the closeness of the current assignment to a perfect equilibrium assignment, by the following equation:

$$Best\ Relative\ Gap = \frac{f\ (v) - BLB}{f\ (v)} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The solution of the subproblem provides another criterion named 'absolute gap' for characterizing the closeness of an assignment to a perfect equilibrium assignment which can be computed as follows:

$$Absolute\ Gap = f(v) - LB = (\sum volume * cost) - (\sum_m \sum demand\ assigned_m * travel\ cost_m) .. (9)$$

However, using the absolute gap directly as a stopping criterion is not practical since its order of magnitude varies from one application to another. Therefore, two measures (i) relative gap, and (ii) normalized gap, are derived from the absolute gap to use as stopping criteria. These measures can be determined by following equations:

$$Relative\ Gap = \frac{Absolute\ Gap}{\sum volume * cost} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$Normalized\ Gap = \frac{Absolute\ Gap}{\sum_m \sum demand\ assigned_m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

A sample of multiclass traffic assignment performance is shown in Appendix G.

4.4.4.3 Calibration and Validation of the Model

The Halifax regional transport network model is calibrated and validated using a traffic volume-based approach for business-as-usual and lockdown scenarios. The count data is collected from video image processing and HRM count data. The simulated and observed passenger car and truck volumes are then compared in terms of R^2, MPE (Mean Percentage Error) and GEH values. The R^2 values are obtained from regression curve, whereas MPE and GEH are estimated by using equations. Five key locations, including two bridges, were validated for the morning peak period (8:00 am – 8:59 am) for the business-as-usual scenario. Due to data unavailability, the traffic volume during the lockdown period is validated for only two bridges – the Macdonald bridge and the MacKay bridge, where traffic volumes were continuously recorded during the pandemic periods. The validation locations are shown in the following Figure 4-3.

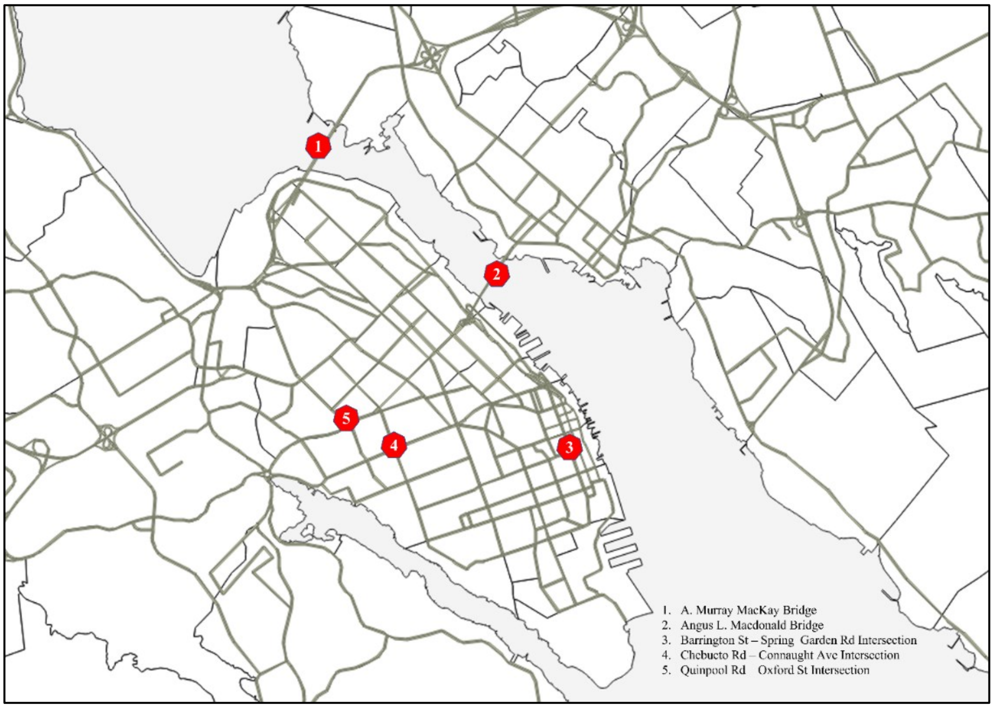


Figure 4-3 Validation Locations for the Study Area

The equations to calculate MPE and GEH are:

$$MPE = \frac{100\%}{n} \sum_{t=1}^{n} \frac{\alpha - \beta}{\alpha} \quad \ldots \ldots (12)$$

$$GEH = \sqrt{\frac{2 * (\alpha - \beta)^2}{\alpha + \beta}} \quad \ldots \ldots (13)$$

Here,

α = observed traffic count data

β = simulated traffic count data

n = number of data points

The validation results are shown below:

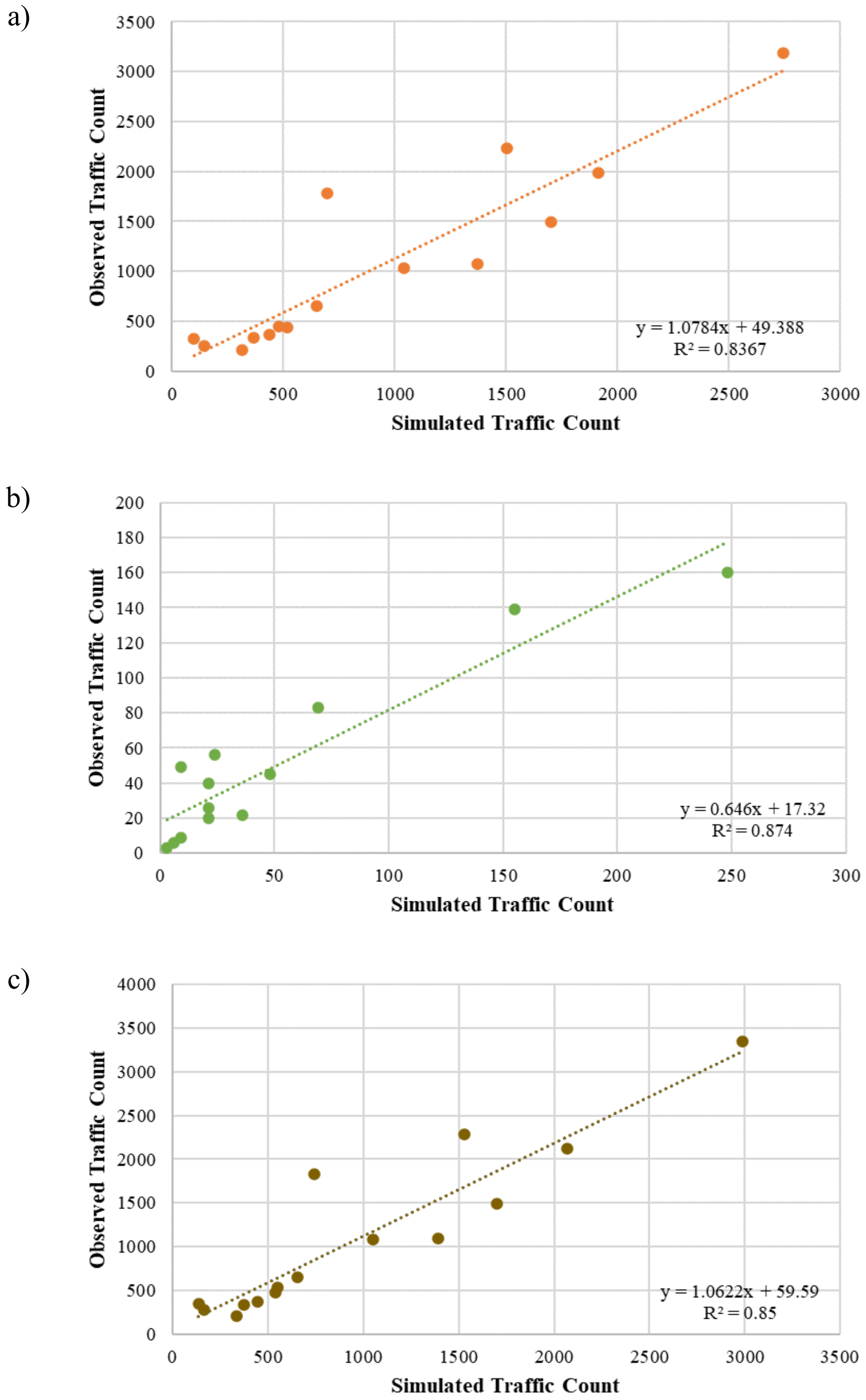


Figure 4-4 Comparison of Observed and Simulated Traffic Count Data of (a) Passenger Car, (b) Truck, and (c) Total Traffic Volume during Business-as-Usual Scenario

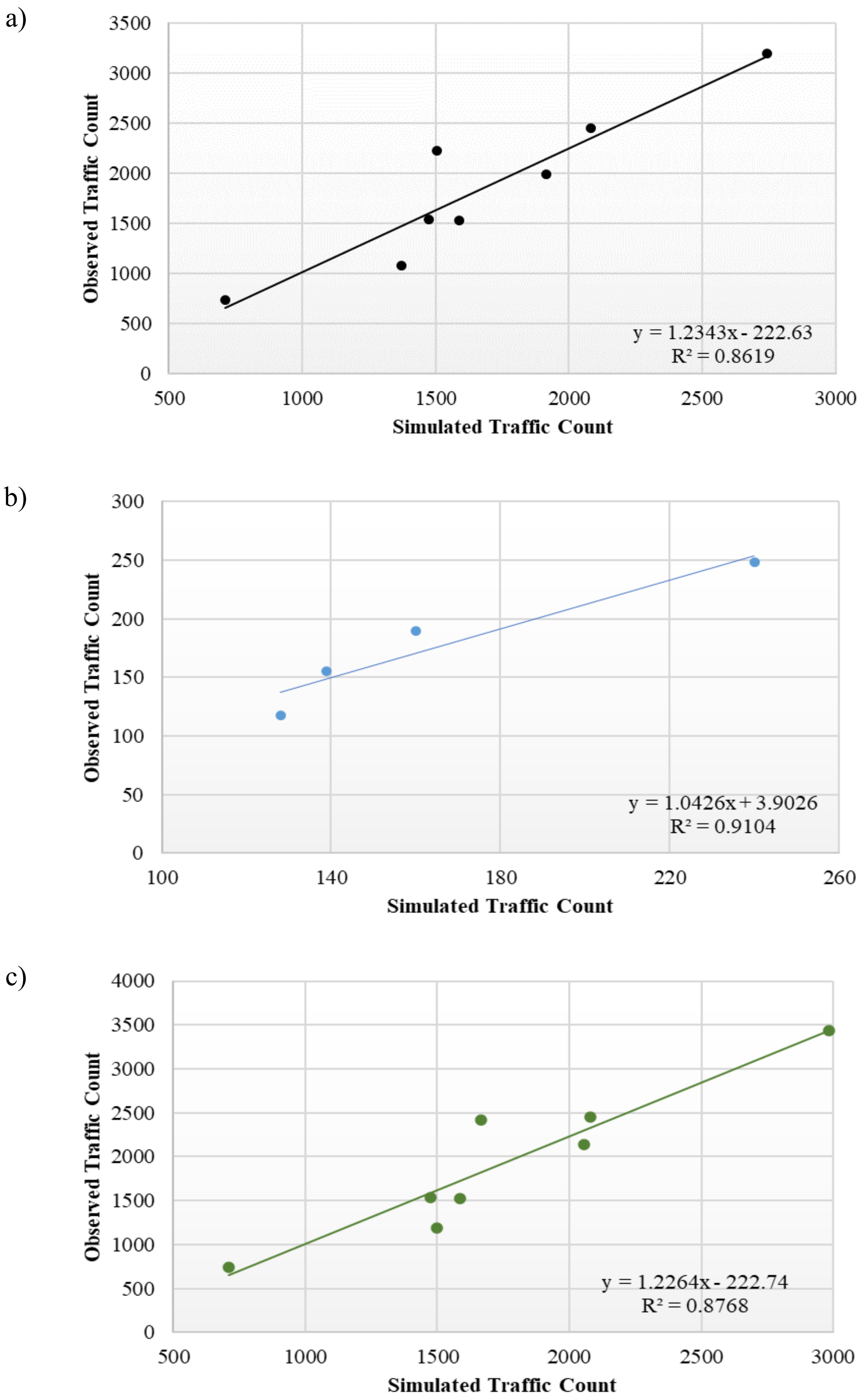


Figure 4-5 Comparison of Observed and Simulated Traffic Count Data of (a) Passenger Car, (b) Truck, and (c) Total Traffic Volume during Lockdown Scenario

The R^2 values for passenger car, truck and total traffic are determined separately for both scenarios. During the business-as-usual scenario, the R^2 values for three modes (passenger car, truck, and total traffic) are 0.84, 0.87 and 0.85 (Figure 4-4) respectively. During the lockdown scenario, the R^2 values for three modes (passenger car, truck, and total traffic) are 0.86, 0.91 and 0.88 (Figure 4-5). The larger the R^2 value, the better the model represents the observed traffic count data. For this study, the value of R^2 is greater than 0.83 for all cases, which proves that the model is a good fit. Another goodness of fit measure, mean percentage error (MPE), computes the average percentage errors of a model as it differs from actual values of the traffic volume. Moreover, during the business-as-usual scenario, the MPE values for three modes (passenger car, truck, and total traffic) are 5.18%, 6.20% and 4.52%. Similarly, during the lockdown scenario, the MPE values for three modes (passenger car, truck, and total traffic) are 5.28%, 5.22% and 5.31%. GEH value is also calculated and found to be less than 5% for all types of movements for both scenarios, which is considered to be a good match between simulated and observed data.

4.4.5 Emission Model

The emission model for Halifax Regional Municipality (HRM) is developed within the latest version of USEPA's Motor Vehicle Emission Simulator (MOVES2014b) platform for the pandemic scenarios. The platform has the capability for three analysis scales: (i) Macro-scale; (ii) Meso-scale; and (iii) Micro-scale *(US Environment, 2009 and 2015)*. The emission modelling framework is developed by following three steps: pre-processing, execution, and post-processing. In the pre-processing step, a RunSpec is created by utilizing several inventories from multiple data sources and results from a multiclass traffic assignment model. Then, in the MOVES County Data Manager (CDM) tool, the emission model is developed. Required different MOVES inventories, for instance, source type population, vehicle type VMT distribution, and average speed distribution are obtained from the Halifax regional transport network model. The emission model is run for two peak periods – (i) Morning Peak Period (7:00am-8:59am), and (ii) Evening Peak Period (4:00pm-5:59pm). The Table 4-1 shows the source type population for business-as-usual and lockdown scenarios. And the Table 4-2 summarizes the vehicle type VMT (HPMSVtypeDay) for one day.

Table 4-1 Source Type Population during Business-as-Usual and Lockdown Scenarios

Source Type ID	Mode	Business-as-Usual Scenario		Lockdown Scenario	
		Morning Peak	Evening Peak	Morning Peak	Evening Peak
21	Passenger Car	480219	486601	300582	176132
52	Delivery Truck	57328	85884	1952	3369
62	Combination Long-haul Truck	23265	33450	10975	16455

Table 4-2 Vehicle Type VMT for One Day during Business-as-Usual and Lockdown Scenarios

HPMSVtype ID	Mode	Business-as-Usual Scenario	Lockdown Scenario
25	Passenger Car	1025608	487218
50	Delivery Truck	118066	4345
60	Combination Long-haul Truck	315509	163629

Meteorology data, vehicle age distribution and road type distribution data are collected from various available sources. Hourly meteorological data are obtained from the Halifax Naval Dockyard weather station by Environment Canada *(Environment Canada, 2021)* for February 2020 (business-as-usual scenario), and April 2020 (lockdown scenario). The Figure 4-6 and Figure 4-7 show the hourly profile of environment temperature and relative humidity respectively for business-as-usual and lockdown scenarios.

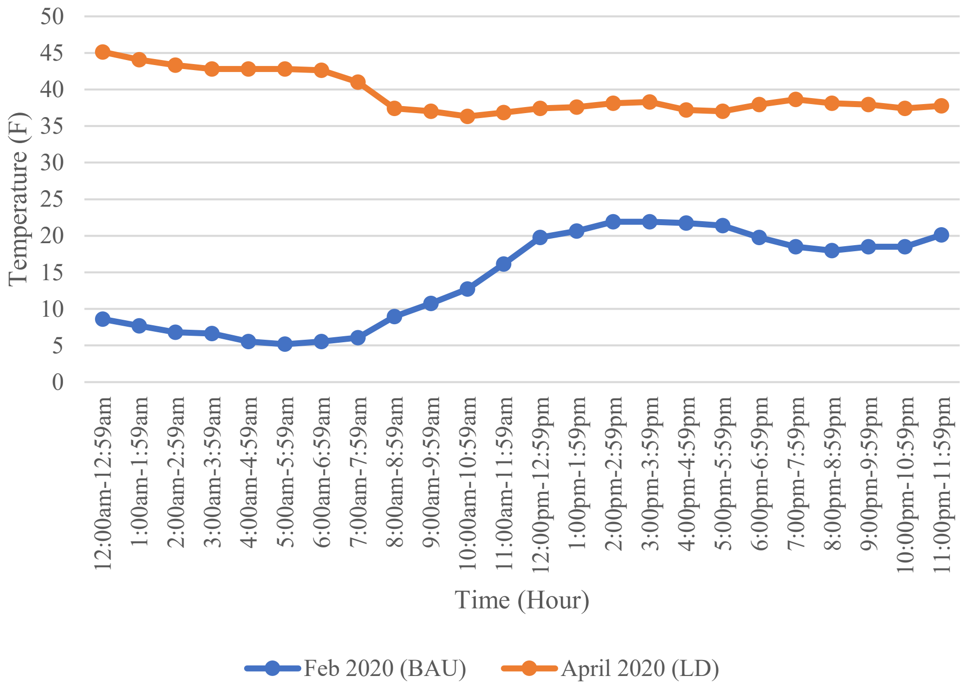


Figure 4-6 Hourly Profile of Temperature during Business-as-Usual (BAU) and Lockdown (LD) Scenarios

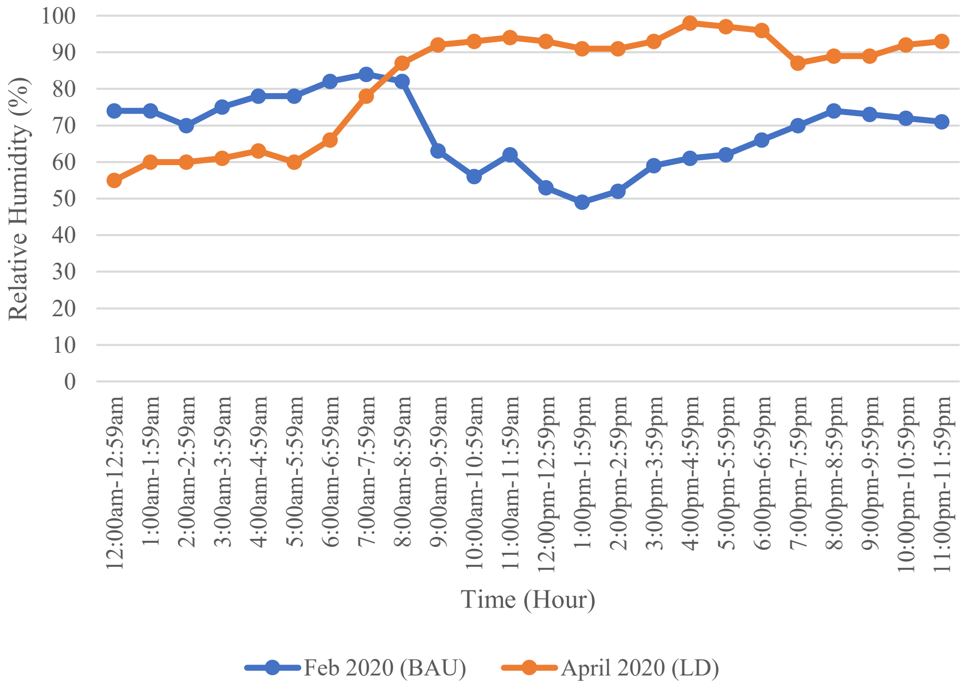


Figure 4-7 Hourly Profile of Relative Humidity during Business-as-usual (BAU) and Lockdown (LD) Scenarios

MOVES defines five different road types – (i) Off-network, (ii) Rural restricted access, (iii) Rural unrestricted access, (iv) Urban restricted access, and (v) Urban unrestricted access. However, all roads of HRM fall in the category of unban restricted, urban unrestricted and rural unrestricted access type road. In this model, all passenger cars are assumed to be operated by gasoline fuel and trucks are assumed to be operated by diesel fuel. Additionally, for fuel and I/M programs, default data from MOVES is utilized. After pre-processing, the model is executed within MOVES to estimate the emission through multiple iterations. After the execution is completed, a summary report for emission has been generated in the post-processing step, which provides the emission by all source types.

MOVES estimates results of emission of various pollutants, GHG as CO_2 Equivalent, carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), particulate matter ranging from 2.5 µm to 10 µm (PM_{10}), particulate matter smaller than 2.5 µm ($PM_{2.5}$), total hydrocarbons (THC), and volatile organic compounds (VOC) by considering multiple sources. These sources include running exhaust, start exhaust, break wear, tire wear, evaporative fuel leaks, auxiliary power exhaust and others. The "CO_2 Equivalent" in the pollutants is the sum of the global warming potential of other greenhouse gases expressed as a unit of CO_2. The CO_2 equivalent factors in MOVES are shown in Table 4-3.

Table 4-3 CO_2 Equivalent Factors in MOVES

Pollutant	CO_2 Equivalent
Carbon Dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298

Greenhouse gas emission is calculated as CO_2 Equivalent emissions using following weighted equation 3. In this study, CO_2 Equivalent is referred as Greenhouse Gas (GHG).

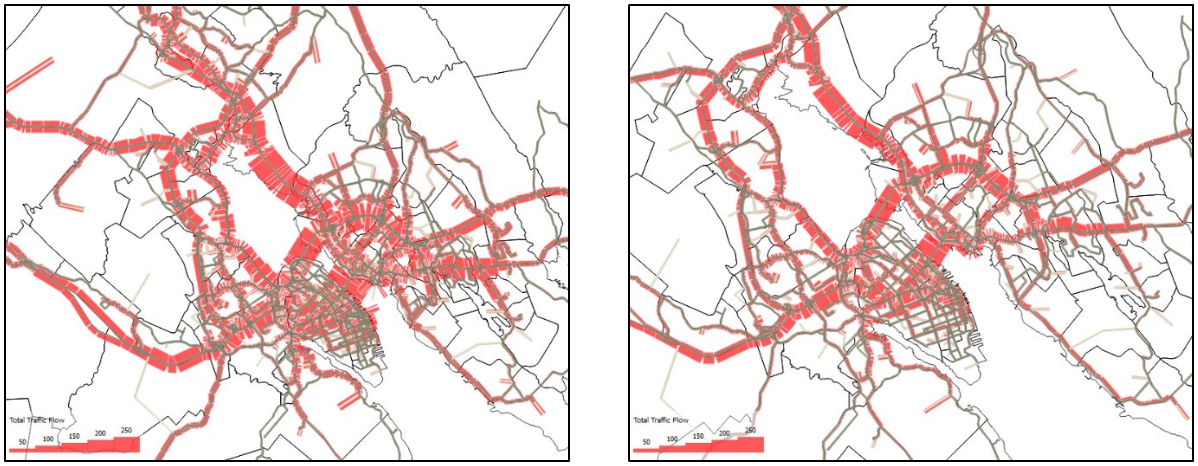
$$GHG\ Emission\ (as\ CO_2\ Equivalent) = 1 \times CO_2\ emission + 25 \times CH_4\ emission + \ 298 \times \ N_2O\ emission \ldots (14)$$

4.5 Result Analysis

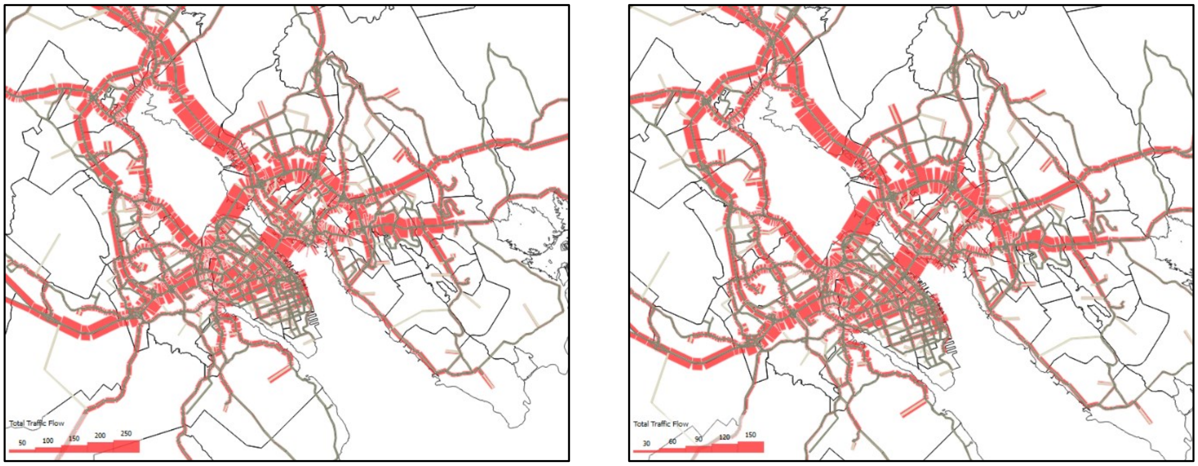
This study explores the impact of the COVID-19 pandemic on traffic volume and vehicular emission. The multiclass traffic assignment model results generate a comparative analysis of traffic flow by link in lockdown scenario with pre-COVID levels. To better understand the impact of COVID-19 mobility restrictions on air quality in the HRM, results obtained from the multiclass traffic assignment model are used to generate vehicular emissions. The emission modelling enables a comparative analysis of hourly profiles of total emissions of pollutants, spatial distribution, and zonal emissions for two peak periods in Halifax. The results obtained from this study are discussed in the following sections.

4.5.1 Result of Multiclass Traffic Assignment Model

In the Halifax Regional Transport Network Model, the passenger car, delivery truck, and long-haul truck movements are modelled. The result of the multiclass traffic assignment model provides link volume for all modes. The model generates results for four hours of two peak periods. The link volume for total traffic of morning peak period (7:00-7:59 am, and 8:00-8:59 am) are represented in Figure 4-8 which demonstrate the comparison of total traffic flow between business-as-usual and lockdown scenarios. The total traffic volume by link during evening peak period (4:00-4:59 pm, and 5:00-5:59 pm) are shown in the Figure 4-9.

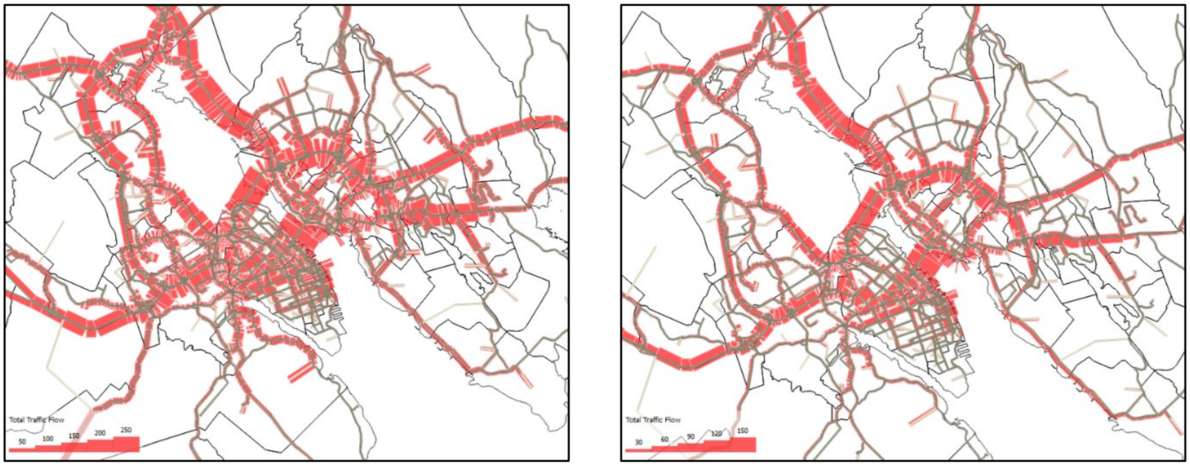


a) Business-as-Usual Scenario (7:00 am-7:59 am) b) Lockdown Scenario (7:00 am-7:59 am)

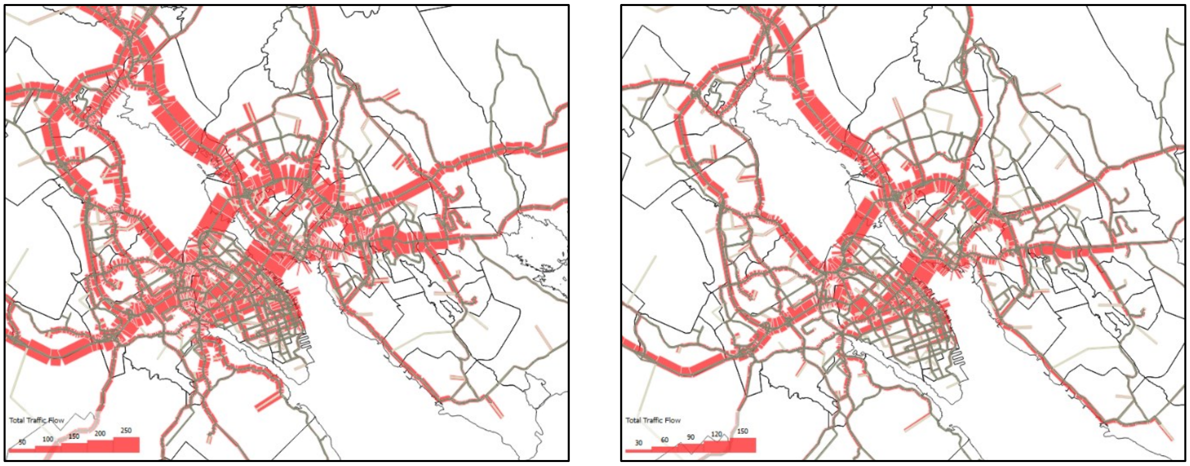


c) Business-as-Usual Scenario (8:00 am-8:59 am) d) Lockdown Scenario (8:00 am-8:59 am)

Figure 4-8 Comparison of Link Volume of Total Traffic Flow during Business-as-Usual and Lockdown Scenarios (Morning Peak Period)



a) Business-as-Usual Scenario (4:00 pm-4:59 pm) b) Lockdown Scenario (4:00 pm-4:59 pm)



c) Business-as-Usual Scenario (5:00 pm-5:59 pm) d) Lockdown Scenario (5:00 pm-5:59 pm)

Figure 4-9 Comparison of Link Volume of Total Traffic Flow during Business-as-Usual and Lockdown Scenarios (Evening Peak Period)

Generally, the road network of the HRM urban core experiences higher traffic flows than suburban and rural areas. From Figure 4-8 and Figure 4-9, it is evident that total traffic volume experienced a significant decrease in all links for the lockdown scenario. During morning and evening peak, total traffic volume decreased by 44% and 68% respectively.

4.5.2 Result from Emission Model

4.5.2.1 Hourly Profiles of Emission of Pollutants

Table 4-4 and Table 4-5 represent the hourly profiles for total emission from passenger cars, delivery trucks, and combination long-haul trucks during both business-as-usual and lockdown scenarios. In this study, vehicular emissions for major pollutants: GHG as CO_2 equivalent, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC are estimated.

Table 4-4 Hourly Profiles for Total Emission during Business-as-Usual Scenario

		Pollutants	**GHG**	**CO**	**NO_x**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**THC**	**VOC**
			Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
	Mode	Time								
Morning Peak Period	Passenger Car	7am to 8am	195.74	2.36	0.12	0.01	0.01	0.00	0.24	0.23
		8am to 9am	203.67	2.37	0.13	0.01	0.01	0.00	0.24	0.23
		Total	399.41	4.73	0.25	0.01	0.01	0.00	0.48	0.47
	Delivery Truck	7am to 8am	26.43	0.05	0.06	0.00	0.00	0.00	0.01	0.01
		8am to 9am	85.59	0.25	0.19	0.01	0.01	0.00	0.06	0.05
		Total	112.02	0.30	0.24	0.01	0.01	0.00	0.08	0.06
	Long-Haul Truck	7am to 8am	177.36	0.13	0.38	0.02	0.02	0.00	0.02	0.02
		8am to 9am	478.44	0.28	1.03	0.05	0.04	0.00	0.06	0.05
		Total	655.80	0.41	1.40	0.06	0.06	0.01	0.08	0.07
Evening Peak Period	Passenger Car	4pm to 5pm	172.37	2.34	0.15	0.01	0.01	0.00	0.24	0.24
		5pm to 6pm	168.16	2.37	0.15	0.01	0.01	0.00	0.25	0.24
		Total	340.53	4.70	0.31	0.01	0.01	0.00	0.49	0.48
	Delivery Truck	4pm to 5pm	47.60	0.07	0.10	0.00	0.00	0.00	0.02	0.02
		5pm to 6pm	39.68	0.04	0.08	0.00	0.00	0.00	0.01	0.01
		Total	87.28	0.10	0.19	0.01	0.01	0.00	0.03	0.03
	Long-Haul Truck	4pm to 5pm	322.66	0.17	0.67	0.03	0.03	0.00	0.03	0.03
		5pm to 6pm	274.83	0.14	0.57	0.02	0.02	0.00	0.03	0.02
		Total	597.49	0.31	1.25	0.05	0.05	0.01	0.06	0.05

Table 4-5 Hourly Profiles for Total Emission during Lockdown Scenario

		Pollutants	**GHG**	**CO**	**NO_x**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**THC**	**VOC**
			Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
	Mode	Time								
Morning Peak Period	Passenger Car	7am to 8am	100.92	1.38	0.07	0.00	0.00	0.00	0.15	0.14
		8am to 9am	99.28	1.35	0.07	0.00	0.00	0.00	0.15	0.14
		Total	200.20	2.73	0.15	0.01	0.01	0.00	0.29	0.29
	Delivery Truck	7am to 8am	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		8am to 9am	3.53	0.01	0.01	0.00	0.00	0.00	0.00	0.00
		Total	4.09	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	7am to 8am	85.16	0.06	0.18	0.01	0.01	0.00	0.01	0.01
		8am to 9am	254.86	0.15	0.55	0.02	0.02	0.00	0.03	0.02
		Total	340.02	0.21	0.73	0.03	0.03	0.00	0.04	0.03
Evening Peak Period	Passenger Car	4pm to 5pm	105.63	1.40	0.07	0.00	0.00	0.00	0.15	0.14
		5pm to 6pm	94.57	1.33	0.07	0.00	0.00	0.00	0.15	0.14
		Total	200.20	2.73	0.15	0.01	0.01	0.00	0.29	0.29
	Delivery Truck	4pm to 5pm	2.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		5pm to 6pm	1.98	0.01	0.00	0.00	0.00	0.00	0.00	0.00
		Total	4.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	4pm to 5pm	186.89	0.11	0.40	0.02	0.02	0.00	0.02	0.02
		5pm to 6pm	153.13	0.10	0.33	0.01	0.01	0.00	0.02	0.02
		Total	340.02	0.21	0.73	0.03	0.03	0.00	0.04	0.03

During the business-as-usual scenario, the total emissions of GHG, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC for passenger cars during the morning peak period are 399.41 ton, 4.73 ton, 0.25 ton, 0.01 ton, 0.01 ton, 0 ton, 0.48 ton and 0.47 ton respectively. In contrast, during the lockdown period, total emission by passenger car decreased and was found to be 200.20 ton, 2.73 ton, 0.15 ton, 0.01 ton, 0.01 ton, 0.0 ton, 0.29 ton and

0.29 ton for CO_2, GHG, CO, N_2O, NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC, and VOC, respectively. A similar pattern is noticed for the evening peak period.

4.5.2.2 Changes in Major Pollutants during Lockdown Scenario

The imposed restrictions due to COVID-19 includes mobility restrictions which eventually decreased the emission of major pollutants during lockdown. The model results show that, Greenhouse gas (GHG) emission by passenger car was 399 ton during business-as-usual scenario which got reduced to 200 ton during lockdown scenario in the morning peak period (Figure 4-10). The morning peak period is of two hours starting from 7:00 am and ending at 8:59 am. Similarly, vehicular emission from commercial vehicle shows a noticeable decrease in the lockdown scenario during both peak periods. GHG emission by commercial vehicle was reported to be 768 ton which decreased to 344 ton in the morning peak period of lockdown scenario (Figure 4-11). While considering all mode, the GHG emission during lockdown got reduced to 544 ton compared to 1167 ton in the business-as-usual scenario (Figure 4-12). In both peak periods, similar pattern for GHG emission is noticed.

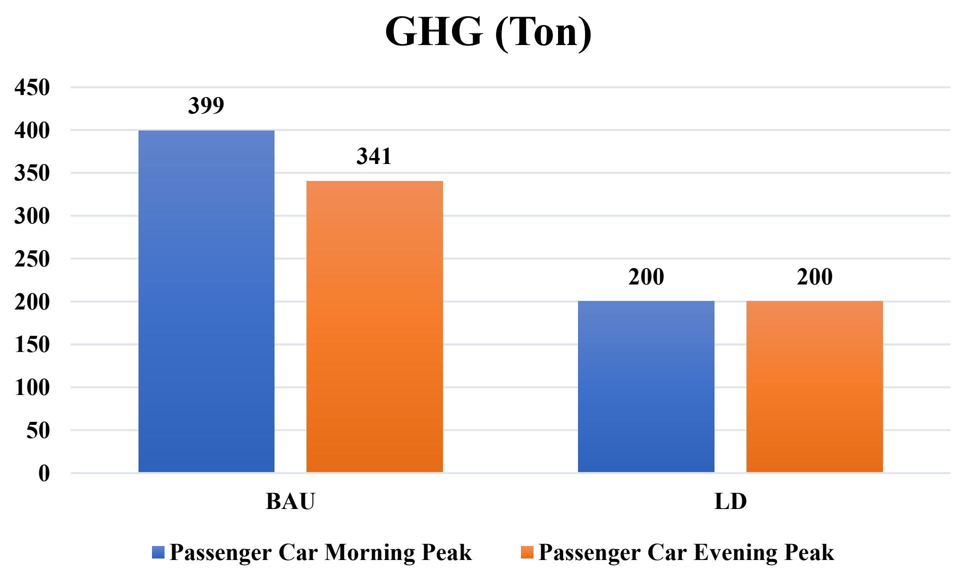


Figure 4-10 GHG Emission by Passenger Car during Business-as-Usual (BAU) Scenario and Lockdown Scenario

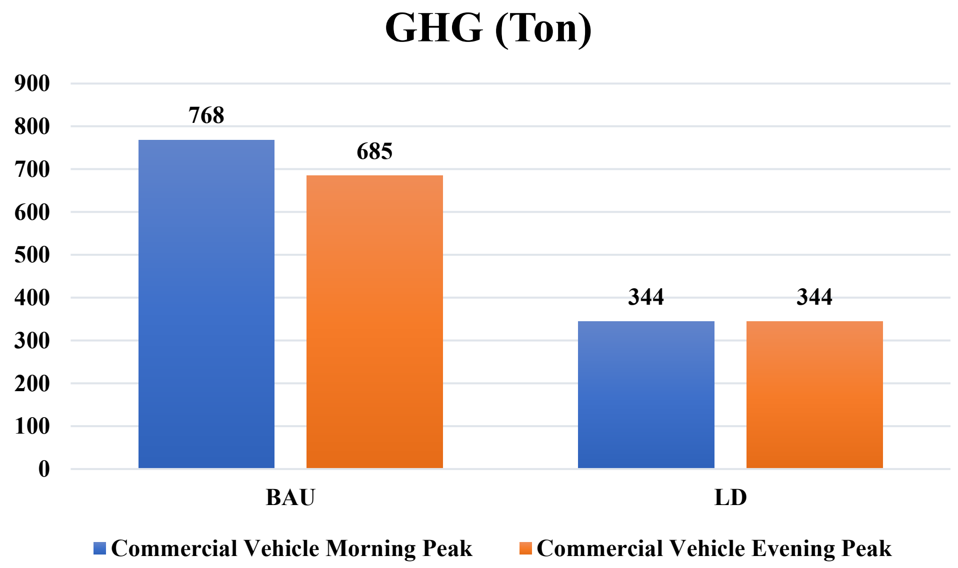


Figure 4-11 GHG Emission by Commercial Vehicle during Business-as-Usual (BAU) Scenario and Lockdown Scenario

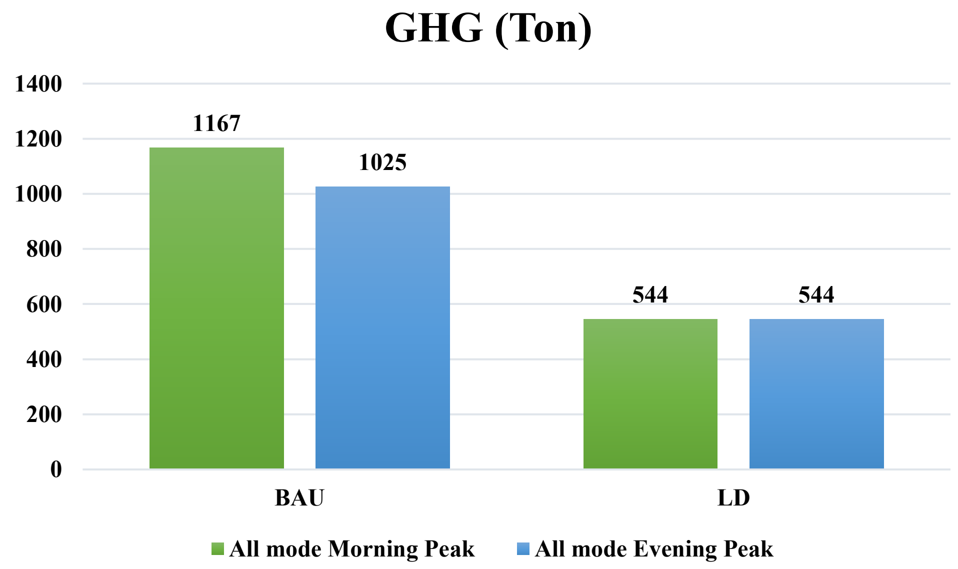


Figure 4-12 GHG Emission by All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

Similar trend of Carbon Monoxide (CO) emission is illustrated in the model. For both peak periods, CO emission reduced in the HRM. In the morning peak period, CO emission from passenger car dropped to 2732 kg from 4728 kg in the business-as-usual scenario (Figure 4-13) whereas for commercial vehicle, the CO emission is 220 kg in the lockdown scenario which is 604 kg decrease with respect to business-as-usual scenario (Figure 4-14). The reduction in CO emission during morning peak is 2599 kg and evening peak is 2369 kg considering all modes compared to business-as-usual scenario (Figure 4-15).

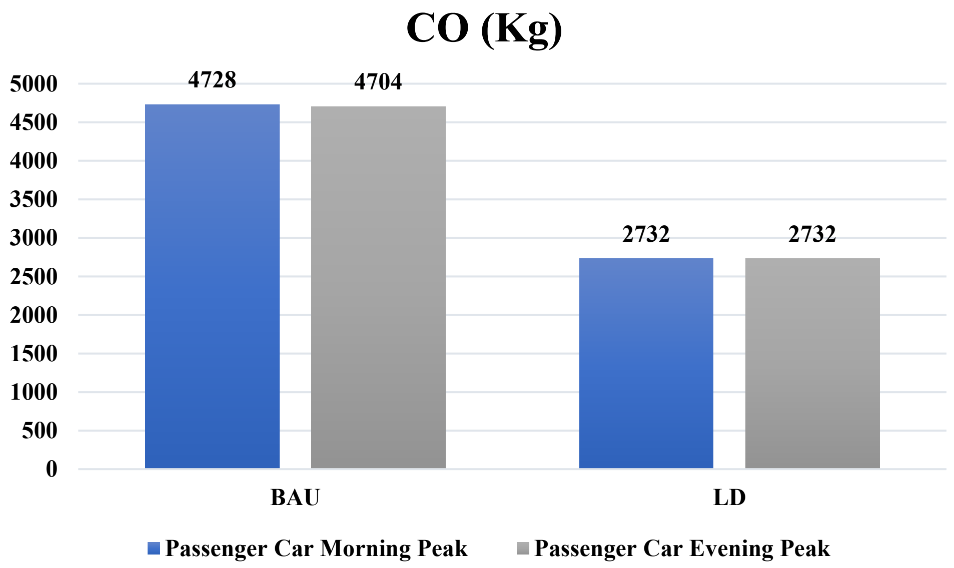


Figure 4-13 CO Emission by Passenger Car during Business-as-Usual (BAU) Scenario and Lockdown Scenario

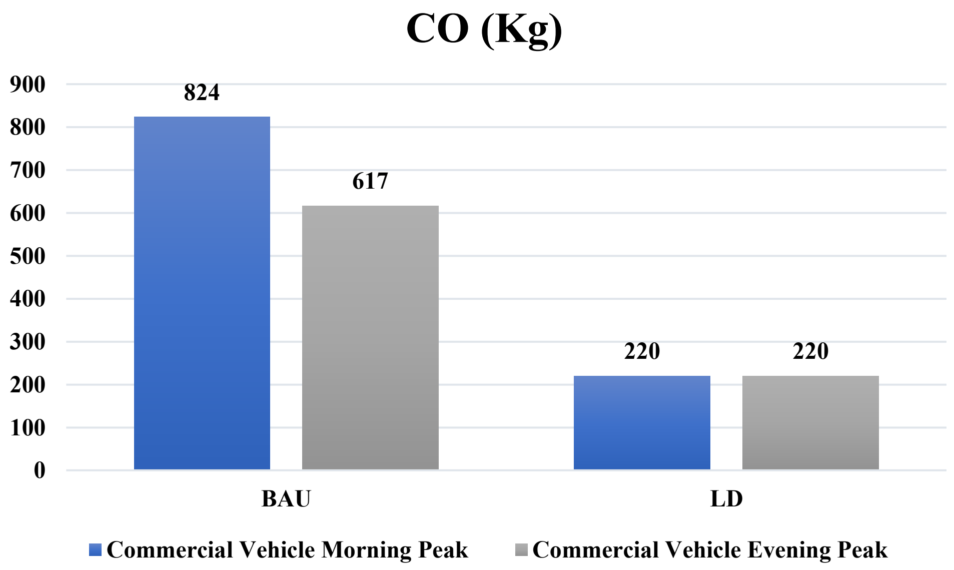


Figure 4-14 CO Emission by Commercial Vehicle during Business-as-Usual (BAU) Scenario and Lockdown Scenario

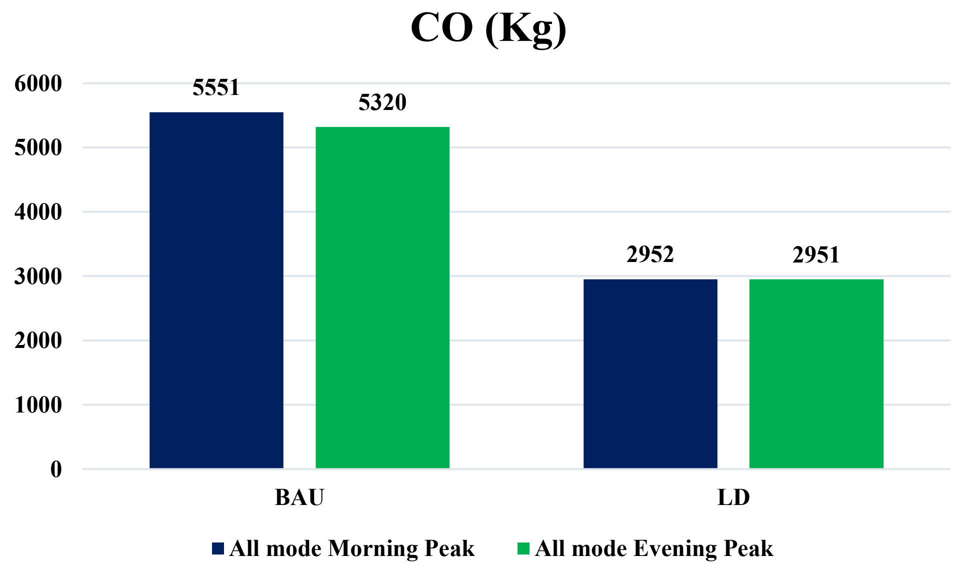


Figure 4-15 CO Emission by All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

Moreover, the rest of the pollutants (NO_x, SO_2, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC) also represent the same pattern of emission reduction during the lockdown period. The following Figures (Figure 4-16 – Figure 4-21) show the change in emissions considering passenger car, commercial vehicle and all mode for morning and evening peak periods.

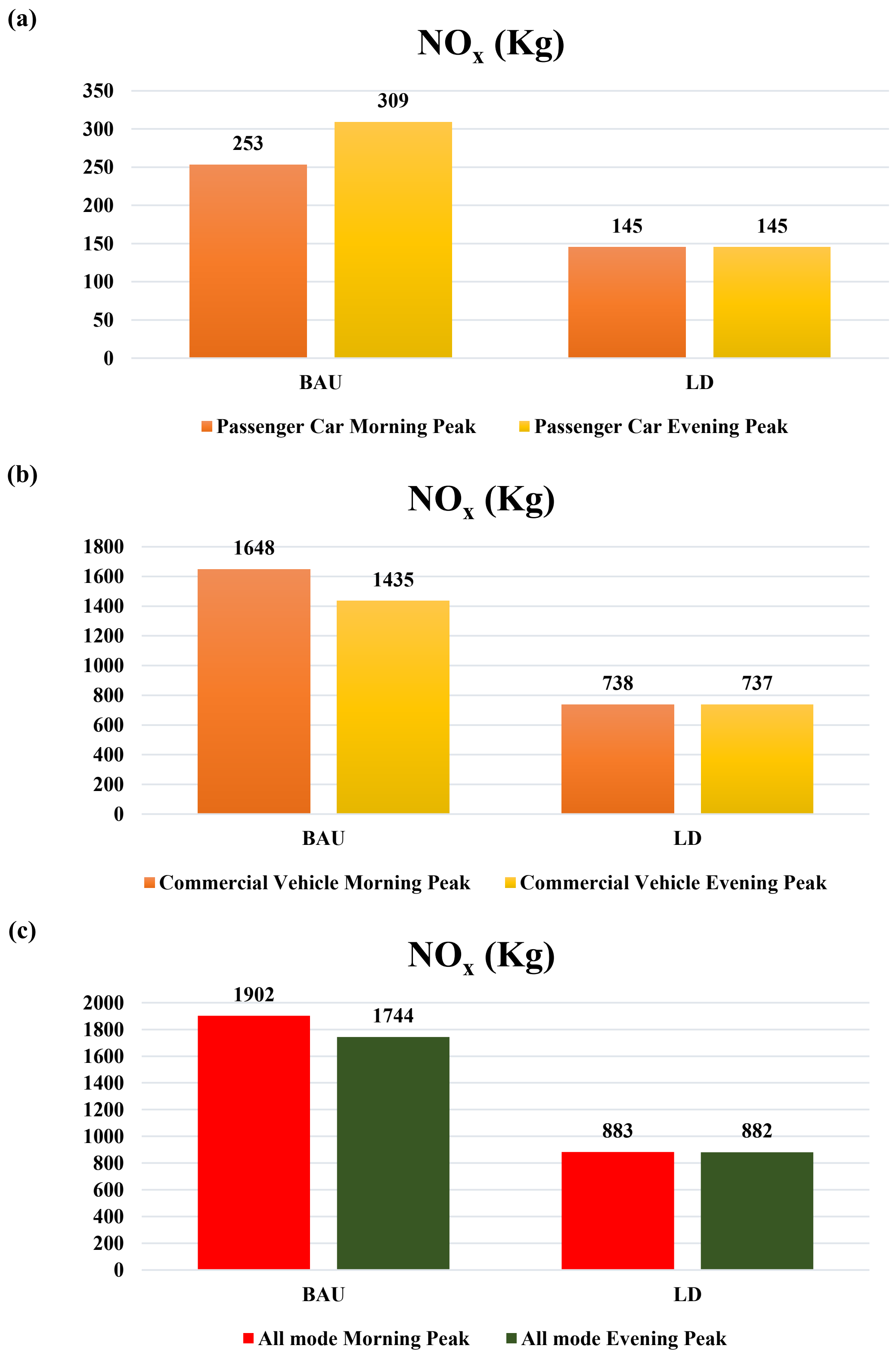


Figure 4-16 NO_X Emission by a) Passenger Car, b) Commercial Vehicle, and c) All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

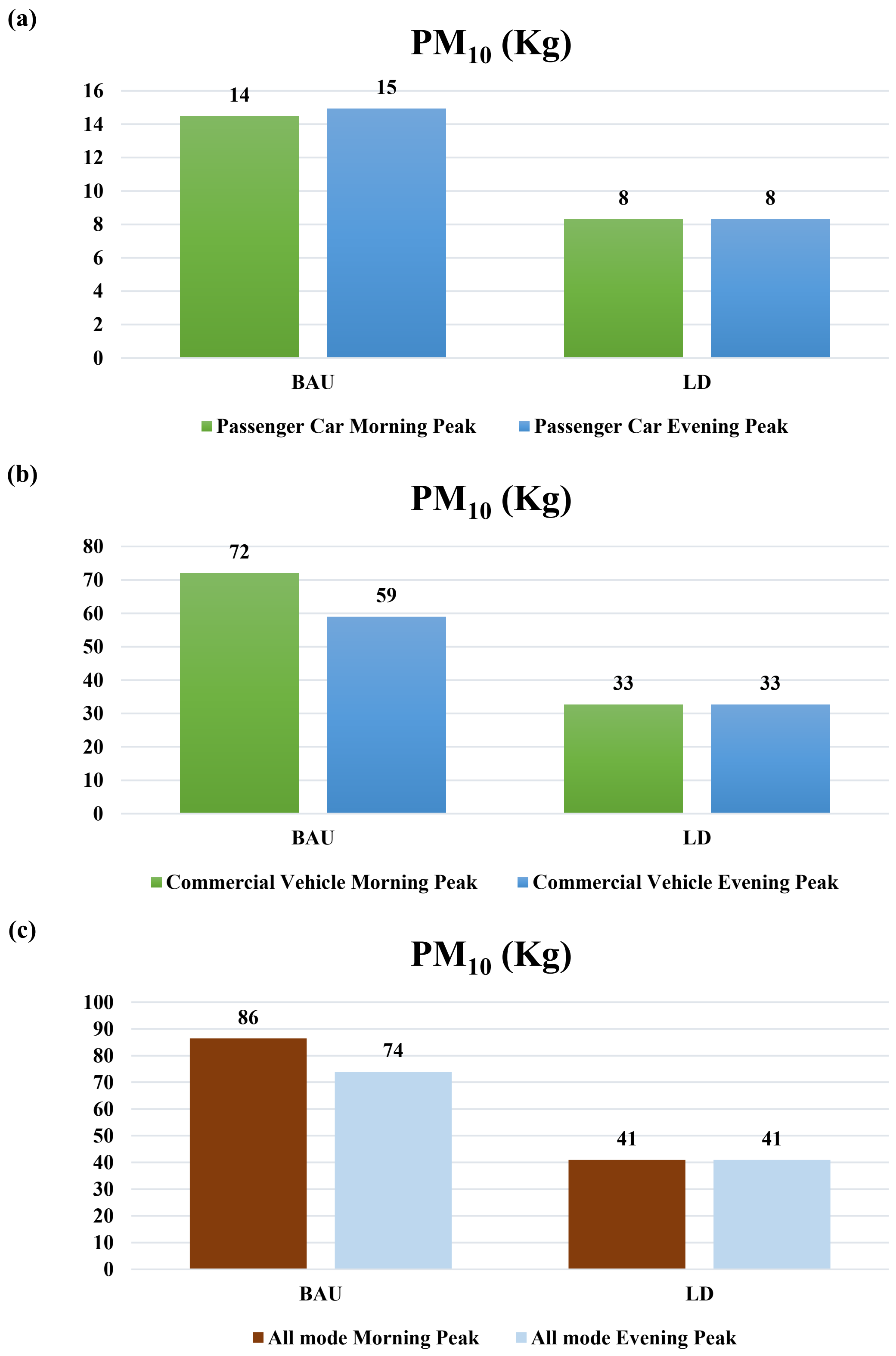


Figure 4-17 PM_{10} Emission by a) Passenger Car, b) Commercial Vehicle, and c) All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

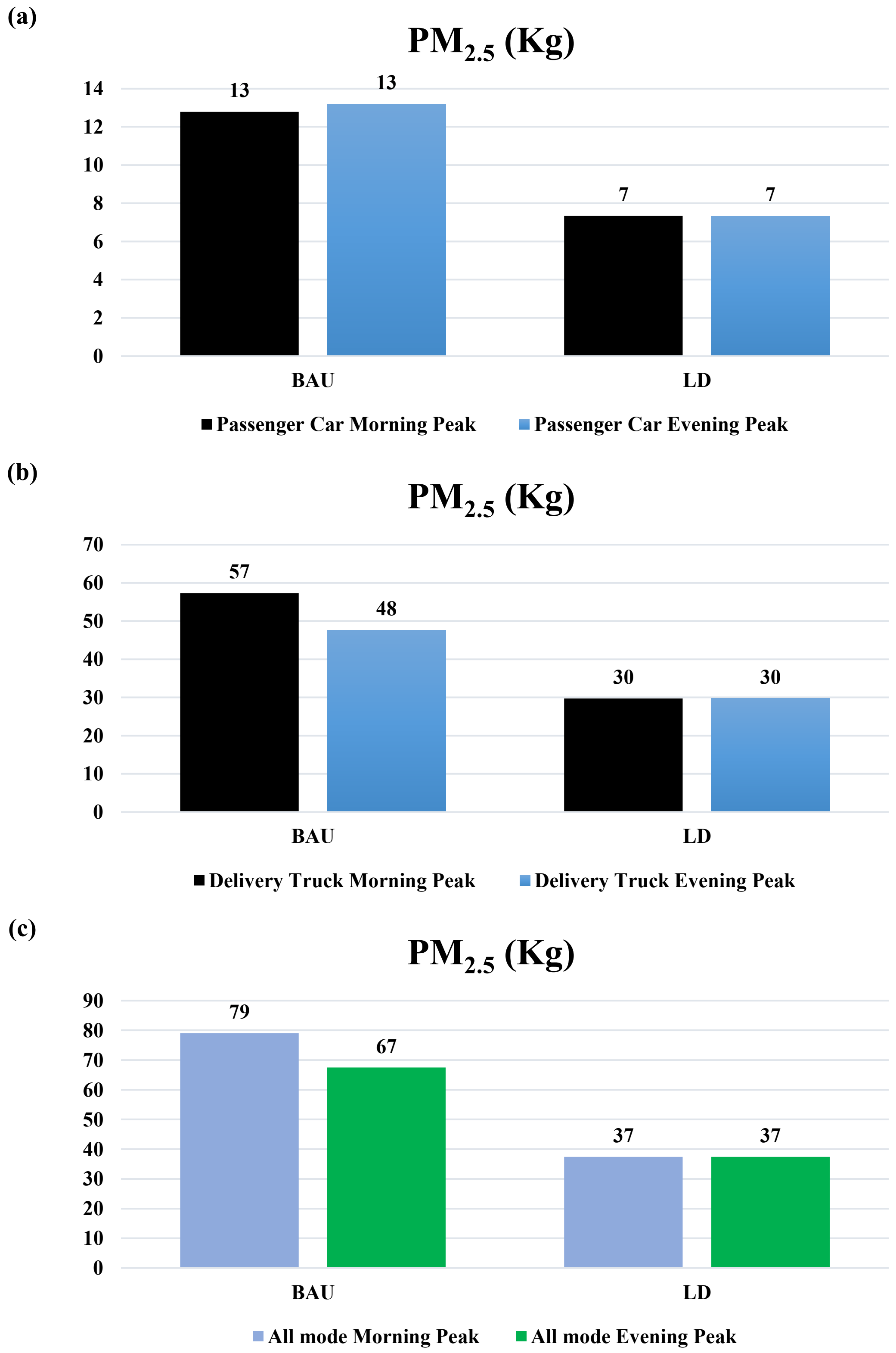


Figure 4-18 $PM_{2.5}$ Emission by a) Passenger Car, b) Commercial Vehicle, and c) All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

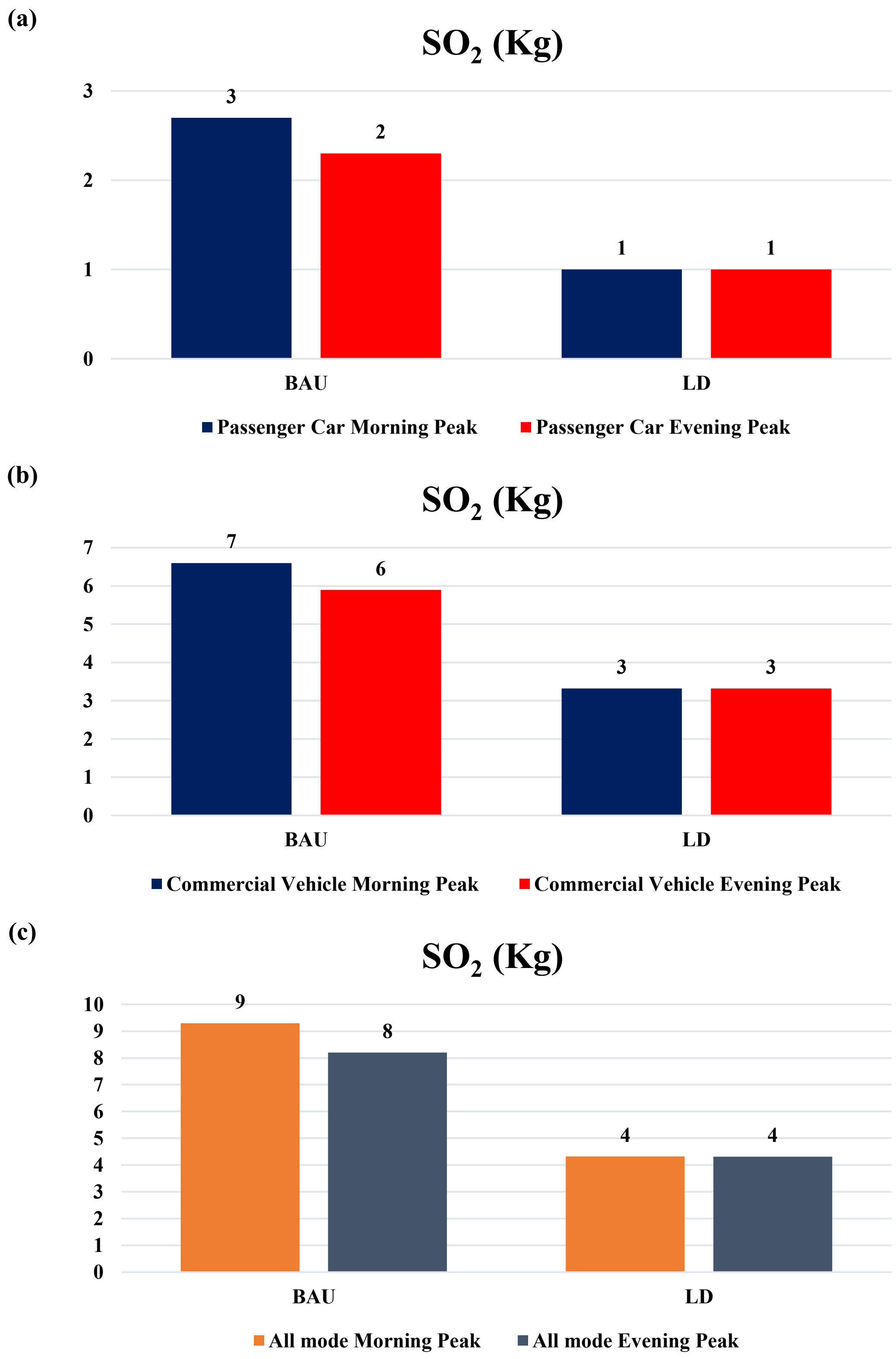


Figure 4-19 SO_2 Emission by a) Passenger Car, b) Commercial Vehicle, and c) All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

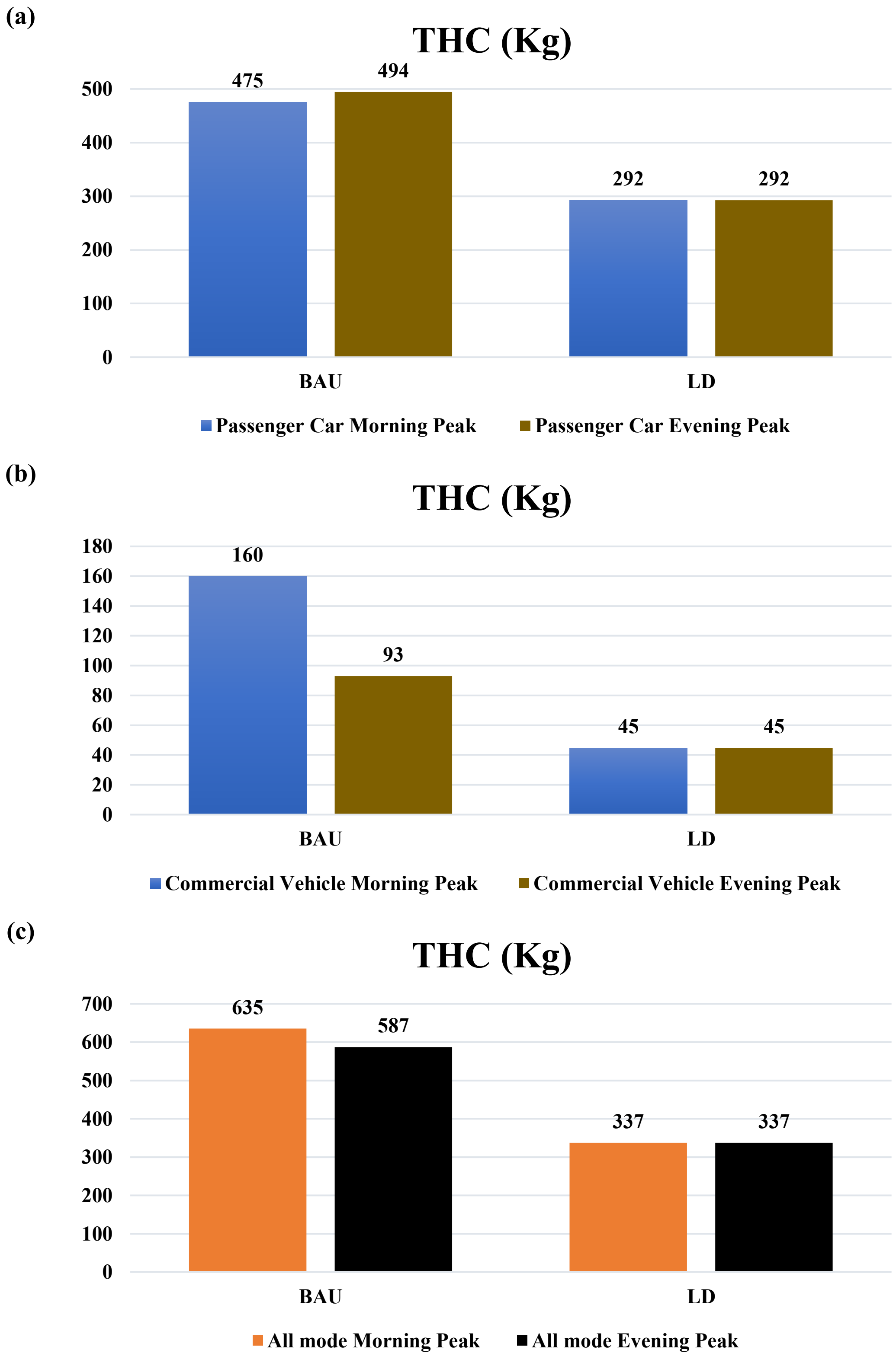


Figure 4-20 THC Emission by a) Passenger Car, b) Commercial Vehicle, and c) All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

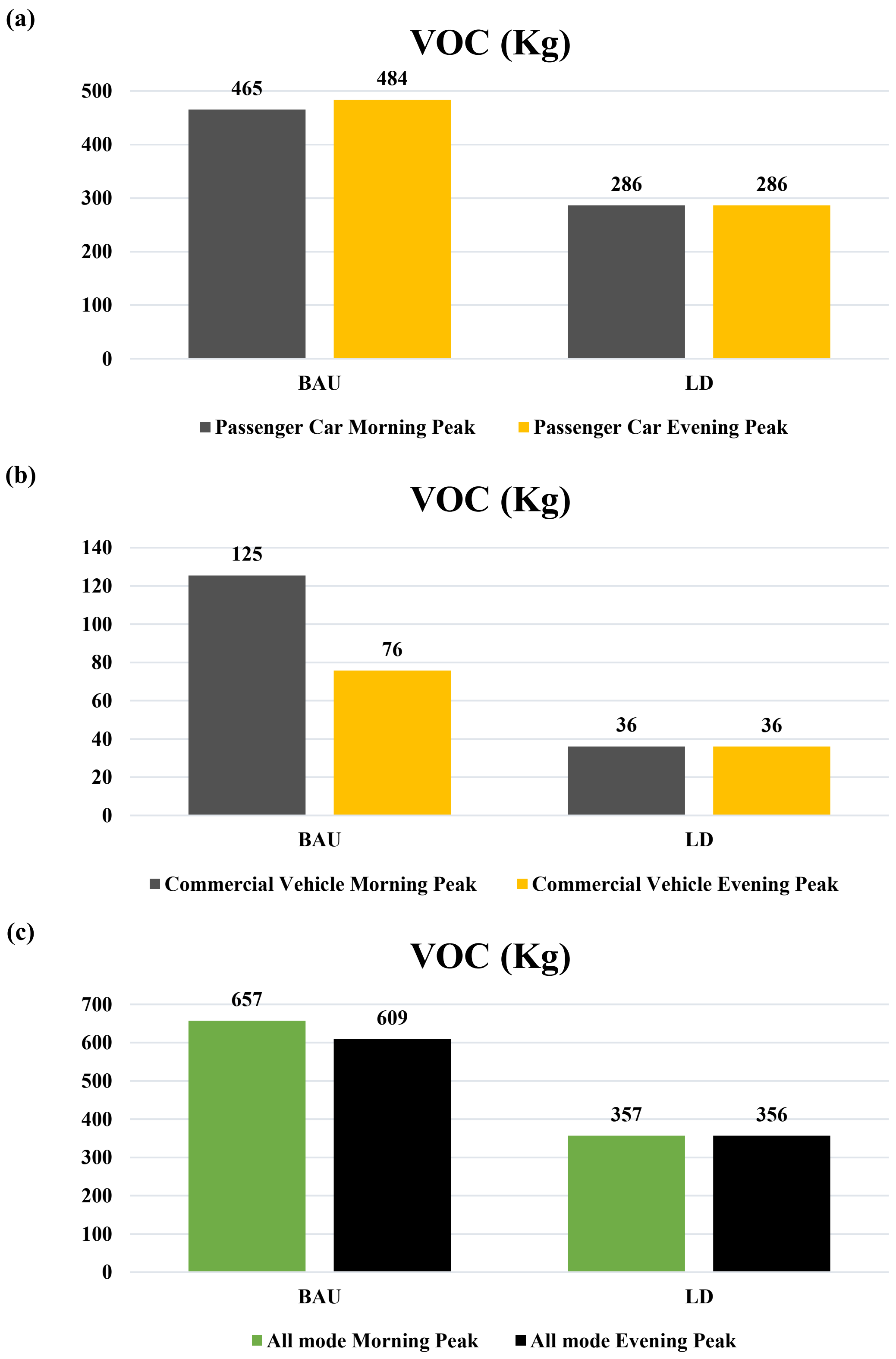
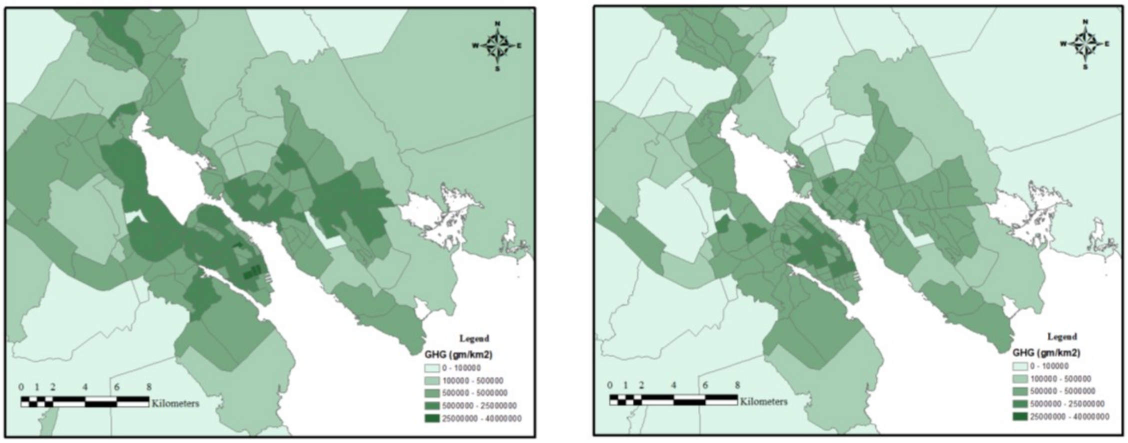


Figure 4-21 VOC Emission by a) Passenger Car, b) Commercial Vehicle, and c) All Mode during Business-as-Usual (BAU) Scenario and Lockdown Scenario

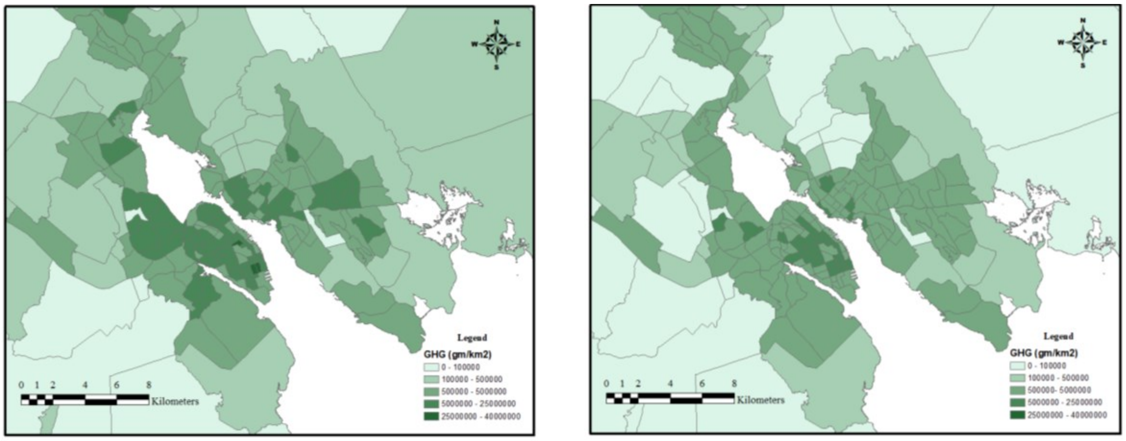
The fundamental reason for the significant reductions in emissions is the implied mobility restrictions during lockdown. Many essential businesses were told to run at a reduced capacity, while many non-essential businesses were forced to close during lockdown. The restrictions in activity participations directly reduced the traffic volume as well as the vehicular emissions.

4.5.2.3 Spatial Distribution of Pollutants

The spatial analysis of the emission data is conducted within *ArcGIS 10.5* to represent the emission density for each TAZ. Figure 4-22 and Figure 4-23 show the comparison of emission density for two peak periods between business-as-usual and lockdown scenarios for GHG as CO_2 equivalent and CO.



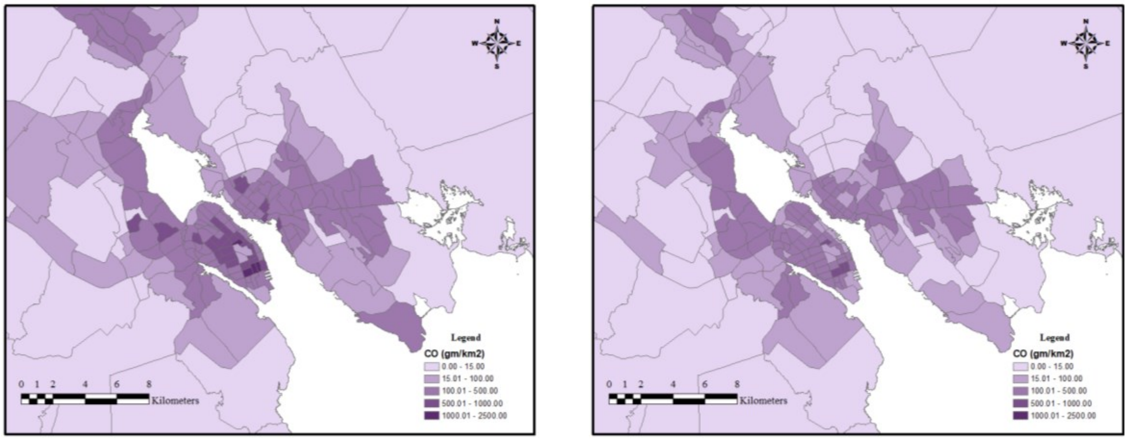
a) Business-as-Usual Scenario (Morning Peak) b) Lockdown Scenario (Morning Peak)



c) Business-as-Usual Scenario (Evening Peak) d) Lockdown Scenario (Evening Peak)

Figure 4-22 Comparison of GHG as CO_2 Equivalent Emission Density during Business-as-Usual and Lockdown Scenario for Two Peak Periods

a) Business-as-Usual Scenario (Morning Peak) b) Lockdown Scenario (Morning Peak)



c) Business-as-Usual Scenario (Evening Peak) d) Lockdown Scenario (Evening Peak)

Figure 4-23 Comparison of CO Emission Density during Business-as-Usual and Lockdown Scenario for Two Peak Periods

Both Figure 4-22 and Figure 4-23 show that the highest concentration of GHG and CO occurs in the downtown core of Halifax and Dartmouth. However, all TAZs experienced a considerable decrease in emissions during lockdown as illustrated in the figures. These figures illustrate the changes of emission in traffic analysis zones level to better understand the impact of pandemic on zonal level. The spatial distribution of the rest of the pollutants (NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC) are enclosed in Appendix F.

4.5.2.4 Comparison of Zonal Emission of Major Pollutants

This study illustrates the density distribution of major pollutants for different HRM zones (urban, suburban, and rural). During the morning peak period in urban regions, a 53% decrease of GHG (644,311,239 gm/km^2) is predicted during the lockdown scenario. Similarly, during the morning peak period, the urban region lockdown scenario projects a reduction of CO emissions by 46% (2,569,736 gm/km^2), and NO_x emissions by 54% (1,054,175 gm/km^2), respectively. Likewise, GHG emission of is estimated to drop by 47% (363,274,728 gm/km^2) in the lockdown scenario during the evening peak period in the urban region. The emissions for CO, and NO_x got decreased by 42%, and 49% respectively. Also, the suburban and urban regions demonstrated a similar trend of emission reduction. The total zonal emissions by pollutants for Business-as-Usual scenario and lockdown scenario are shown in the following Table 4-6 and Table 4-7.

Table 4-6 Zonal Emission of Major Pollutants during Business-as-Usual Scenario

Business-as-Usual Scenario

Morning Peak

Region	GHG (gm/km^2)	CO (gm/km^2)	NO_x (gm/km^2)	PM_{10} (gm/km^2)	$PM_{2.5}$ (gm/km^2)	SO_2 (gm/km^2)	THC (gm/km^2)	VOC (gm/km^2)
Urban	881,415,321	4,104,897	1,436,166	65,253	59,649	6,854	479,664	446,051
Suburban	320,985,150	1,494,881	523,009	23,763	21,722	2,496	174,679	162,438
Rural	4,903,235	22,835	7,989	363	332	38	2,668	2,481
Total	1,207,303,705	5,622,613	1,967,164	89,379	81,703	9,388	657,012	610,971

Evening Peak

Region	GHG (gm/km^2)	CO (gm/km^2)	NO_x (gm/km^2)	PM_{10} (gm/km^2)	$PM_{2.5}$ (gm/km^2)	SO_2 (gm/km^2)	THC (gm/km^2)	VOC (gm/km^2)
Urban	774,234,315	3,863,263	1,317,221	55,808	50,946	6,027	443,579	422,466
Suburban	281,953,027	1,406,885	479,692	20,324	18,553	2,195	161,538	153,849
Rural	4,306,996	21,491	7,328	310	283	34	2,468	2,350
Total	1,060,494,338	5,291,640	1,804,241	76,442	69,782	8,256	607,584	578,666

Table 4-7 Zonal Emission of Major Pollutants during Lockdown Scenario

Lockdown Scenario								
Morning Peak								
Region	GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	THC	VOC
	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)
Urban	411,023,492	2,228,812	666,545	30,938	28,238	3,175	254,658	243,602
Suburban	149,682,487	811,667	242,736	11,267	10,283	1,156	92,739	88,713
Rural	2,286,487	12,399	3,708	172	157	18	1,417	1,355
Total	562,992,466	3052,877	912,989	42,376	38,679	4,349	348,813	333,670
Evening Peak								
Region	**GHG**	**CO**	**NO_x**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**THC**	**VOC**
	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)
Urban	410,959,587	2,228,764	666,040	30,929	28,233	3,176	254,643	243,588
Suburban	149,659,215	811,649	242,552	11,264	10,282	1,157	92,733	88,708
Rural	2,286,132	12,398	3,705	172	157	18	1,417	1,355
Total	562,904,933	3,052,812	912,297	42,365	38,671	4,350	348,793	333,651

4.6 Conclusion

The main contribution of this chapter is by proposing a modelling framework to examine the impact of COVID-19 restrictions on traffic volume and vehicular emissions of Halifax Regional Municipality (HRM) during the lockdown scenario. The activity-based travel demand model and traffic assignment models in EMME are integrated with the emission model in MOVES platform in this study. The multiclass traffic network model is calibrated and validated using video image processing-based traffic count data and an HRM traffic count dataset. During the business-as-usual scenario, the R^2 values for three modes (passenger car, truck, and total traffic) are found to be 0.84, 0.87 and 0.85. During the lockdown scenario, the R^2 values for three modes (passenger car, truck, and total traffic) are found to be 0.86, 0.91 and 0.88. This study offers a better understanding of the spatial distribution of vehicle movements and associated emissions in Halifax during the lockdown scenario.

The result of this study provides critical insights. The hourly profile of emission during business-as-usual scenario describes that passenger car generates 399.41 ton GHG during the morning peak period, whereas the total emissions from delivery truck and long-haul truck are 112.02 ton and 655.80 ton, respectively. Similarly, the total GHG emission by passenger car is 340.53 ton for the evening peak period, whereas delivery truck and long-haul truck are responsible for 87.28 ton and 597.49 ton of GHG respectively. In the lockdown scenario, a substantial reduction of 44% and 68% in total traffic volume is estimated during morning and evening peak period respectively. This traffic volume decrease is a result of mobility restrictions during lockdown scenario which leads to vehicular emission reductions in the lockdown scenario. During morning and evening peak periods, GHG emission by passenger car got decreased by 199 ton and 141 ton respectively. Whereas a 424 ton and 341 ton GHG emission decrease for commercial vehicle is reported during morning and evening peak respectively. A total of 623 ton and 481 ton GHG emission reduction is estimated considering all modes during morning peak and evening peak period. Similar trend of emission reduction is also reported for other pollutants as well. For instance, the CO emission considering all mode dropped to 2,952 kg from 5,551 kg in the business-as-usual scenario during morning peak period. The CO emission reduction in evening peak period also depicts the same tendency.

The spatial distribution of pollutants reveals that the highest concentrations of GHG and CO exist in the Halifax and Dartmouth downtown cores. However, during lockdown, all TAZs in these areas experience significant reductions in emissions. Since the downtown core of Halifax and Dartmouth is the most densely populated area in HRM, it may be hypothesized as the reason behind the most significant share of emissions during the business-as-usual scenario. Due to different movement constraints imposed by the provincial government, these localities show a significant reduction in emissions during a lockdown scenario. This study also examines the density distribution of major pollutants for local area type of HRM. During the lockdown scenario, emissions in the urban area decreased by 53%, 46%, and 54% for GHG, CO, and NO_x, respectively in the morning peak period. Likewise, GHG emission is estimated to drop by 47% in the lockdown scenario during the evening peak period in the urban region. The emissions for CO and NO_x decreased by 42% and 49% respectively. Similar trend is noticed for the other pollutants and in the suburban and rural areas also.

This major limitation of this study is the unavailability of travel survey data for Halifax Regional Municipality. As a result, various assumptions from other travel survey were considered while developing the model. Additionally, even though transit was considered in the network model, the transit assignment procedure is not done within the EMME/4 platform. Another limitation is not validating the emission model due to unavailability of emission data. The immediate future works should include conducting a travel survey in HRM as well as incorporating transit assignment in the Halifax Regional Transport Network model. However, the results of this model give better understanding about the impact of future emergency like COVID-19 pandemic on traffic network and vehicular emission. The significant GHG emission decrease during lockdown period gives us insights about the impact of mobility restrictions on emissions by reducing private vehicle movements. Choosing alternative modes, for instance, walk, bike, or public transit, can be reasonable options for decreasing vehicular emissions. Results from this study will help the policymakers to plan for any future pandemics. The model will aid transportation professionals to develop multiple post-pandemic scenarios to understand traffic network impact and overall vehicular emissions in the Halifax Regional Municipality (HRM). Moreover, the model will help to better understand the necessity of sustainable transportation system to mitigate the vehicular emission and to achieve the goal of being carbon neutral city.

Chapter 5

Impact during Phased Reopening Scenarios

5.1 Introduction

The impact of vehicular emission during the phased reopening scenarios is of a major concern. The reduction in emission due to COVID-19 lockdown is temporary because of the lack of structural changes in the transportation system and planning. Though the global emission of carbon dioxide sharply dropped during the early stage of pandemic, it got picked up with the reopening phases *(Nature, 2021).* As the countries are lifting the lockdown restrictions, the improvement in air quality, which was achieved during lockdown period, will not persist *(Ikhlasse et al., 2021)*.

According to the Carbon Monitor *(Carbon Monitor, 2021),* a huge increase in CO_2 emissions is noticed for the world as well as many countries individually, for example, United Kingdom, France, Germany, India, China, United States of America, Spain, Japan, Russia. During lockdown period (April 2020), the global CO_2 emission due to ground transportation was 11.49 Metric ton which eventually got increased to 17.24 Metric ton by the end of August 2020. Similar trend is noticed for the individual counties as well *(Carbon Monitor, 2021).* A study of France shows that, emission of NO_2, NO_x and PM_{10} pollutant got increased by 42.32%, 15.08% and 38.15% respectively compared to their average in the lockdown period *(Ikhlasse et al., 2021)*. Similarly, many studies demonstrate that, with the withdrawal of lockdown restrictions, economic activities and traffic will be higher resulting in increase of GHG emission *(Wang et al., 2020, Zambrano-Monserrate et al. 2020)*. There are various focusing on the global and national level of vehicular emission due to COVID-19. But there is a clear study gap in comparative analysis of the impact of COVID-19 in regional level considering passenger car, delivery truck and combination long haul truck during phased reopening scenarios.

Therefore, this chapter aims to develop a modelling framework to illustrate the impact of COVID-19 on vehicular emission during phased reopening scenarios within the

Halifax Regional Municipality (HRM), Nova Scotia, Canada. The modelling framework develops reopening scenarios within the activity-based travel demand model replicating the restrictions imposed by the government. The activity-based travel demand model is integrated with the multiclass traffic network model within Equilibre Multimodal Multimodal Equilibrium (EMME) platform with an emission modelling framework based on the Motor Vehicle Emission Simulator (MOVES).

5.2 Modelling Approach

This modelling approach of this chapter is same as the modelling framework of Chapter 4 (Figure 4-2). For this chapter, the reopening scenarios are developed within this model.

5.2.1 Development of Reopening Scenarios within Activity-Based Travel Demand Model

The reopening scenarios are developed within the activity-based travel demand model following the directions of government of Nova Scotia supported by multiple available data sources. For the passenger car and transit volume during reopening scenarios, Google COVID-19 Community Mobility Reports *(Google, 2020)* and Apple Mobility Trend Reports *(Apple Inc., 2020)* are utilized for change in activity patterns and modal share respectively. The detailed description of these reports can be found on section **3.4.2 Activity Mobility Estimation**. For the delivery truck and combination long haul truck volume during reopening scenarios, Mobility Trends in Calgary Report is used *(Mobility Trends in Calgary, 2020)*. The assumed percentages of operational delivery truck and combination long haul truck during reopening scenarios are shown in the Table 5-1.

Table 5-1 Percentage of Operational Truck Volume during Reopening Scenarios with respect to Business-as-Usual Scenario

Mode	Reopening Scenario - 1	Reopening Scenario - 2
	May, 2020	**August, 2020**
Delivery Truck	80%	90%
Combination Long-Haul Truck	90%	90%

5.3.1.1 Reopening Scenario - 1

In this model, the timeline of May 1st, 2020, to June 14th, 2020, is considered as the "Reopening Scenario - 1". After 38 days of lockdown, on May 1st, the government of Nova Scotia, started to reopen the parks, trail and fishing. People were allowed to visit community garden, small businesses, and nurseries *(Province of NS, 2020).* From May 15th, more restrictions were lifted. People could go to beaches, boating, paddling. Government introduced family bubble concept and increased the limit of gathering to 10 persons. From June 5th, the government allowed to reopen the takeout services of restaurants, bars, and fitness facilities. The Apple Mobility Trend Reports indicate a 38% increase of auto trip during this period from lockdown scenario *(Apple Inc., 2020)*. Similarly, shopping activity got increased to 93% of business-as-usual scenario and recreational activity also increased by 26% from lockdown phase according to Google's COVID-19 Community Mobility Report *(Google, 2020)*.

In the activity-based travel demand model, these percentages are used to limit individuals' participation in different types of activities. Additionally, mode choices are also limited within this reopening scenario. The output from the activity-based travel demand model, provides the passenger car and transit volume during the reopening scenarios. The restrictions due to COVID-19 also affected the delivery truck and combination long-haul truck volume. A report shows that, during the month of May 2020, delivery truck volume was 80% and combination long haul truck was 90% compared to the business-as-usual scenario *(Mobility Trends in Calgary, 2020)*. These percentages are utilized to develop the hourly origin-destination matrices of delivery trucks and combination long-haul trucks.

5.3.1.2 Reopening Scenario - 2

The study considers the timeline from June 15th, 2020, to August 31st, 2020, as the "Reopening scenario - 2". From June 15th, 2020, the provincial government allowed more flexibility in outdoor restrictions as well as reopening the childcare centres at 50% capacity. Gathering limit of people were increased and people were allowed to visit the long-term care facilities. Travel within Atlantic bubble (Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland and Labrador) was permitted.

According to the Google's COVID-19 Community Mobility Report, people's participation in shopping activities got increased by 3%. The report also gives the change in the participation of people in various type of activities. The activity participation is controlled within the activity-based travel demand model according to the report to replicate the reopening scenario *(Google, 2020)* to develop the model and the output from the model is used to calculate the auto and transit volume during the reopening scenario. According to Mobility Trends in Calgary report, during the month of August 2020, volume of delivery truck and combination long haul truck both were 90% compared to the business-as-usual scenario *(Mobility Trends in Calgary, 2020)*. The hourly origin-destination (O-D) matrices of delivery trucks and combination long-haul trucks are developed by considering these values.

5.2.2 Halifax Regional Transport Network Model

The Halifax regional transport network model developed within the within the Equilibre Multimodal Multimodal Equilibrium (EMME/4) platform includes 222 Traffic Analysis Zones, 222 zonal centroids, 2459 link nodes, and 5272 links *(Bela and Habib, 2020)*. Four modes are considered in this model- passenger car, delivery truck, combination long-haul truck, and public transit. This network model integrates three separate models- (i) Passenger car demand forecasting model, (ii) Tour-based local delivery truck demand model and (iii) Long-haul truck demand model. The detailed description of this models can be found under the section of **4.4.3 Halifax Regional Transport Network Model.**

5.2.3 Multiclass Traffic Assignment Model

A multiclass traffic assignment model is performed by utilizing a user equilibrium assignment principle within the developed transport network model. The detailed description of this model can be found under the section of **4.4.4 Multiclass Traffic Assignment Model**.

5.2.3.1 Calibration and Validation of the Model

The multiclass traffic assignment model is calibrated and validated using a traffic volume-based approach for reopening scenario - 1 and reopening scenario - 2. The count data is collected from "Harbourside Transportation Consultants", Dartmouth, NS, Canada. The simulated and observed passenger car and total volumes (passenger cars, trucks) are then compared in terms of R^2, APE (Absolute Percentage Error), MAPE (Mean Absolute Percentage Error) and GEH values. The R^2 values are obtained from regression curve, whereas APE, MAPE and and GEH are estimated by using equations. Five key locations, including Macdonald Bridge, were validated for the morning peak period (7:00 am – 8:59 am) for the reopening scenario - 1. Another five key locations, including major arterial roads and MacKay Bridge, were validated for the evening peak period (4:00 pm – 5:59 pm) for the reopening scenario - 2. The following equations are used to calculate APE, MAPE and GEH.

$$\text{APE} = \left|\frac{\alpha-\beta}{\alpha}\right| \times 100\% \qquad (1)$$

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{\alpha-\beta}{\alpha}\right| \qquad (2)$$

$$GEH = \sqrt{\frac{2*(\alpha-\beta)^2}{\alpha+\beta}} \qquad (3)$$

Here,

α = observed traffic count data

β = simulated traffic count data

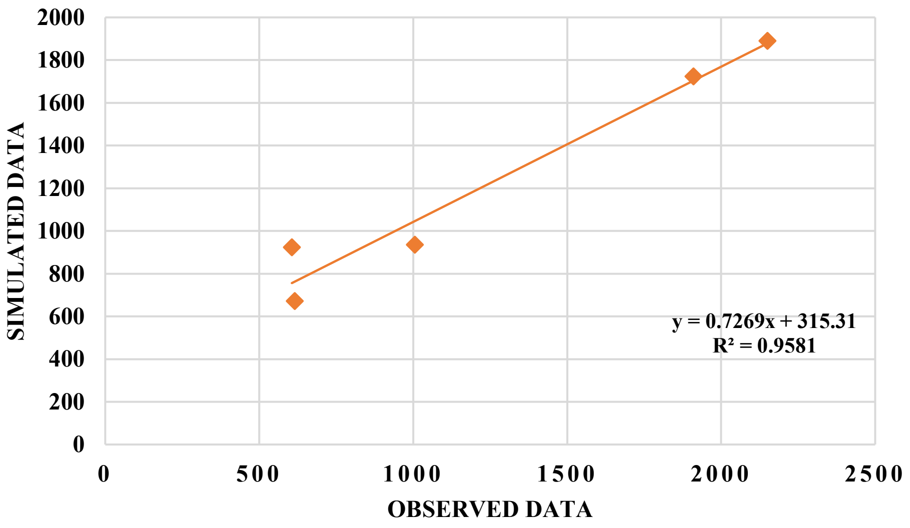
n = number of data points

The validation locations for the reopening scenarios are enlisted in the Table 5-2.

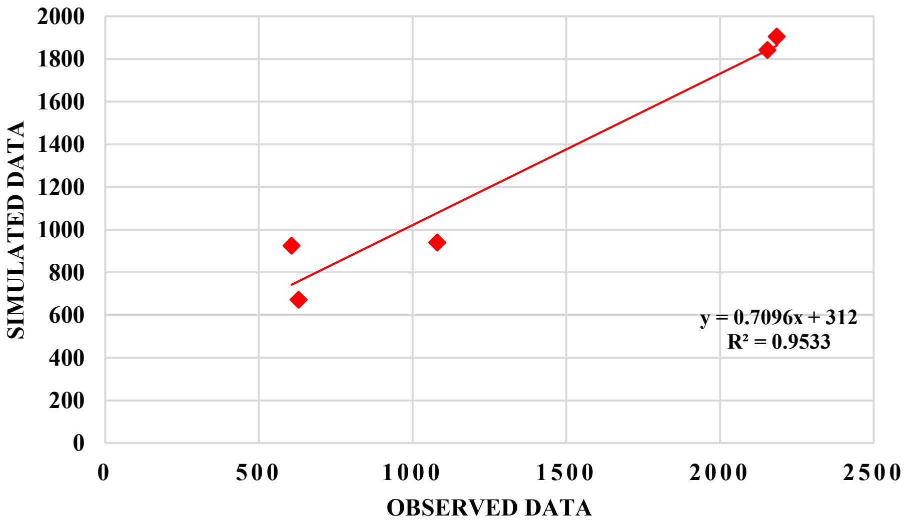
Table 5-2 Validation Locations for Phased Reopening Scenarios

Scenarios	Validation Locations	
Reopening Scenario -1	1	Barrington St. - Between Valour Wy and Marjorie Russell Ln
	2	Robie St - Between North St and Albans St
	3	Mumford Rd - Btw Olivet St and Railway Bridge
	4	Quinpool Rd - Btw Armdale Roundabout and Railway Bridge
	5	Angus L. Macdonald Bridge
Reopening Scenario -2	1	Bedford Hwy - Btw Oakmount Dr and Hwy 102
	2	Hammonds Plains Rd - Between Smiths Rd and Hwy 102
	3	Lacewood Dr - Between Chain Lake Dr and Hwy 102
	4	Micmac Blvd - Between Hwy 111 Overpass and Ramps (North)
	5	MacKay Bridge Ramp - Between Princess Margaret Blvd and Bridge

The validation results for both reopening scenarios are shown below:

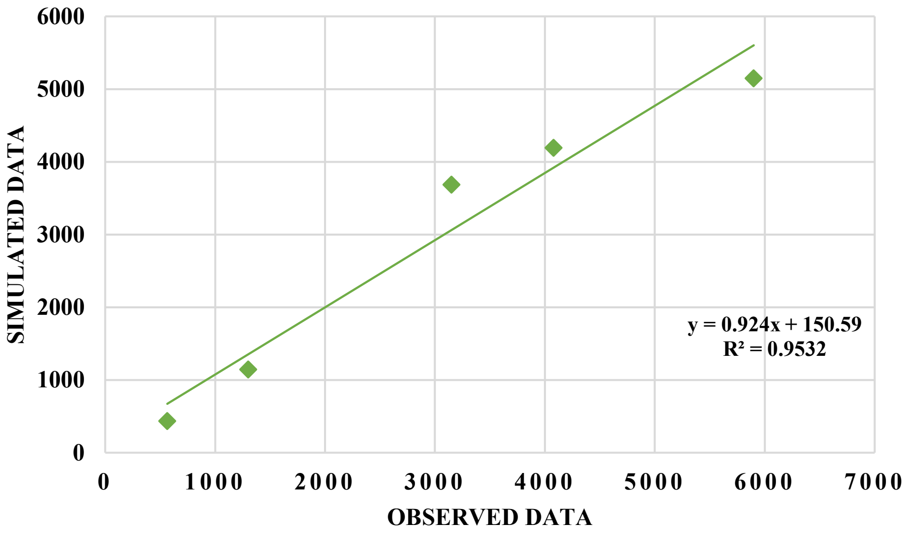


a) **Passenger Car**

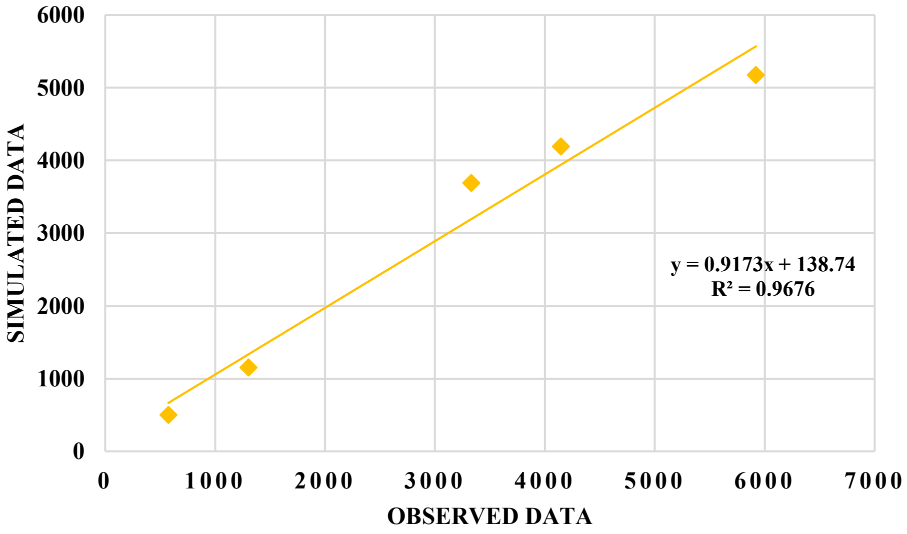


b) **Total Traffic**

Figure 5-1 Comparison of Observed and Simulated Traffic Count Data of during Reopening Scenario - 1



a) **Passenger Car**



b) **Total Traffic**

Figure 5-2 Comparison of Observed and Simulated Traffic Count Data during Reopening Scenario - 2

The value for R^2 ranges from 0 to 1 where closer value to 1 indicates the best fit of the model. APE measures the range from 0% to 100%, where 0% represents the perfect fit of simulated data with the observed traffic count data. The MAPE value can be measured by taking the average of the APE values. Values of MAPE also vary within 0% to 100%, with 0% being a perfect fit. GEH denotes an empirical formula that has proven useful for a variety of traffic analysis purposes. For traffic modelling work in the "baseline" scenario, a GEH of less than 5.0 is considered a good match between the modelled and observed hourly volumes. 85% of the volumes in a traffic model should have a GEH less than 5.0. GEHs in the range of 5.0 to 10.0 may warrant investigation. If the GEH is greater than 10.0, there is a high probability that there is a problem with either the travel demand model or the traffic count data. The calculated validation parameters for both reopening scenarios are shown in the Table 5-3.

Table 5-3 Validation Parameters of Reopening Scenarios

	Passenger Car						Total Traffic					
	Observed	Simulated	R^2	APE	MAPE	GEH	Observed	Simulated	R^2	APE	MAPE	GEH
Reopening Scenario - 1	1910	1724	0.96	10%	18%	4.36	2154	1842	0.95	14%	20%	6.98
	1005	936		7%		2.21	1080	940		13%		4.41
	615	672		9%		2.25	629	672		7%		1.69
	2150	1890		12%		5.78	2185	1904		13%		6.21
	606	924		52%		11.50	606	924		52%		11.50
Reopening Scenario - 2	4080	4192	0.95	3%	13%	1.74	4145	4192	0.97	1%	10%	0.73
	3150	3688		17%		9.20	3330	3688		11%		6.04
	5900	5148		13%		10.12	5920	5172		13%		10.04
	1300	1144		12%		4.46	1305	1152		12%		4.37
	565	436		23%		5.77	575	502		13%		3.15

The R^2 values for passenger car, and total traffic are determined separately for both reopening scenarios. During the reopening scenario - 1, the R^2 values for passenger car and total traffic are 0.96 and 0.95 (Figure 5-1) respectively. During the reopening scenario - 2, the R^2 values for passenger car, and total traffic are 0.95 and 0.97 (Figure 5-2). The larger the R^2 value, the better the model represents the observed traffic count data. For this study, the value of R^2 is greater than 0.95 for all cases, which proves that the model is a good fit. Another goodness of fit measure, MAPE (Mean Absolute Percentage Error), computes the average percentage errors of a model as it differs from actual values of the traffic volume. Moreover, during the reopening scenario - 1, the MAPE values for modes (passenger car, and total traffic) are 18% and 20%. Similarly, during the reopening scenario - 2, the MAPE values for modes (passenger car, and total traffic) are 13% and 20%. In addition, 85% of the volumes in a traffic model is found a GEH less than 5.0., which is considered to be a good match between simulated and observed traffic count data.

5.2.4 Emission Model

The phased reopening scenarios for Halifax Regional Municipality (HRM) are developed within the Motor Vehicle Emission Simulator (MOVES2014b) platform. The detailed description of emission modelling can be found on section **4.4.5 Emission Model**. The Table 5-4 shows the source type population for reopening scenario – 1 and reopening scenario - 2. And the Table 5-5 summarizes the vehicle type VMT (HPMSVtypeDay) for one day.

Table 5-4 Source Type Population during Reopening Scenario - 1 and Reopening Scenario - 2

Source Type ID	Mode	Reopening Scenario - 1		Reopening Scenario - 2	
		Morning Peak	Evening Peak	Morning Peak	Evening Peak
21	Passenger Car	427,682	337,449	457,386	238,607
52	Delivery Truck	2,083	1,971	2,083	1,971
62	Combination Long-haul Truck	16,397	14,725	16,397	24,510

Table 5-5 Vehicle Type VMT for One Day during Reopening Scenario - 1 and Reopening Scenario - 2

HPMSVtype ID	Mode	Reopening Scenario - 1	Reopening Scenario - 2
25	Passenger Car	763,020	699,209
50	Delivery Truck	3,324	3,324
60	Combination Long-haul Truck	187,085	240,694

The Figure 5-3 and Figure 5-4 show the hourly profile of Environment temperature and relative humidity during reopening scenario - 1 (May 2020) and reopening scenario - 2 (August 2020).

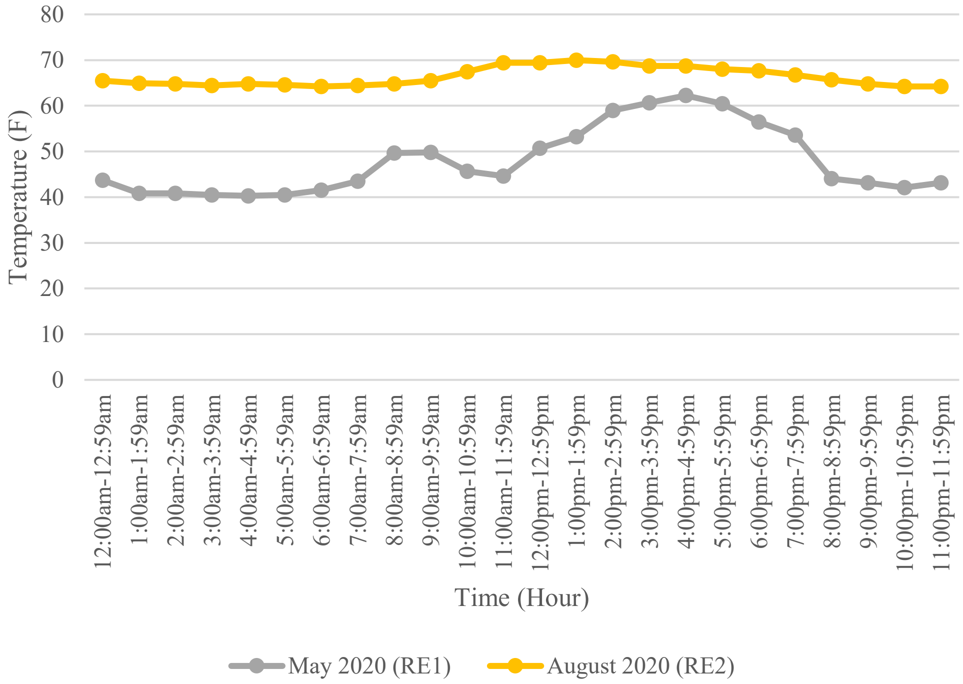


Figure 5-3 Hourly Profile of Temperature during Reopening Scenario - 1 (RE1) and Reopening Scenario – 2 (RE2)

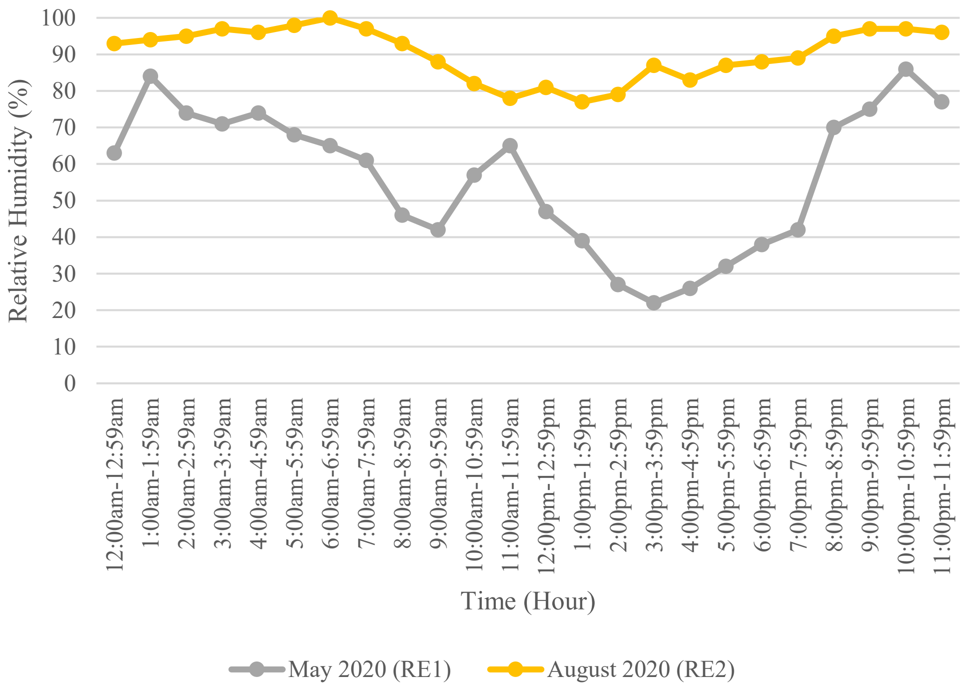


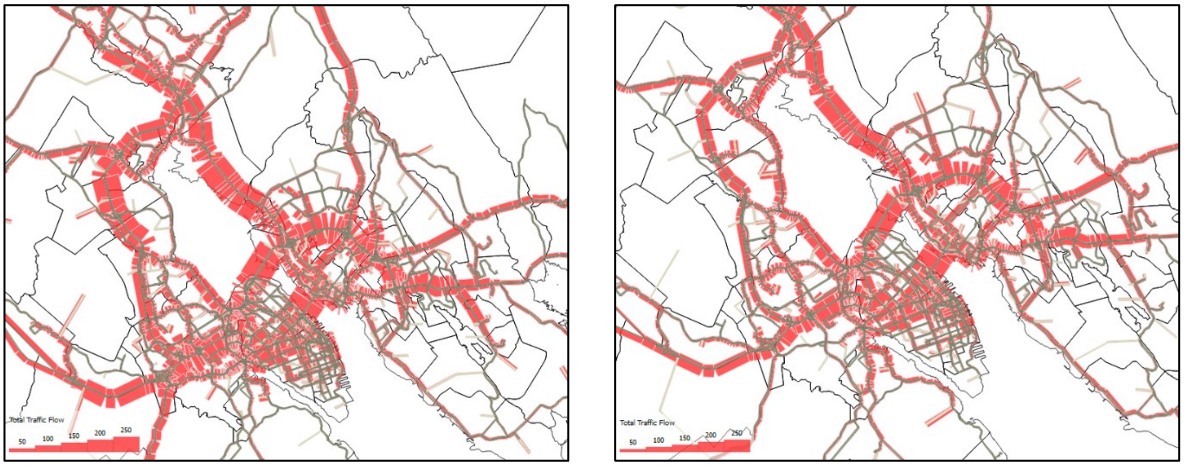
Figure 5-4 Hourly Profile of Relative Humidity during Reopening Scenario - 1 (RE1) and Reopening Scenario – 2 (RE2)

5.3 Result Analysis

This chapter investigates the impact of COVID-19 during reopening scenarios. The focus of this chapter is to demonstrate the gradual change in traffic volume and vehicular emission due to the impact of the COVID-19 pandemic. The multiclass traffic assignment model generates the total traffic volume by link in both reopening scenarios. The results from the traffic assignment model are used to evaluate the vehicular emission utilizing the developed emission model. The results obtained from this study are discussed in the following sections.

5.3.1 Result of Multiclass Traffic Assignment Model

The result of the multiclass traffic assignment model provides link volume for all modes. Here, passenger car, delivery truck, and long-haul truck movements are modelled. The model provides the link volume for total traffic of morning peak period (7:00 am-8:59 am) and evening peak period (4:00 pm-5:59 pm) as shown in the following Figure 5-5 and Figure 5-6.

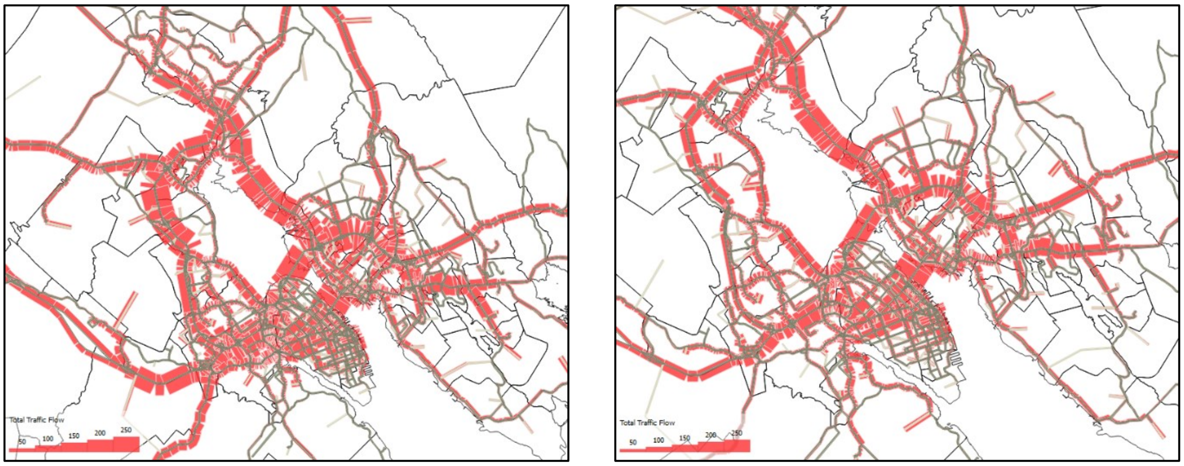


a) Reopening Scenario - 1

(7:00 am-7:59 am)

b) Reopening Scenario - 2

(7:00 am-7:59 am)



c) Reopening Scenario - 1

(8:00 am-8:59 am)

d) Reopening Scenario - 2

(8:00 am-8:59 am)

Figure 5-5 Comparison of Link Volume of Total Traffic Flow during Reopening Scenario - 1 and Reopening Scenario - 2 (Morning Peak Period)

a) Reopening Scenario - 1
(4:00 pm-4:59 pm)

b) Reopening Scenario - 2
(4:00 pm-4:59 pm)

c) Reopening Scenario - 1
(5:00 pm-5:59 pm)

d) Reopening Scenario - 2
(5:00 pm-5:59 pm)

Figure 5-6 Comparison of Link Volume of Total Traffic Flow during Reopening Scenario - 1 and Reopening Scenario - 2 (Evening Peak Period)

For both scenarios, reopening scenario – 1 and reopening scenario – 2, total traffic volume got increased from lockdown period. But still the traffic volume is less than the business-as-usual scenario. For instance, in the morning peak period, traffic volume got increased by 42% in the reopening scenario – 1 and 51% in the reopening scenario – 2 with respect to lockdown scenario. If we consider BAU scenario as a baseline, the decrease of traffic volume can be expressed as 20% decrease in the reopening scenario – 1 and 15% decrease in the reopening scenario – 2. Similarly, in the evening peak period, traffic volume got increased by 76% and 35% during the reopening scenario – 1 and reopening scenario – 2 respectively compared to lockdown scenario. This can be expressed as a 41.5% and 56% decrease in traffic volume in the reopening scenario – 1 and reopening scenario – 2 respectively.

5.3.2 Result from Emission Model

5.3.2.1 Hourly Profiles of Emission of Pollutants

The hourly profiles for total emission during reopening scenario - 1 and reopening scenario - 2 are shown in the following Table 5-6 and Table 5-7.

Table 5-6 Hourly Profiles for Total Emission during Reopening Scenario - 1

		Pollutants	GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	THC	VOC
			Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
	Mode	Time								
Morning Peak Period	Passenger Car	7am to 8am	132.67	1.45	0.09	0.00	0.00	0.00	0.16	0.16
		8am to 9am	134.29	1.37	0.09	0.00	0.00	0.00	0.15	0.15
		Total	266.96	2.82	0.18	0.01	0.01	0.00	0.31	0.30
	Delivery Truck	7am to 8am	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		8am to 9am	2.67	0.01	0.01	0.00	0.00	0.00	0.00	0.00
		Total	3.20	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	7am to 8am	97.49	0.08	0.21	0.01	0.01	0.00	0.01	0.01
		8am to 9am	291.47	0.18	0.63	0.03	0.03	0.00	0.03	0.03
		Total	388.96	0.25	0.84	0.04	0.03	0.00	0.05	0.04
Evening Peak Period	Passenger Car	4pm to 5pm	103.39	0.90	0.06	0.00	0.00	0.00	0.08	0.08
		5pm to 6pm	107.34	0.92	0.07	0.00	0.00	0.00	0.08	0.08
		Total	210.74	1.82	0.13	0.00	0.00	0.00	0.16	0.16
	Delivery Truck	4pm to 5pm	2.34	0.00	0.01	0.00	0.00	0.00	0.00	0.00
		5pm to 6pm	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Total	2.44	0.00	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	4pm to 5pm	95.67	0.05	0.20	0.01	0.01	0.00	0.01	0.01
		5pm to 6pm	258.44	0.13	0.55	0.02	0.02	0.00	0.02	0.02
		Total	354.11	0.18	0.75	0.03	0.03	0.00	0.03	0.03

Table 5-7 Hourly Profiles for Total Emission during Reopening Scenario - 2

		Pollutants	**GHG**	**CO**	**NO_x**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**THC**	**VOC**
			Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
	Mode	Time								
Morning Peak Period	Passenger Car	7am to 8am	151.02	1.84	0.11	0.01	0.01	0.00	0.22	0.22
		8am to 9am	149.27	1.59	0.10	0.01	0.00	0.00	0.18	0.18
		Total	300.28	3.43	0.21	0.01	0.01	0.00	0.40	0.39
	Delivery Truck	7am to 8am	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		8am to 9am	2.62	0.01	0.01	0.00	0.00	0.00	0.00	0.00
		Total	3.14	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	7am to 8am	120.15	0.09	0.22	0.01	0.01	0.00	0.01	0.01
		8am to 9am	379.67	0.22	0.71	0.04	0.03	0.00	0.04	0.04
		Total	499.82	0.31	0.93	0.05	0.04	0.00	0.06	0.05
Evening Peak Period	Passenger Car	4pm to 5pm	126.48	1.20	0.10	0.00	0.00	0.00	0.12	0.11
		5pm to 6pm	110.62	1.16	0.09	0.00	0.00	0.00	0.12	0.12
		Total	237.10	2.36	0.19	0.01	0.01	0.00	0.24	0.23
	Delivery Truck	4pm to 5pm	2.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		5pm to 6pm	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Total	2.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	4pm to 5pm	252.37	0.13	0.45	0.02	0.02	0.00	0.02	0.02
		5pm to 6pm	205.67	0.11	0.37	0.02	0.02	0.00	0.02	0.02
		Total	458.04	0.23	0.83	0.04	0.04	0.00	0.04	0.04

During the reopening scenario - 1, the total emissions of GHG, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC for passenger cars during the morning peak period are 266.96

ton, 2.82 ton, 0.18 ton, 0.01 ton, 0.01 ton, 0.00 ton, 0.31 ton and 0.30 ton respectively. But during the reopening scenario - 2, as the activity increased, the emission also got increased. The total emissions of GHG, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC are reported as 300.28 ton, 3.43 ton, 0.21 ton, 0.01 ton, 0.01 ton, 0.00 ton, 0.40 ton and 0.39 ton respectively. For the delivery truck and lock haul truck, similar trend of increased emission is noticed as well. Even during the evening peak period, the emission for almost all pollutants have increased.

5.3.2.2 Changes in Major Pollutants during Phased Reopening Scenarios

During the lockdown, COVID-19-imposed limitations reduced key pollutant emissions; but, after the restrictions were lifted, the emissions began to increase. The emission model results predict the emission during the phased reopening scenarios mentioned earlier. During reopening scenario - 1 (RE-1), greenhouse gas (GHG) emission by passenger car got increased from lockdown scenario, which is 33% and 38% of GHG emission in business-as-usual (BAU) scenario during morning and evening peak period respectively (Figure 5-7). The GHG emission by passenger car got increased during the reopening scenario – 2 (RE-2) as well. During morning peak period, the GHG emission is 25% of GHG of BAU whereas 30% of GHG emission is also reported in the evening peak period (Figure 5-7). Similarly, GHG emission by commercial vehicle (delivery truck and combination long-haul truck) is also increased in the reopening scenario -1 and reopening scenario – 2 compared to the lockdown scenario in both peak periods (Figure 5-8). The Figure 5-9 shows the GHG emission reduction from BAU scenario considering all modes.

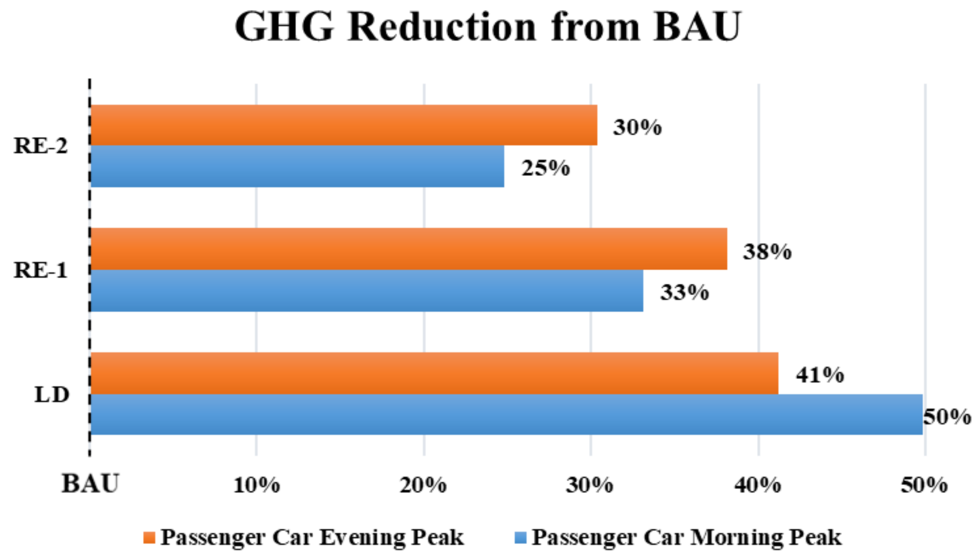


Figure 5-7 Reduction of GHG Emission by Passenger Car during Phased Reopening Scenarios with respect to Business-as-Usual (BAU) Scenario

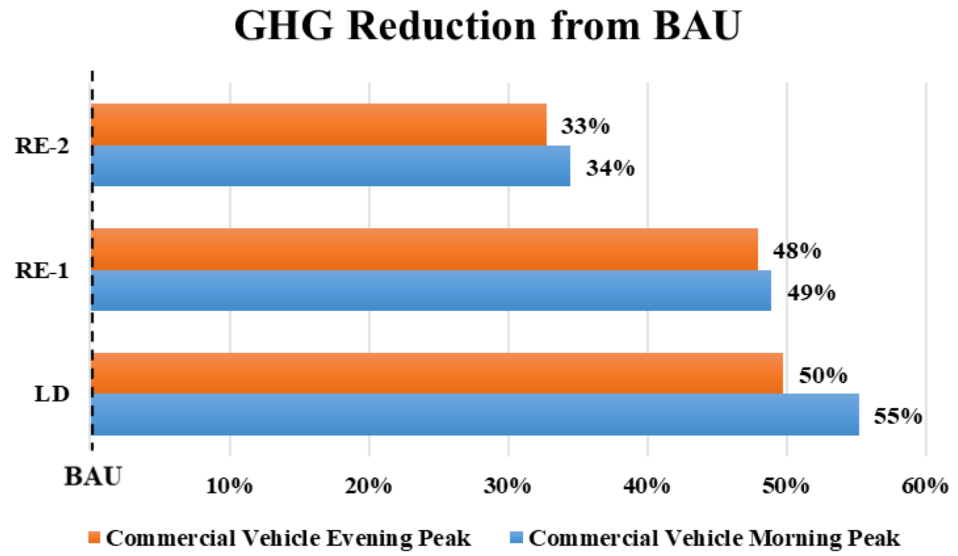


Figure 5-8 Reduction of GHG Emission by Commercial Vehicles during Phased Reopening Scenarios with respect to Business-as-Usual (BAU) Scenario

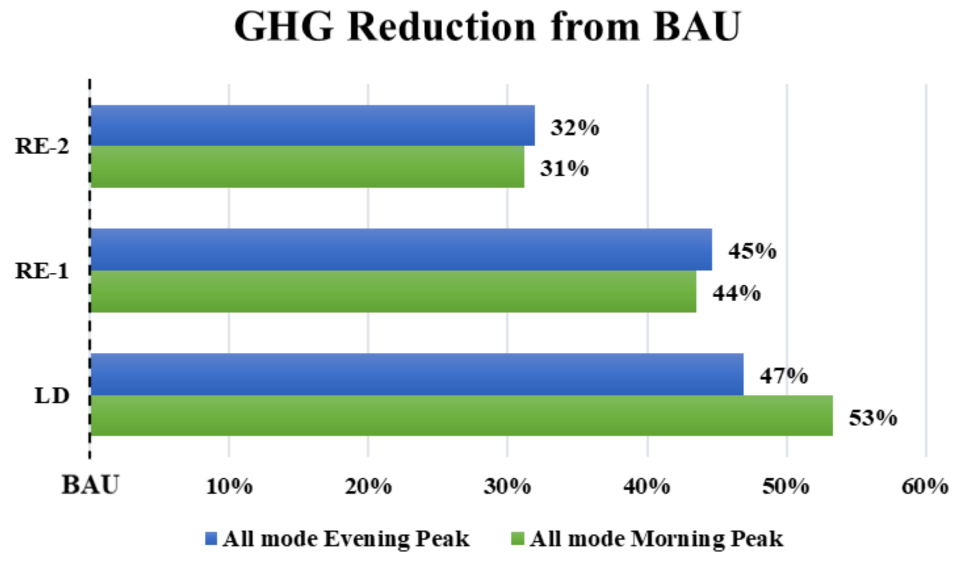
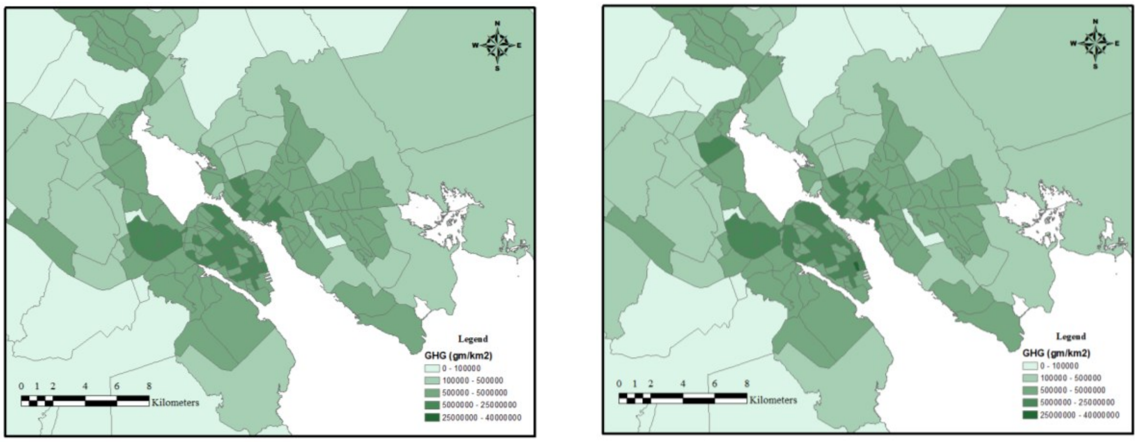


Figure 5-9 Reduction of GHG Emission by All Modes during Phased Reopening Scenarios with respect to Business-as-Usual (BAU) Scenario

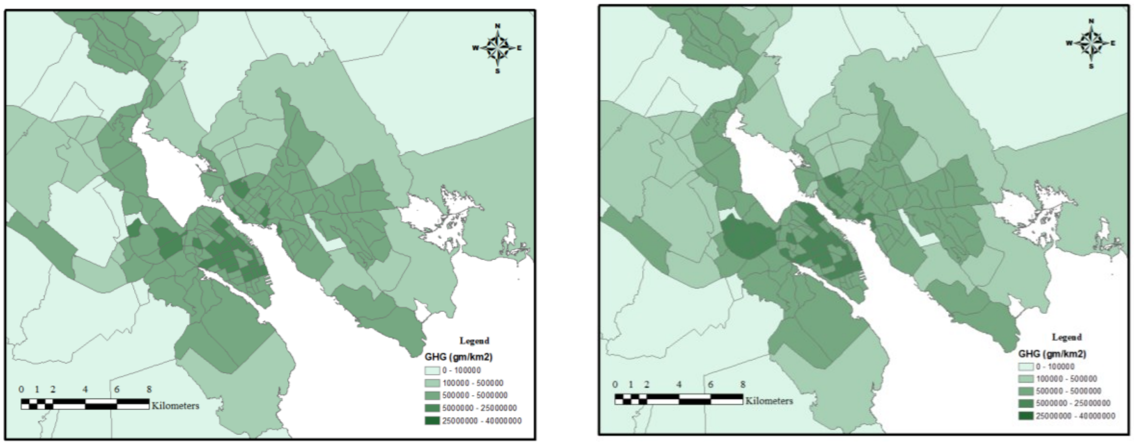
Similar pattern is noticed for the rest of the pollutants as well. The underlying reason of the increased emission in reopening scenarios is the lifting of activity and mobility restrictions. The activity participations got increased during this time which eventually elevated the traffic volume and vehicular emission. The changes in emission of the rest of the pollutants (CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC) are included in Appendix E.

5.3.2.3 Spatial Distribution of Pollutants

The emission density of different pollutants is also analysed with the spatial analysis of the emission data conducted within *ArcGIS 10.5*. The emission density of each traffic analysis zones (TAZ) are calculated and spatially distributed in the *ArcGIS* platform. Figure 5-10 and Figure 5-11 demonstrate the GHG and CO emission density during reopening scenario – 1 and reopening scenario -2.

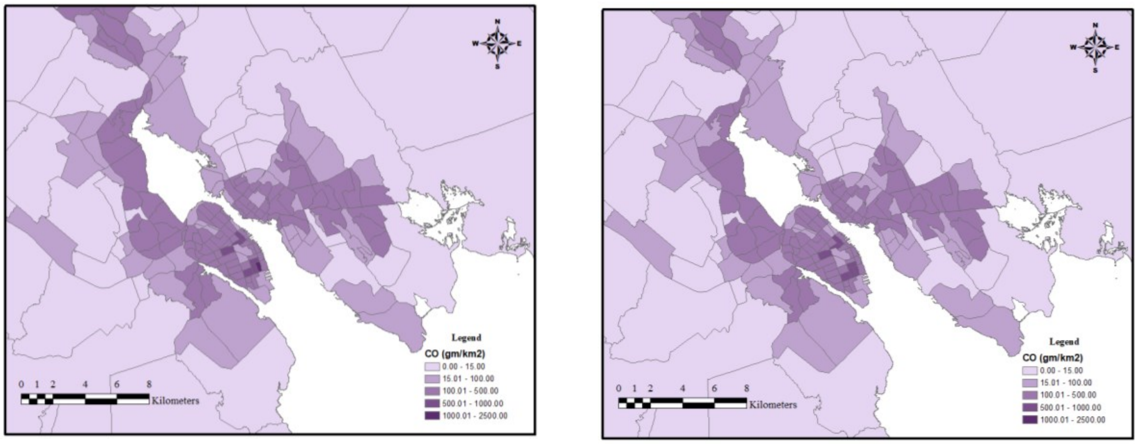


a) Reopening Scenario – 1 (Morning Peak) b) Reopening Scenario – 2 (Morning Peak)

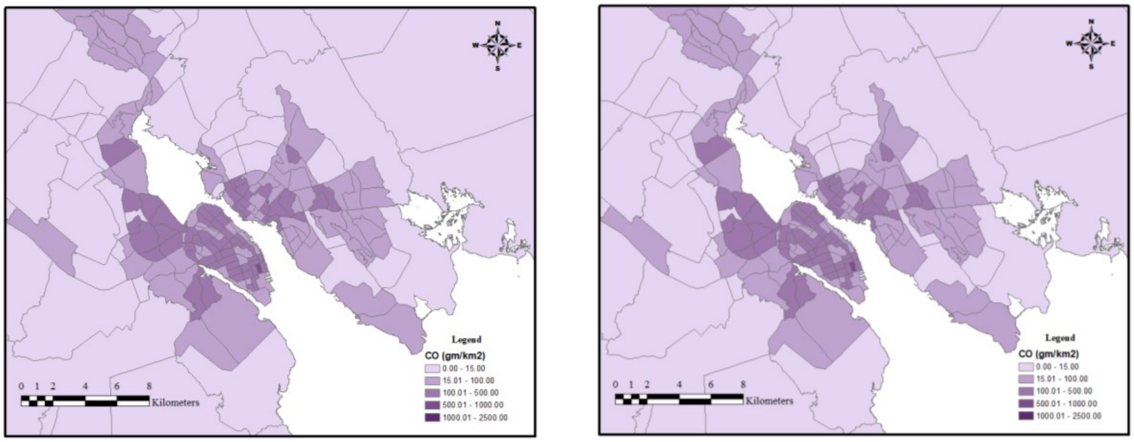


c) Reopening Scenario - 1 (Evening Peak) d) Reopening Scenario – 2 (Evening Peak)

Figure 5-10 GHG as CO_2 Equivalent Emission Density during Reopening Scenario -1 and Reopening Scenario - 2 for Two Peak Periods



a) Reopening Scenario - 1 (Morning Peak) b) Reopening Scenario - 2 (Morning Peak)



c) Reopening Scenario - 1 (Evening Peak) d) Reopening Scenario - 2 (Evening Peak)

Figure 5-11 CO Emission Density during Reopening Scenario -1 and Reopening Scenario - 2 for Two Peak Periods

Both Figure 5-10 and Figure 5-11 demonstrate that the highest concentration of GHG and CO occurs in the downtown core of Halifax and Dartmouth. The spatial distribution of the rest of the pollutants (NO_x, PM_{10}, $PM_{2.5}$, SO_2, THC and VOC) are enclosed in Appendix F.

5.3.2.4 Comparison of Zonal Emission of Major Pollutants

The zonal density distribution of major pollutants is also analysed in this chapter. In the urban core of Halifax, GHG emission got reduced by 53%, 40% and 34% during lockdown, reopening-1, and reopening-2 scenarios respectively in the morning peak period. Similar tend is noticed in the evening peak as well which is 47%, 42% and 34% GHG emission reduction during lockdown, reopening-1, and reopening-2 scenarios respectively. All other pollutants also reveal the same pattern. Moreover, the suburban and urban regions demonstrate the increase of emission in the reopening scenarios. The total zonal emissions by pollutants for reopening scenario - 1 and reopening scenario - 2 are shown in the following Table 5-8 and Table 5-9.

Table 5-8 Zonal Emission of Major Pollutants during Reopening Scenario - 1

Reopening Scenario - 1								
Morning Peak								
Region	**GHG**	**CO**	**NO$_x$**	**PM$_{10}$**	**PM$_{2.5}$**	**SO$_2$**	**THC**	**VOC**
	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)
Urban	522,887,064	2,786,664	799,998	37,220	33,923	3,978	341,863	328,470
Suburban	190,419,861	1,014,820	291,335	13,555	12,354	1,449	124,496	119,619
Rural	2,908,774	15,502	4,450	207	189	22	1,902	1,827
Total	716,215,699	3,816,986	1,095,784	50,982	46,466	5,449	468,262	449,916
Evening Peak								
Region	**GHG**	**CO**	**NO$_x$**	**PM$_{10}$**	**PM$_{2.5}$**	**SO$_2$**	**THC**	**VOC**
	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)
Urban	448,285,508	1,915,653	718,123	28,121	25,703	3,435	203,665	197,133
Suburban	163,252,201	697,623	261,519	10,240	9,360	1,250	74,168	71,790
Rural	2,493,772	10,656	3,994	156	142	19	1,132	1,096
Total	614,031,482	2,623,933	983,637	38,518	35,206	4,705	278,967	270,020

Table 5-9 Zonal Emission of Major Pollutants during Reopening Scenario - 2

Reopening Scenario - 2								
Morning Peak								
Region	GHG	CO	NO$_x$	PM$_{10}$	PM$_{2.5}$	SO$_2$	THC	VOC
	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)
Urban	581,391,571	2,367,004	838,271	41,399	37,898	4,513	274,855	264,875
Suburban	211,725,456	861,992	305,273	15,076	13,801	1,644	100,094	96,459
Rural	3,234,229	13,167	4,663	230	211	25	1,529	1,473
Total	796,351,256	3,242,164	1,148,207	56,705	51,910	6,182	376,478	362,808
Evening Peak								
Region	**GHG**	**CO**	**NO$_x$**	**PM$_{10}$**	**PM$_{2.5}$**	**SO$_2$**	**THC**	**VOC**
	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)	(gm/km^2)
Urban	506,870,733	1,555,744	724,791	33,295	30,515	3,969	153,376	146,927
Suburban	184,587,191	566,555	263,947	12,125	11,113	1,445	55,855	53,507
Rural	2,819,677	8,654	4,032	185	170	22	853	817
Total	694,277,601	2,130,954	992,771	45,606	41,797	5,436	210,084	201,251

5.4 Conclusion

This chapter proposes a comprehensive modelling framework for measuring the impact of COVID-19 pandemic on traffic volume and vehicular emissions of Halifax Regional Municipality (HRM) during phased reopening scenarios. One of the most significant contributions of this research is the integration of the activity-based travel demand and traffic assignment models in EMME with the emission model in MOVES. A multiclass traffic assignment model is deployed within the EMME platform to investigate the impact of COVID-19 on the traffic volume. The origin-destination (O-D) matrices for different scenarios extracted from the output of the Shorter-term Decisions Simulator (SDS), are utilized in EMME to understand the network impact for both reopening scenarios. Considering the output of the EMME model, the emission model for Halifax Regional Municipality (HRM) is developed within the MOVES platform. The multiclass traffic network model is calibrated and validated using traffic count data collected from

Harbourside Transportation Consultants. During the reopening scenario - 1, the R^2 values for passenger car and for total traffic are 0.96 and 0.95. During the reopening scenario - 2, the R^2 values for passenger car and for total traffic are found to be 0.95 and 0.97. This study offers a better understanding of the spatial distribution of vehicle movements and associated emissions in Halifax during the pandemic.

The results of multiclass traffic network model give the insights about the change in traffic volume during the phased reopening scenarios of COVID-19 pandemic in Halifax Regional Municipality (HRM). For both reopening scenarios, as the restrictions lifted, the vehicular movements got increased compared to the lockdown scenario. For instance, in the reopening scenario – 1, traffic volume got increased by 42% during morning peak period with respect to the traffic volume of lockdown scenario. Similarly, 76% increase during evening peak period is reported. Likewise, in the and reopening scenario – 2, traffic volume got increased by 51% and 35% in the morning and evening peak period respectively. Therefore, the increase of traffic volume results in the rise of emissions in the phased reopening scenarios. The hourly profile of emission during reopening scenario - 1 describes that passenger car generates 266.96 ton GHG during the morning peak period, whereas the total emissions from delivery truck and long-haul truck are 3.2 ton and 388.96 ton, respectively. Similarly, the total GHG emission by passenger car is 210.74 ton for the evening peak period, whereas delivery truck and long-haul truck are responsible for 2.44 ton and 354.11 ton of GHG respectively. Similarly, the hourly profile of emission during reopening scenario - 2 estimates 300.28 ton GHG during the morning peak period. The total emissions from delivery truck and long-haul truck are 3.14 ton and 499.82 ton, respectively. Likewise, the total GHG emission by passenger car is 237.10 ton for the evening peak period, whereas delivery truck and long-haul truck are responsible for 2.46 ton and 458.04 ton of GHG respectively. During morning and evening peak periods of reopening scenario - 1, GHG emission by passenger car got increased which is 33% and 38% of the GHG emission in BAU scenario. Moreover, in the reopening scenario -2, the GHG emissions considering all modes are estimated to be 31% and 32% of the GHG emission of BAU scenario during morning and evening peak period respectively.

The spatial distribution of various pollutants from this model shows the emission density distribution in the Halifax Regional Municipality. The distribution shows that the highest concentrations of pollutants exist in the Halifax and Dartmouth downtown cores. This study also examines the density distribution of major pollutants for different area type of HRM. During the morning peak period of reopening scenario - 1, GHG, CO and NO_x emission got increased by 27%, 25% and 56% with respect to lockdown period. Similarly, during the evening peak period of reopening scenario - 2, increases of 23%, 30% and 8% for GHG, CO and NO_x compared to lockdown scenario are reported. Also, the suburban and urban regions demonstrate the increase of emission in the reopening scenarios.

This study has some certain limitations. Due to the unavailability of HRM travel survey data, the associated models are constructed using readily available data sources. The immediate future work is to conduct a comprehensive travel-activity survey, capturing pandemic-induced travel behaviours. Moreover, subsequent studies should include dynamic traffic assignment (DTA) based approach to take advantage of granular level of activity participation and destination choices available in the model. Nevertheless, this research provides vital insights on the Halifax region's traffic network impact and emissions during COVID-19 pandemic. Results of this study will aid policymakers in developing interventions during emergencies, and this modelling framework can be utilized to develop multiple post-pandemic scenarios to understand traffic network impact and overall vehicular emissions in the Halifax Regional Municipality (HRM). Recently, the HRM has adopted a comprehensive emission reduction strategy, known as HalifACT 2050, which includes the reduction of emission by 80% below 2016 levels and becoming carbon neutral by 2050. The results from this study could be helpful to set this target, monitor the outcome, and evaluate accordingly. In addition, transportation professionals can utilize this study's results to mitigate emission. Moreover, to develop policy for carbon pricing adopted by the Federal Government of Canada, the integration of the urban transport network model and emission model is required. Finally, the emission results are also relevant to the epidemiological studies of environment pollution and corresponding health issues.

Chapter 6

Conclusion

6.1 Summary

The research is motivated by the sudden disruption of the world health and economy by COVID-19 pandemic. This type of disruption also accelerates the transformation of urban and transportation planning. Policymakers will have to reconsider updating the urban and transportation planning to ensure a sustainable transport system and be prepared for any sudden disruptions. The COVID-19 pandemic has changed our activity participation, travel behaviour, mode choice as well as recreational activities. The changes in activity and mobility restrictions during the pandemic, have affected the income of business establishments, traffic volume and vehicular emission.

As one of the growing cities of Canada and a major economic center of Atlantic Canada, Halifax is largely concentrated with government services and private sector companies. Even two container terminals and one intermodal terminal in Halifax generate a huge traffic flow. The significant truck traffic contributes to the city's local traffic volume and vehicular emissions. But during the pandemic, imposed activity participation and mobility restrictions significantly affected these sectors. Many non-essential businesses got shut down and a huge percentage of people lost their jobs. The mobility restrictions also have a positive impact on the vehicular emission during lockdown period. But with the lifting of restrictions, the economic sector and vehicular emission started to get back to the pre-COVID situation. Therefore, this thesis develops a comprehensive modelling framework to assess the changes in sales volume of business establishments, traffic volume and vehicular emissions due to mobility restrictions imposed by the government during the COVID-19 pandemic lockdown and reopening phases.

The third chapter of this research presents an innovative modelling framework to **estimate the impact of the mobility restrictions due to COVID-19 pandemic on sales volume of business establishments** during the lockdown and phased reopening scenarios for the Halifax Regional Municipality (HRM). The business establishment dataset is geocoded and spatially joined with attributes of Halifax to estimate the sales of Traffic analysis zones (TAZ) in the business-as-usual scenario. Pandemic scenarios are developed within this model and sales of business establishments are estimated for lockdown and reopening scenarios. This chapter includes the integration of activity-based travel demand model and latent class regression model to estimate the sales volume of business establishments during the lockdown and phased reopening scenarios for the HRM. This chapter reveals that the Halifax Regional Municipality (HRM) faced an average economic loss of 87% during the lockdown period in comparison to the business-as-usual scenario. However, through the multistage reopening of the business establishments and activities, the sales volume started to increase and expected to reach the pre pandemic period soon.

The fourth and fifth chapters develop a **modelling framework to examine the impact of activity and mobility restrictions on traffic volume and vehicular emissions** of major pollutants. The modelling framework is developed for business-as-usual scenario, lockdown scenario, reopening scenario - 1 and reopening scenario - 2. The modelling framework includes the integration of activity-based travel demand model, Halifax regional transport network model and an emission model. This model adapts multiclass traffic assignment methods that incorporates both passenger car and commercial vehicle movements. The model is calibrated and validated for lockdown scenario as well as both reopening scenarios to acquire actual traffic condition in the network. The goodness of fit of this model is measured in terms of R^2, MPE, and GEH in the lockdown scenario whereas R^2, APE, MAPE, and GEH values are calculated for reopening scenarios. The results from the model reveal that during the lockdown scenario, Halifax experiences a substantial reduction in vehicular movements by 44% and 68% during morning and evening peak periods respectively. Significant decrease of GHG emission and other pollutants have been demonstrated from this model results. The results also indicate the increase of vehicular movements and emission during the phased reopening scenarios. For instance, in reopening scenario - 1, traffic volume got increased by 42% and 76% with respect to lockdown scenario in the morning and evening peak period respectively. The increase in vehicular movements eventually directed to the rise of vehicular emissions. In the morning peak period of reopening scenarios – 1 and – 2, an increase of 67 tons and 100 tons of GHG emissions is estimated from the lockdown scenario. Additionally, this model shows a similar pattern of increased emissions for other pollutants in the phased reopening scenarios. In summary, the findings of the research will help the policymakers to develop plans to be prepared for any emergencies like COVID-19 pandemic.

6.2 Major Contributions

This thesis has significant contributions in the field of transport and emission modelling regarding COVID-19 pandemic. The major contributions are described below:

1. This thesis examines the changes in sales volume of business establishments by utilizing an activity-based travel demand modelling approach during pandemic scenarios.
2. It offers an innovative modelling framework by integrating activity-based travel demand model, Halifax transport network model and emission model.
3. It gives critical insights about the impact of mobility restrictions on sales volume of local business establishments, traffic volume and vehicular emissions during lockdown and phased reopening scenarios.

6.3 Limitations and Future Scope

The consequence of the ongoing pandemic crisis throughout the world on business establishment sales, traffic volume, and vehicle emissions is the focus of this research. The study addressed the gap of the existing research on the examination of these impacts on regional level. However, this research has some certain limitations. The major limitation of this study is the unavailability of travel survey data. The scenarios of pandemic are developed within the activity-based travel demand model by considering many assumptions from various available data sources. Conducting a comprehensive travel-activity survey to capture the pandemic-induced travel behaviour should be the immediate future work. Another limitation of the study is, while estimating the sales of business establishments, online shopping which has significantly increased during this pandemic, is not considered. Due to time constraints, transit assignment is not considered in the Halifax transport network model. The immediate work should consider the transit assignment module in the model. Another limitation of this study is considering only two peak periods (total four hours) to analyse the impact of the pandemic. Future study should focus on the comprehensive analysis of the impact of pandemic for twenty-four hours. Also, the emission model could not be validated due to the unavailability of emission data during COVID-19 pandemic. The future study should include the validation of emission model to ensure the credibility of this model.

Future study could focus on combining an epidemiological model by implementing health impact parameters within the economic model framework to interpret the pandemic scenarios in the case of future waves. The subsequent studies should include dynamic traffic assignment (DTA) based approach to take advantage of granular level of activity participation and destination choices available in the model. In future, by mitigating the limitations, integration of activity-based travel demand model with the emission model could be more operational. A comprehensive modelling framework can be built based on this study, which will examine the impacts of any mobility disruptive events on economy, traffic network as well as the vehicular emission. The modelling framework will aid policymakers, researchers, and governments to predict the impacts of such emergencies on economy and climate change. With the forecast of this model, the policymakers will be able to adopt new plans to ensure sustainable transportation system. Moreover, the results of this study will be helpful to set the target of 80% reduction of emission below 2016 levels and becoming carbon neutral by 2050 by HalifACT 2050, monitor the outcome and evaluate accordingly. Finally, transportation professionals can utilize this study's results to mitigate emission and develop policy for carbon pricing adopted by the Federal Government of Canada.

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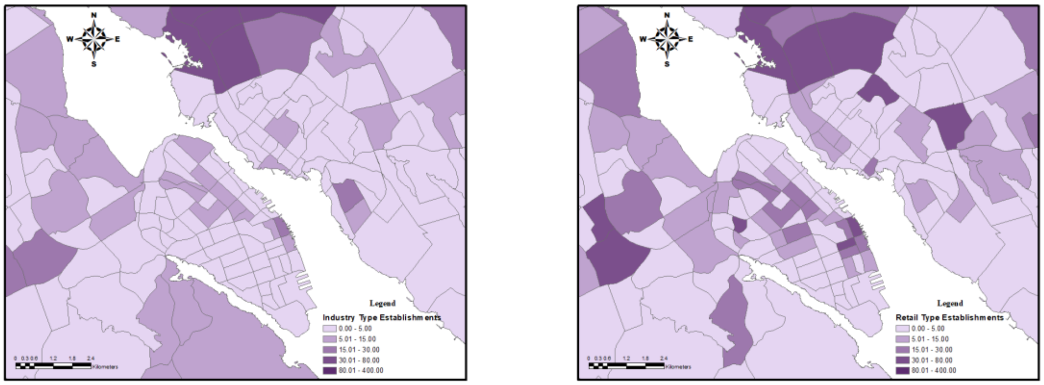
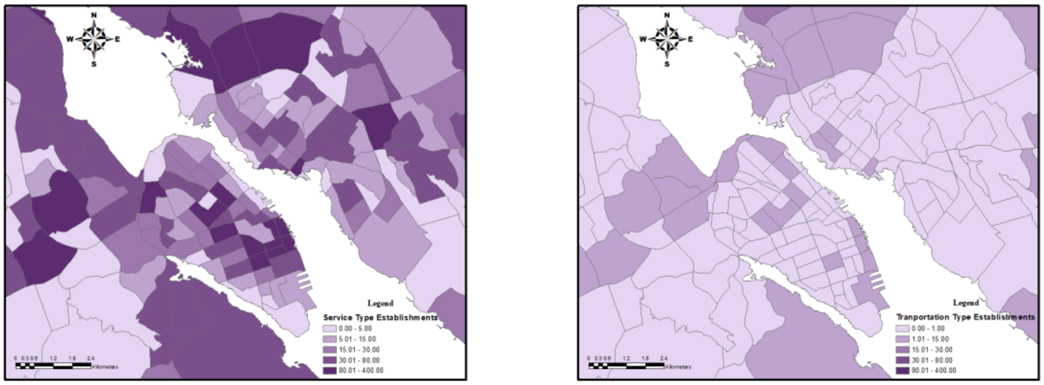
Appendices

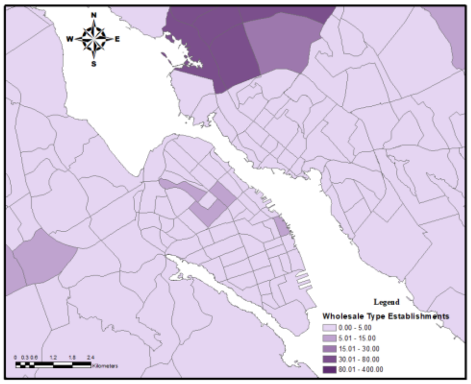
Appendix A Business Establishment Data Analysis



(a) Industry (b) Retail

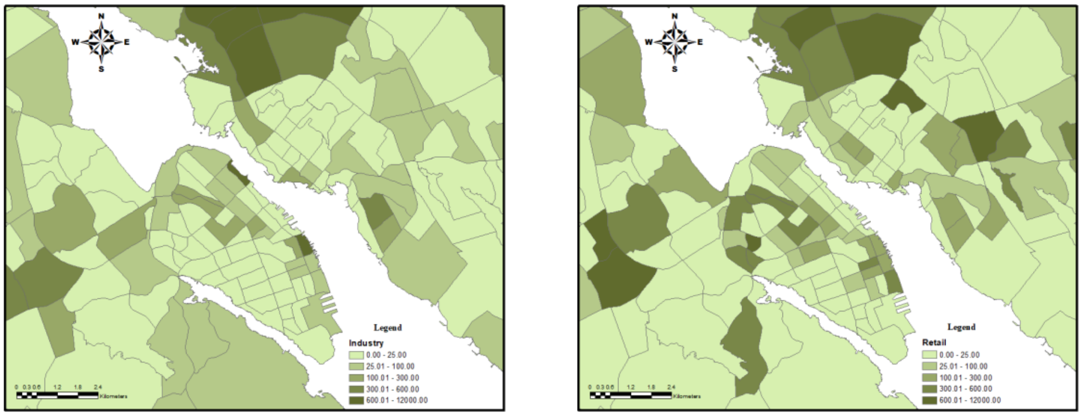


(c) Service (d) Transportation

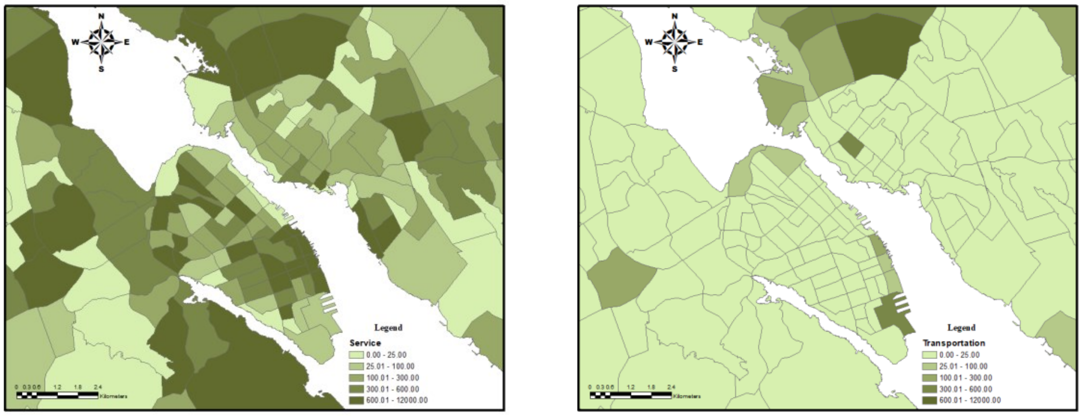


(e) Wholesale

Figure A-1 Number of Business Establishments Distribution throughout Urban Core of HRM by Establishment Types



(a) Industry (b) Retail



(c) Service (d) Transportation

(e) Wholesale (f) All Establishment Types

Figure A-2 **Number of Employee Distribution throughout Urban Core of HRM by Establishment Types**

Appendix B Emission of Major Pollutants during Pandemic Scenarios

a) Business-as-Usual Scenario

		GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	THC	VOC
	Mode	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
Morning Peak Period	Passenger Car	399.41	4.73	0.25	0.01	0.01	0.00	0.48	0.47
	Delivery Truck	112.02	0.30	0.24	0.01	0.01	0.00	0.08	0.06
	Long-Haul Truck	655.80	0.41	1.40	0.06	0.06	0.01	0.08	0.07
Evening Peak Period	Passenger Car	340.53	4.70	0.31	0.01	0.01	0.00	0.49	0.48
	Delivery Truck	87.28	0.10	0.19	0.01	0.01	0.00	0.03	0.03
	Long-Haul Truck	597.49	0.31	1.25	0.05	0.05	0.01	0.06	0.05

b) Lockdown Scenario

		GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	THC	VOC
	Mode	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
Morning Peak Period	Passenger Car	200.20	2.73	0.15	0.01	0.01	0.00	0.29	0.29
	Delivery Truck	4.09	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	340.02	0.21	0.73	0.03	0.03	0.00	0.04	0.03
Evening Peak Period	Passenger Car	200.20	2.73	0.15	0.01	0.01	0.00	0.29	0.29
	Delivery Truck	4.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	340.02	0.21	0.73	0.03	0.03	0.00	0.04	0.03

c) Reopening Scenario - 1

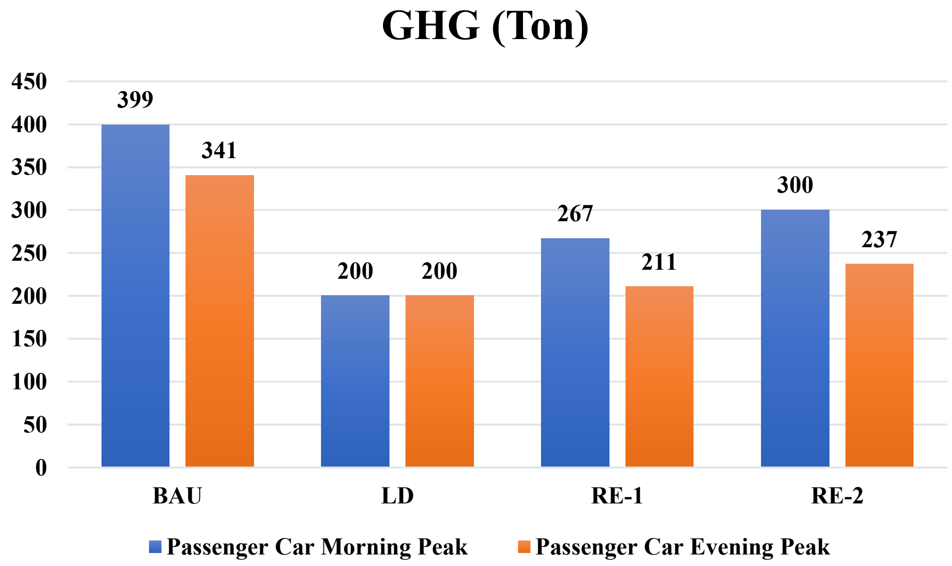
		GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	THC	VOC
	Mode	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
Morning Peak Period	Passenger Car	266.96	2.82	0.18	0.01	0.01	0.00	0.31	0.30
	Delivery Truck	3.20	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	388.96	0.25	0.84	0.04	0.03	0.00	0.05	0.04
Evening Peak Period	Passenger Car	210.74	1.82	0.13	0.00	0.00	0.00	0.16	0.16
	Delivery Truck	2.44	0.00	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	354.11	0.18	0.75	0.03	0.03	0.00	0.03	0.03

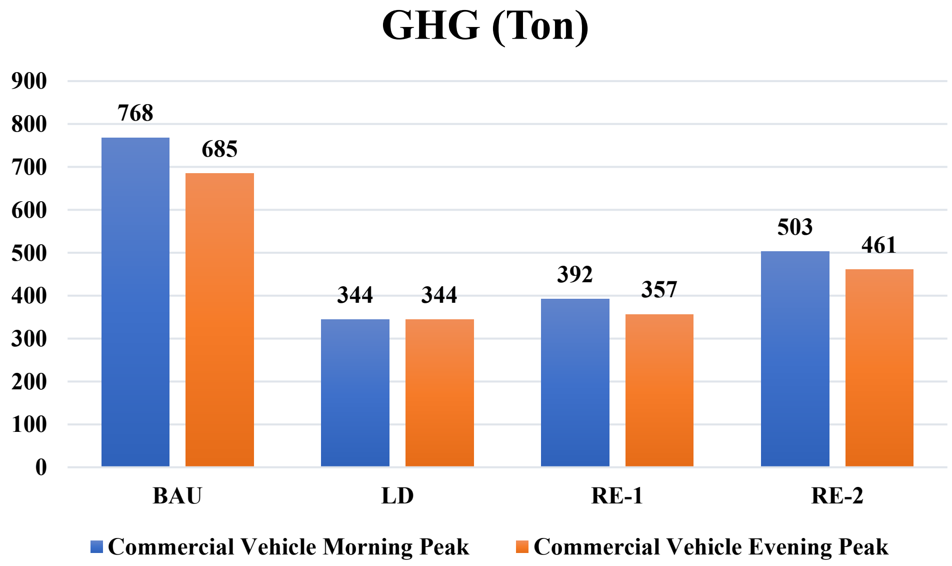
d) Reopening Scenario - 2

		GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	THC	VOC
	Mode	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
Morning Peak Period	Passenger Car	300.28	3.43	0.21	0.01	0.01	0.00	0.40	0.39
	Delivery Truck	3.14	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	499.82	0.31	0.93	0.05	0.04	0.00	0.06	0.05
Evening Peak Period	Passenger Car	237.10	2.36	0.19	0.01	0.01	0.00	0.24	0.23
	Delivery Truck	2.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Long-Haul Truck	458.04	0.23	0.83	0.04	0.04	0.00	0.04	0.04

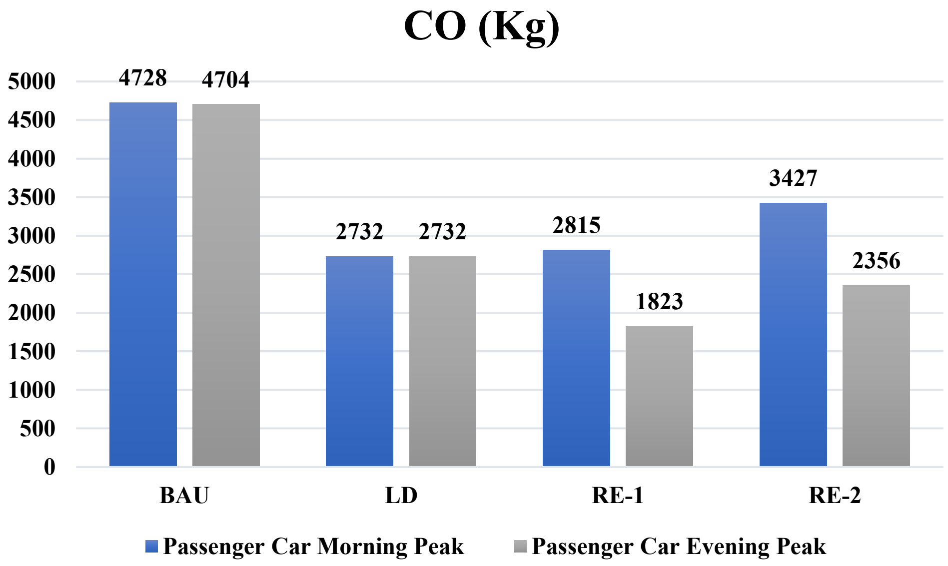
Appendix C Comparison of Emissions of Major Pollutants during Pandemic Scenarios

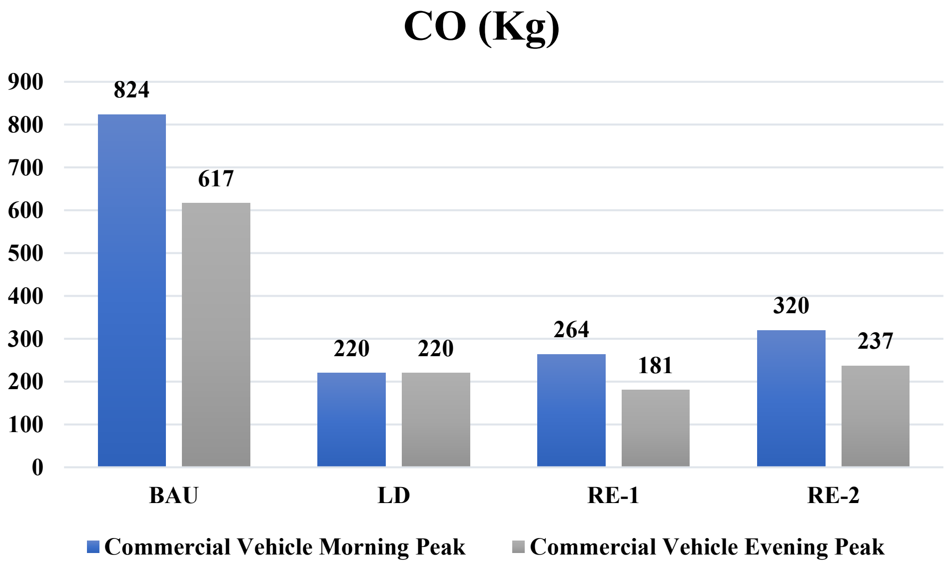
a) Comparison of GHG Emission

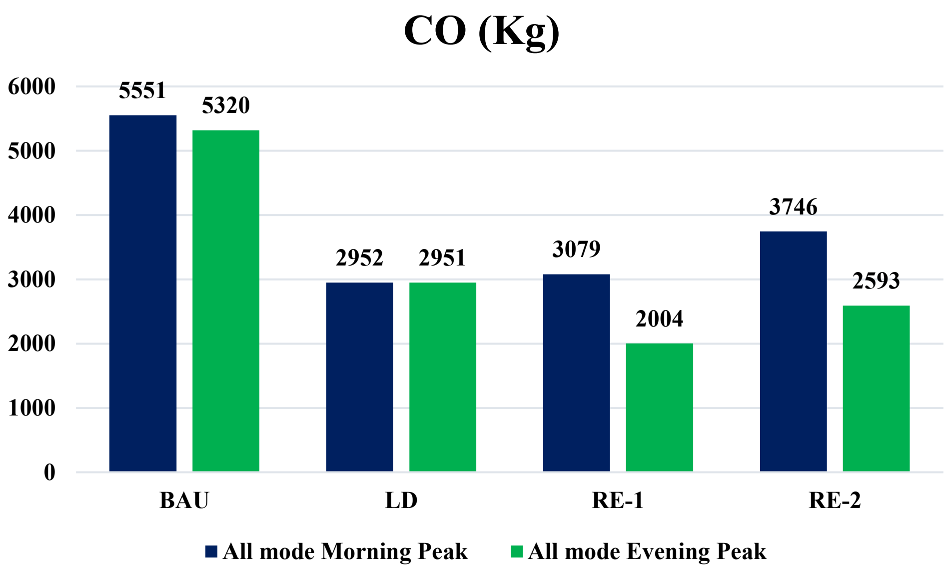




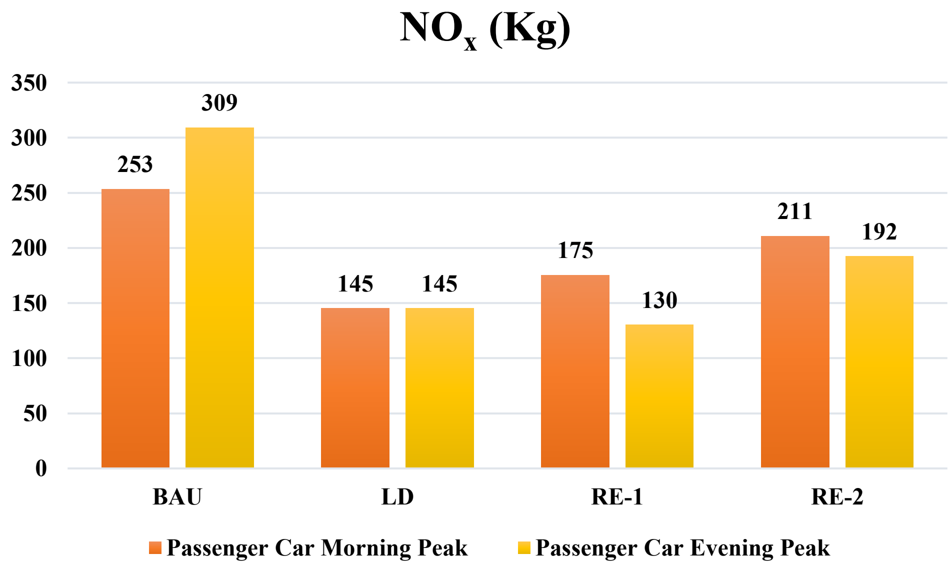
b) Comparison of CO Emission

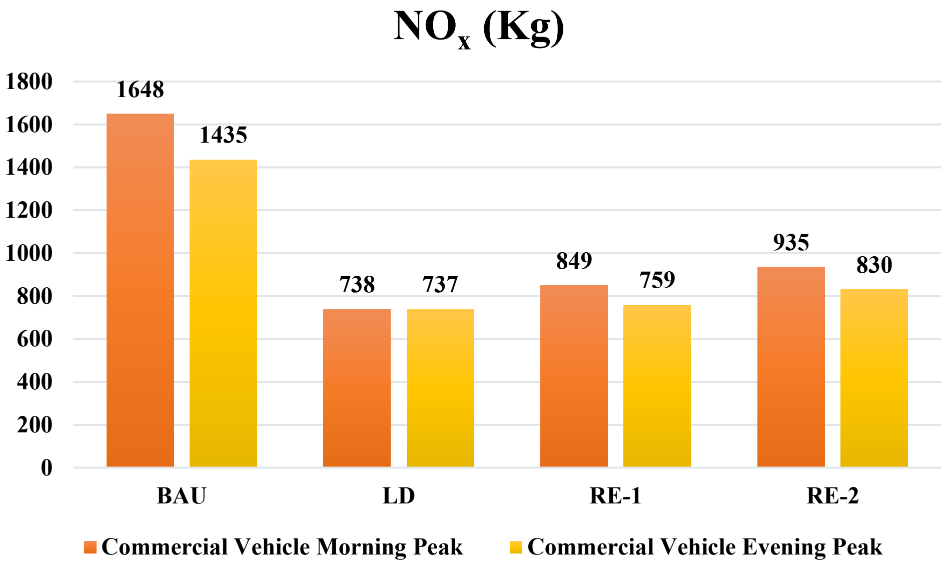


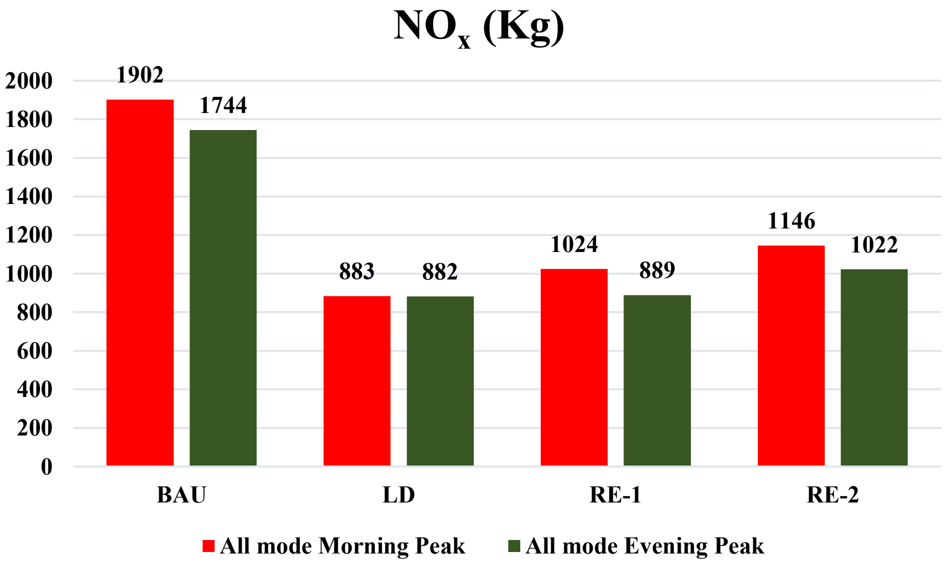




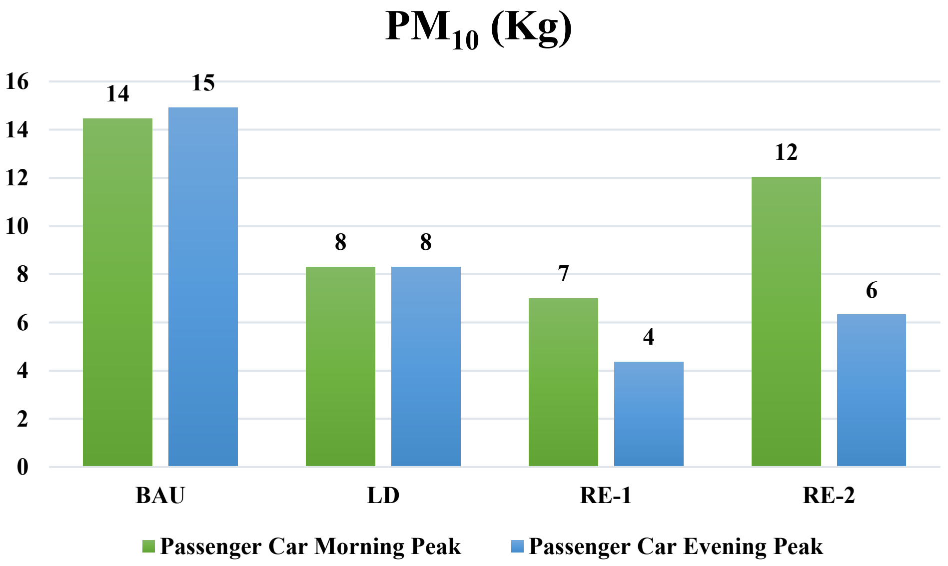
c) Comparison of NO_x Emission

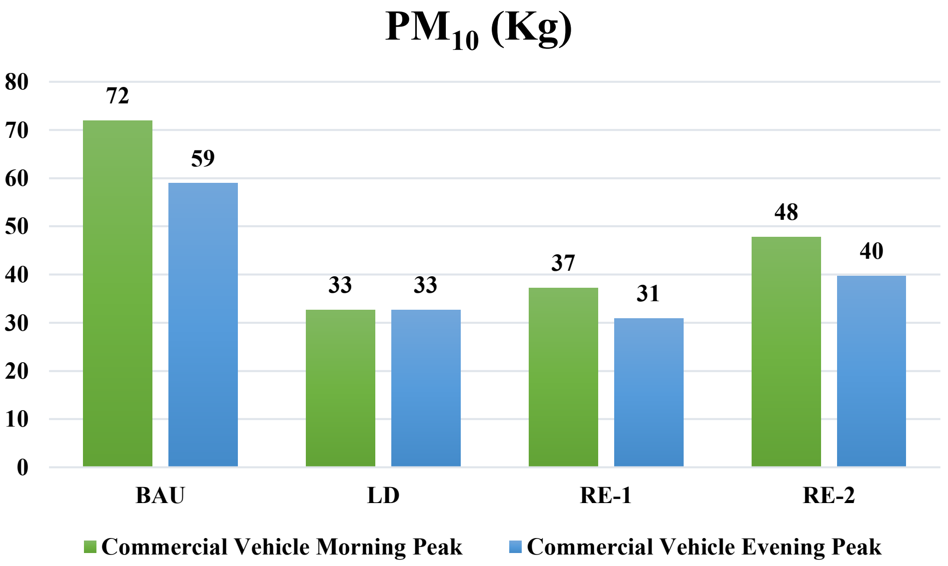


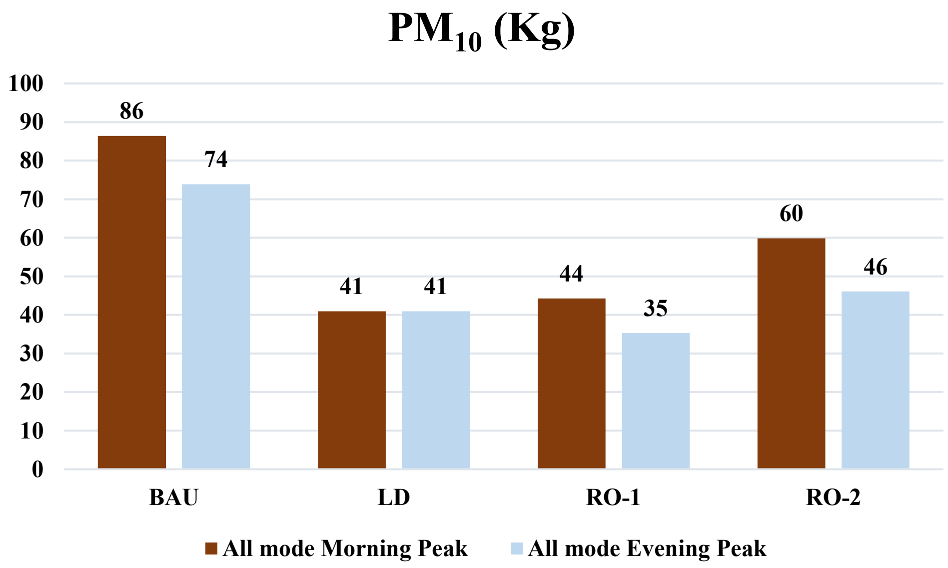

NO$_x$ (Kg)
1800
1600
1400
1200
1000
800
600
400
200
0
1648
1435
738
737
849
759
935
830
BAU
LD
RE-1
RE-2
Commercial Vehicle Morning Peak
Commercial Vehicle Evening Peak


NO$_x$ (Kg)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1902
1744
883
882
1024
889
1146
1022
BAU
LD
RE-1
RE-2
All mode Morning Peak
All mode Evening Peak

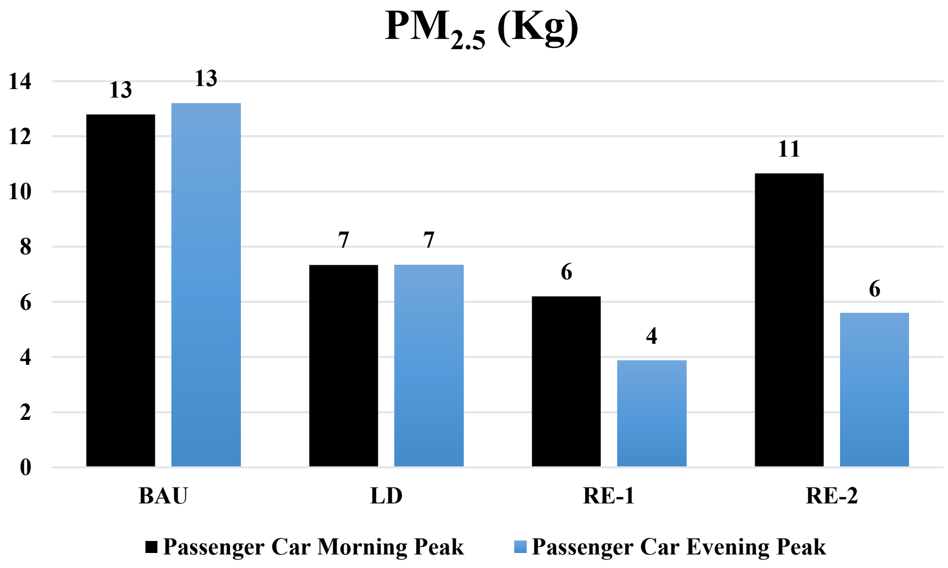
d) Comparison of PM_{10} Emission

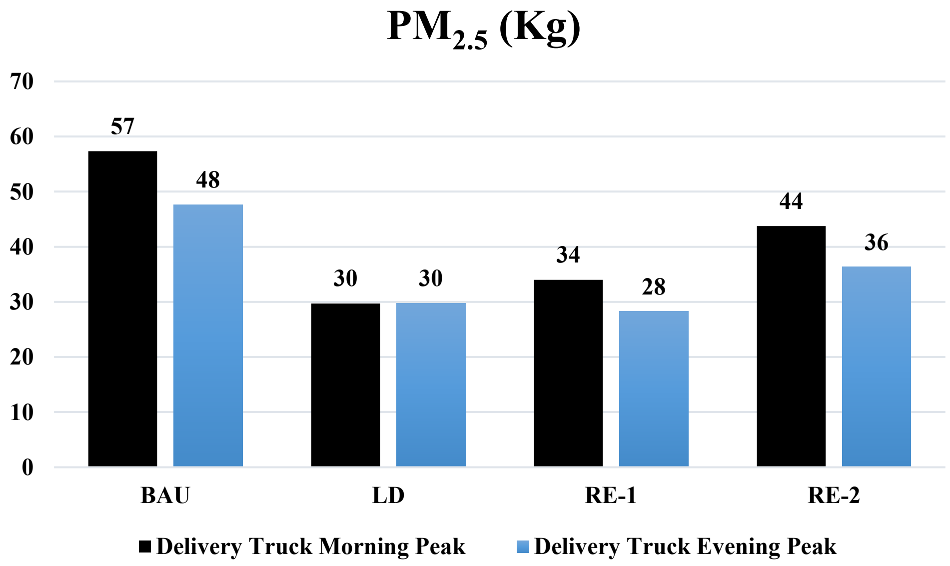


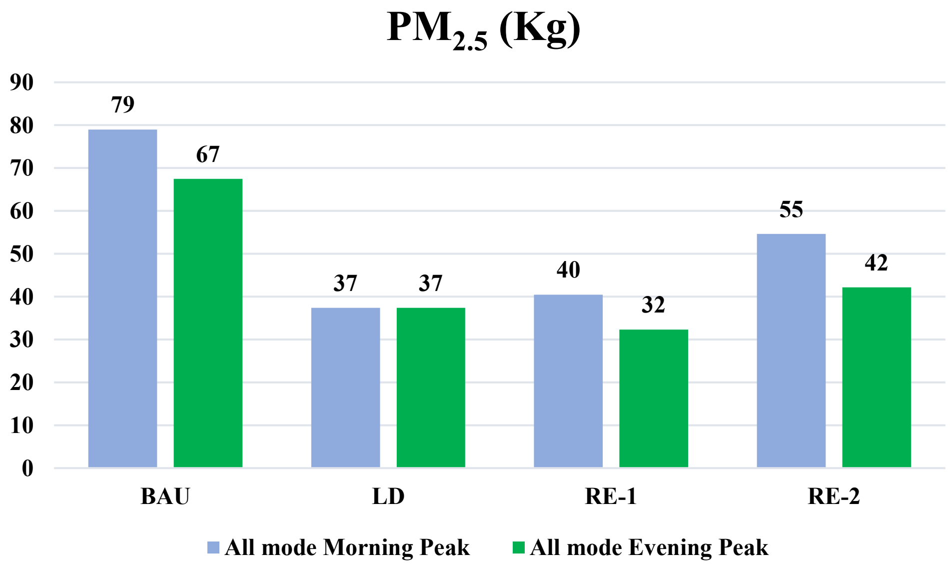




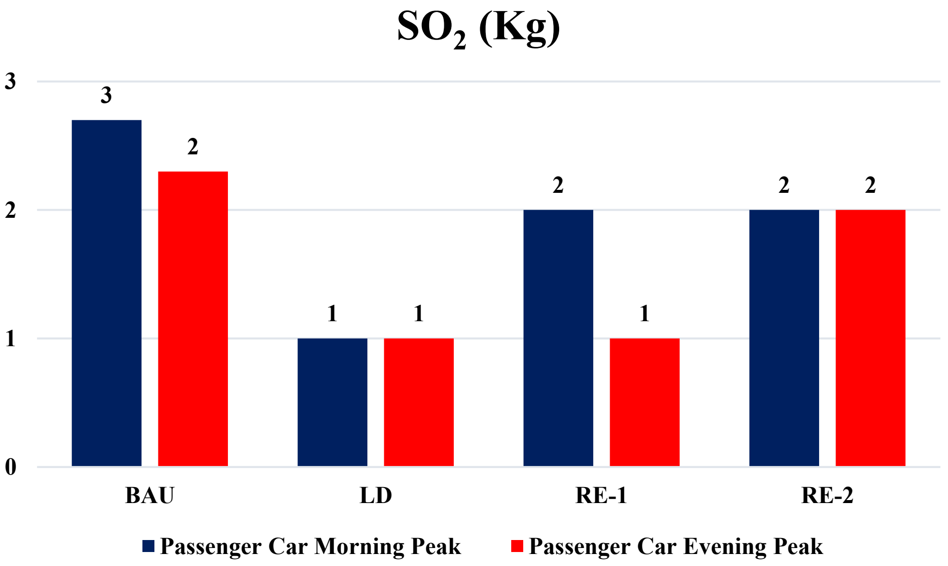
e) Comparison of PM$_{2.5}$ Emission

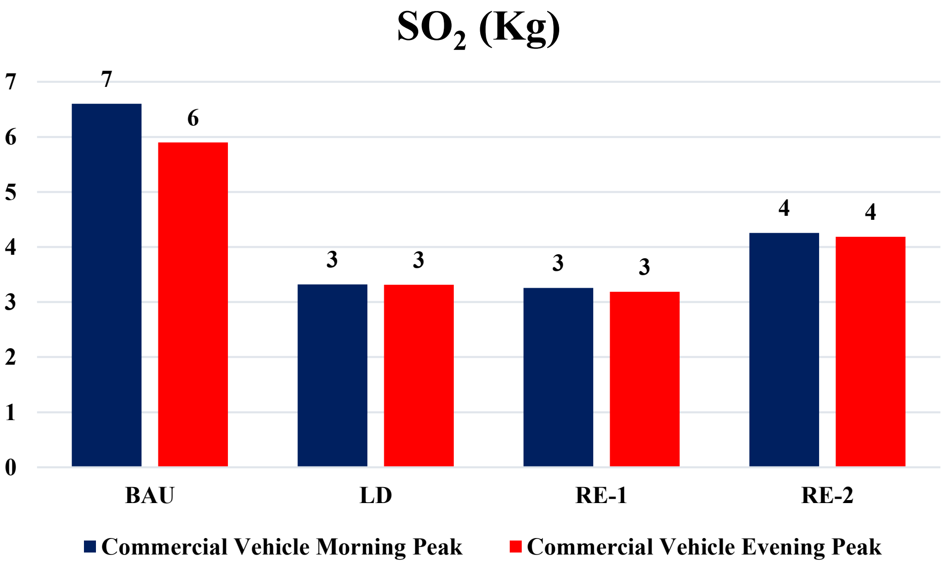


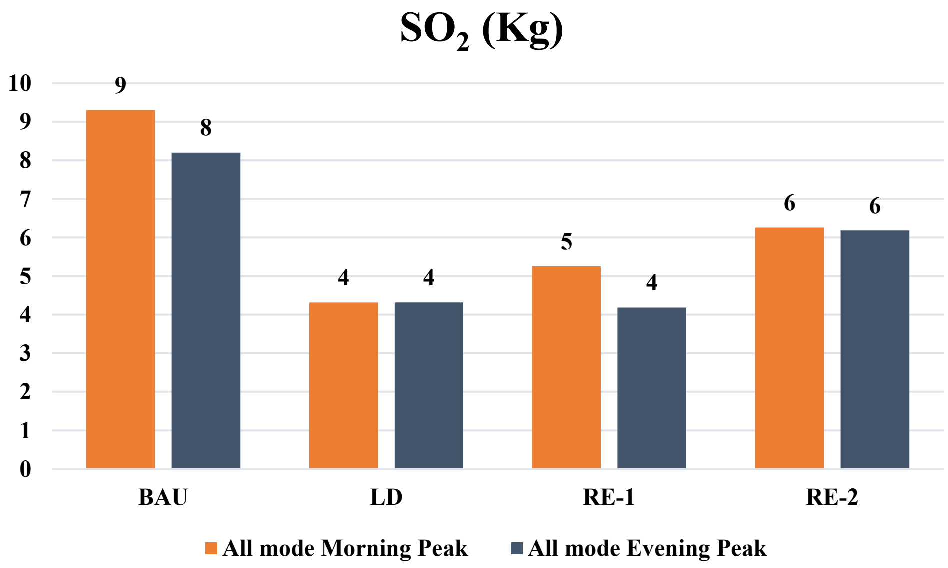

PM2.5 (Kg)
70
60
50
40
30
20
10
0
57
48
30
30
34
28
44
36
BAU
LD
RE-1
RE-2
■ Delivery Truck Morning Peak
■ Delivery Truck Evening Peak


PM2.5 (Kg)
90
80
70
60
50
40
30
20
10
0
79
67
37
37
40
32
55
42
BAU
LD
RE-1
RE-2
■ All mode Morning Peak
■ All mode Evening Peak

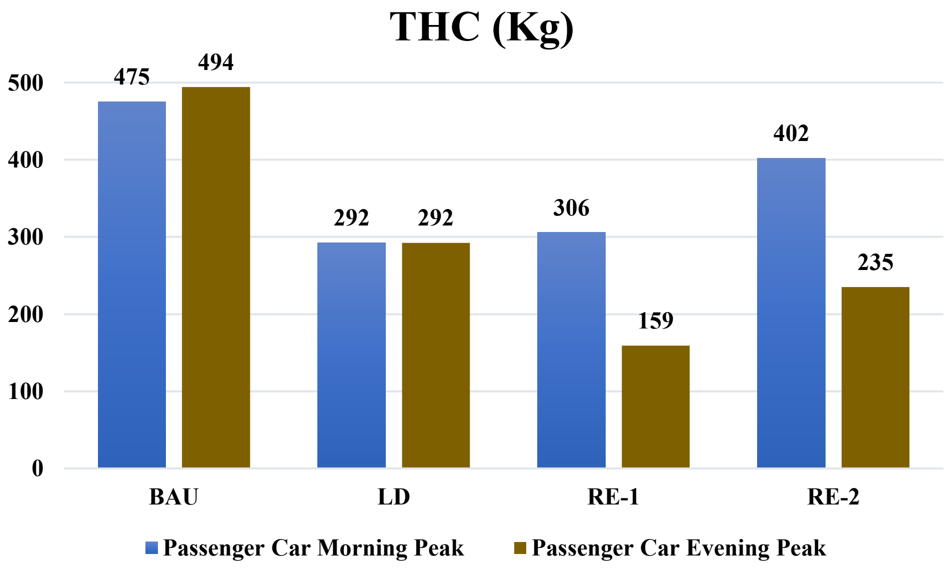
f) Comparison of SO_2 Emission

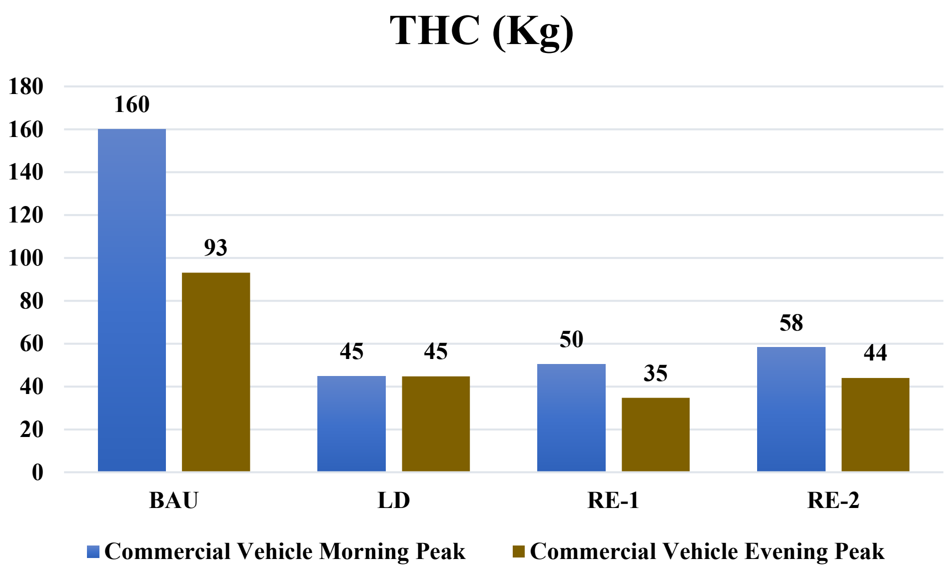


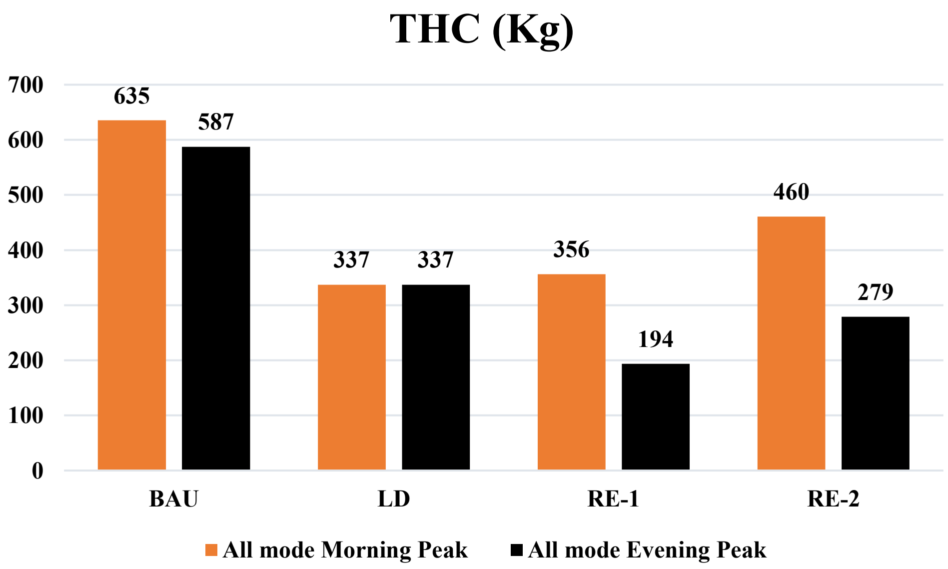




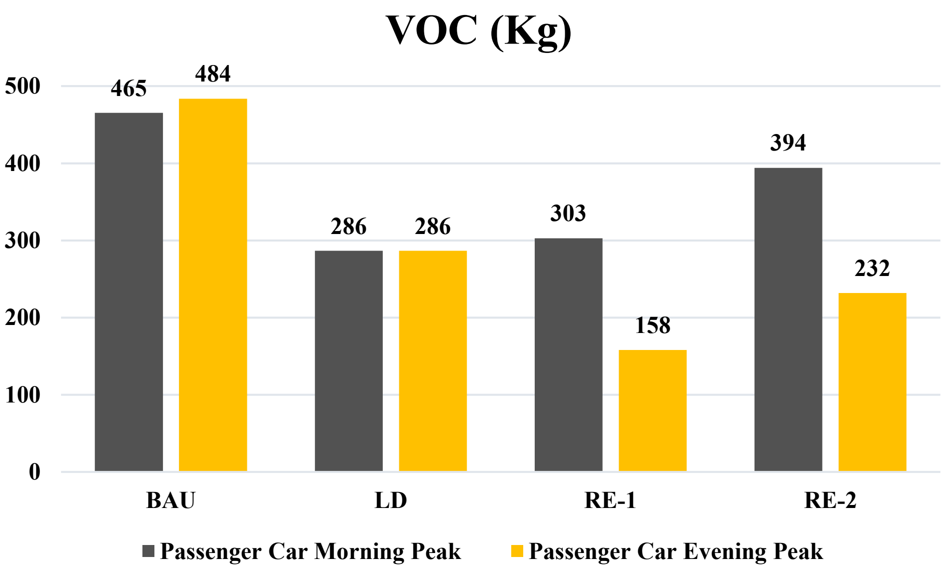
g) Comparison of THC Emission

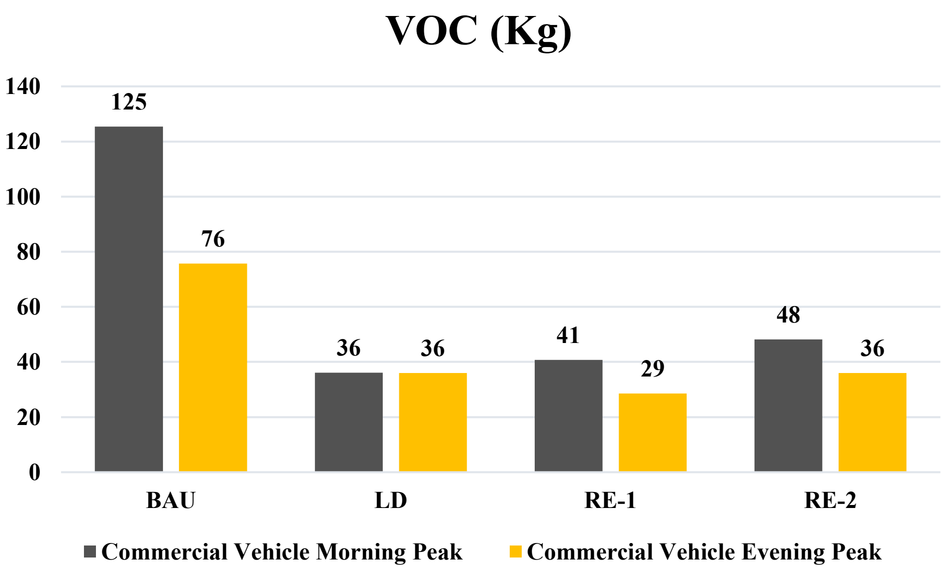


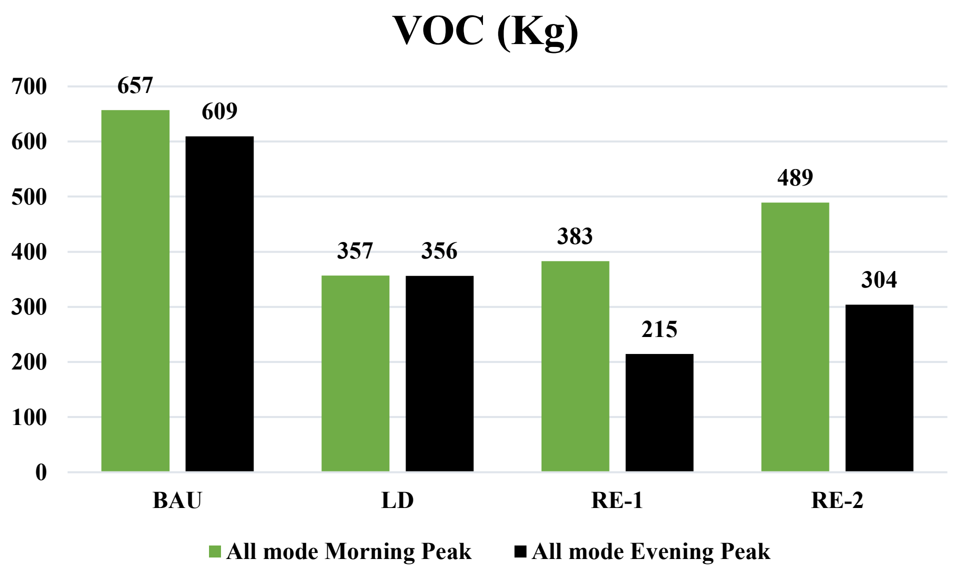

THC (Kg)
180
160
140
120
100
80
60
40
20
0
160
93
45
45
50
35
58
44
BAU
LD
RE-1
RE-2
Commercial Vehicle Morning Peak
Commercial Vehicle Evening Peak


THC (Kg)
700
600
500
400
300
200
100
0
635
587
337
337
356
194
460
279
BAU
LD
RE-1
RE-2
All mode Morning Peak
All mode Evening Peak

h) Comparison of VOC Emission






VOC (Kg)
700
600
500
400
300
200
100
0
657
609
357
356
383
215
489
304
BAU
LD
RE-1
RE-2
All mode Morning Peak
All mode Evening Peak

Appendix D Descriptive Statistics of the Pollutants during Pandemic Scenarios

a) Business-as-Usual Scenario

Morning Peak Period							
Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	380.22	3014.03	9572.27	1236.44	2609.30	4340.61
	Suburban	72.56	6723.56	24470.52	2226.18	5523.35	10328.35
	Rural	310.56	7850.21	19922.39	2846.57	5407.26	12972.48
CO	Urban	1.77	14.04	44.58	5.76	12.15	20.21
	Suburban	0.34	31.31	113.96	10.37	25.72	48.10
	Rural	1.45	36.56	92.78	13.26	25.18	60.41
NO_x	Urban	0.62	4.91	15.60	2.01	4.25	7.07
	Suburban	0.12	10.96	39.87	3.63	9.00	16.83
	Rural	0.51	12.79	32.46	4.64	8.81	21.14
PM_{10}	Urban	0.03	0.22	0.71	0.09	0.19	0.32
	Suburban	0.01	0.50	1.81	0.16	0.41	0.76
	Rural	0.02	0.58	1.47	0.21	0.40	0.96
$PM_{2.5}$	Urban	0.03	0.20	0.65	0.08	0.18	0.29
	Suburban	0.00	0.46	1.66	0.15	0.37	0.70
	Rural	0.02	0.53	1.35	0.19	0.37	0.88
SO_2	Urban	0.00	0.02	0.07	0.01	0.02	0.03
	Suburban	0.00	0.05	0.19	0.02	0.04	0.08
	Rural	0.00	0.06	0.15	0.02	0.04	0.10
THC	Urban	0.21	1.64	5.21	0.67	1.42	2.36
	Suburban	0.04	3.66	13.32	1.21	3.01	5.62
	Rural	0.17	4.27	10.84	1.55	2.94	7.06
VOC	Urban	0.19	1.53	4.84	0.63	1.32	2.20
	Suburban	0.04	3.40	12.38	1.13	2.80	5.23
	Rural	0.16	3.97	10.08	1.44	2.74	6.56

Evening Peak Period

Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	333.99	2647.52	8408.27	1086.09	2292.01	3812.79
	Suburban	63.74	5905.97	21494.88	1955.47	4851.71	9072.42
	Rural	272.80	6895.62	17499.81	2500.43	4749.73	11395.01
CO	Urban	1.67	13.21	41.96	5.42	11.44	19.02
	Suburban	0.32	29.47	107.25	9.76	24.21	45.27
	Rural	1.36	34.41	87.32	12.48	23.70	56.86
NO_x	Urban	0.57	4.50	14.31	1.85	3.90	6.49
	Suburban	0.11	10.05	36.57	3.33	8.25	15.44
	Rural	0.46	11.73	29.77	4.25	8.08	19.39
PM_{10}	Urban	0.02	0.19	0.61	0.08	0.17	0.27
	Suburban	0.00	0.43	1.55	0.14	0.35	0.65
	Rural	0.02	0.50	1.26	0.18	0.34	0.82
$PM_{2.5}$	Urban	0.02	0.17	0.55	0.07	0.15	0.25
	Suburban	0.00	0.39	1.41	0.13	0.32	0.60
	Rural	0.02	0.45	1.15	0.16	0.31	0.75
SO_2	Urban	0.00	0.02	0.07	0.01	0.02	0.03
	Suburban	0.00	0.05	0.17	0.02	0.04	0.07
	Rural	0.00	0.05	0.14	0.02	0.04	0.09
THC	Urban	0.19	1.52	4.82	0.62	1.31	2.18
	Suburban	0.04	3.38	12.31	1.12	2.78	5.20
	Rural	0.16	3.95	10.03	1.43	2.72	6.53
VOC	Urban	0.18	1.44	4.59	0.59	1.25	2.08
	Suburban	0.03	3.22	11.73	1.07	2.65	4.95
	Rural	0.15	3.76	9.55	1.36	2.59	6.22

b) Lockdown Scenario

Morning Peak Period							
Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	380.22	3014.03	9572.27	1236.44	2609.30	4340.61
	Suburban	72.56	6723.56	24470.52	2226.18	5523.35	10328.35
	Rural	310.56	7850.21	19922.39	2846.57	5407.26	12972.48
CO	Urban	1.77	14.04	44.58	5.76	12.15	20.21
	Suburban	0.34	31.31	113.96	10.37	25.72	48.10
	Rural	1.45	36.56	92.78	13.26	25.18	60.41
NO_x	Urban	0.62	4.91	15.60	2.01	4.25	7.07
	Suburban	0.12	10.96	39.87	3.63	9.00	16.83
	Rural	0.51	12.79	32.46	4.64	8.81	21.14
PM_{10}	Urban	0.03	0.22	0.71	0.09	0.19	0.32
	Suburban	0.01	0.50	1.81	0.16	0.41	0.76
	Rural	0.02	0.58	1.47	0.21	0.40	0.96
$PM_{2.5}$	Urban	0.03	0.20	0.65	0.08	0.18	0.29
	Suburban	0.00	0.46	1.66	0.15	0.37	0.70
	Rural	0.02	0.53	1.35	0.19	0.37	0.88
SO_2	Urban	0.00	0.02	0.07	0.01	0.02	0.03
	Suburban	0.00	0.05	0.19	0.02	0.04	0.08
	Rural	0.00	0.06	0.15	0.02	0.04	0.10
THC	Urban	0.21	1.64	5.21	0.67	1.42	2.36
	Suburban	0.04	3.66	13.32	1.21	3.01	5.62
	Rural	0.17	4.27	10.84	1.55	2.94	7.06
VOC	Urban	0.19	1.53	4.84	0.63	1.32	2.20
	Suburban	0.04	3.40	12.38	1.13	2.80	5.23
	Rural	0.16	3.97	10.08	1.44	2.74	6.56

Evening Peak Period

Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	333.99	1086.09	2292.01	2647.52	3812.79	8408.27
	Suburban	63.74	1955.47	4851.71	5905.97	9072.42	21494.88
	Rural	272.80	2500.43	4749.73	6895.62	11395.01	17499.81
CO	Urban	1.67	5.42	11.44	13.21	19.02	41.96
	Suburban	0.32	9.76	24.21	29.47	45.27	107.25
	Rural	1.36	12.48	23.70	34.41	56.86	87.32
NO_x	Urban	0.57	1.85	3.90	4.50	6.49	14.31
	Suburban	0.11	3.33	8.25	10.05	15.44	36.57
	Rural	0.46	4.25	8.08	11.73	19.39	29.77
PM_{10}	Urban	0.02	0.08	0.17	0.19	0.27	0.61
	Suburban	0.00	0.14	0.35	0.43	0.65	1.55
	Rural	0.02	0.18	0.34	0.50	0.82	1.26
$PM_{2.5}$	Urban	0.02	0.07	0.15	0.17	0.25	0.55
	Suburban	0.00	0.13	0.32	0.39	0.60	1.41
	Rural	0.02	0.16	0.31	0.45	0.75	1.15
SO_2	Urban	0.00	0.01	0.02	0.02	0.03	0.07
	Suburban	0.00	0.02	0.04	0.05	0.07	0.17
	Rural	0.00	0.02	0.04	0.05	0.09	0.14
THC	Urban	0.19	0.62	1.31	1.52	2.18	4.82
	Suburban	0.04	1.12	2.78	3.38	5.20	12.31
	Rural	0.16	1.43	2.72	3.95	6.53	10.03
VOC	Urban	0.18	0.59	1.25	1.44	2.08	4.59
	Suburban	0.03	1.07	2.65	3.22	4.95	11.73
	Rural	0.15	1.36	2.59	3.76	6.22	9.55

c) Reopening Scenario - 1

Morning Peak Period							
Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	225.56	1788.03	5678.61	733.50	1547.93	2575.00
	Suburban	43.05	3988.66	14516.79	1320.65	3276.65	6127.15
	Rural	184.24	4657.02	11818.67	1688.69	3207.78	7695.74
CO	Urban	1.20	9.53	30.26	3.91	8.25	13.72
	Suburban	0.23	21.26	77.37	7.04	17.46	32.65
	Rural	0.98	24.82	62.99	9.00	17.10	41.01
NO_x	Urban	0.35	2.74	8.69	1.12	2.37	3.94
	Suburban	0.07	6.10	22.21	2.02	5.01	9.37
	Rural	0.28	7.13	18.08	2.58	4.91	11.77
PM_{10}	Urban	0.02	0.13	0.40	0.05	0.11	0.18
	Suburban	0.00	0.28	1.03	0.09	0.23	0.44
	Rural	0.01	0.33	0.84	0.12	0.23	0.55
$PM_{2.5}$	Urban	0.01	0.12	0.37	0.05	0.10	0.17
	Suburban	0.00	0.26	0.94	0.09	0.21	0.40
	Rural	0.01	0.30	0.77	0.11	0.21	0.50
SO_2	Urban	0.00	0.01	0.04	0.01	0.01	0.02
	Suburban	0.00	0.03	0.11	0.01	0.02	0.05
	Rural	0.00	0.04	0.09	0.01	0.02	0.06
THC	Urban	0.15	1.17	3.71	0.48	1.01	1.68
	Suburban	0.03	2.61	9.49	0.86	2.14	4.01
	Rural	0.12	3.04	7.73	1.10	2.10	5.03
VOC	Urban	0.14	1.12	3.57	0.46	0.97	1.62
	Suburban	0.03	2.51	9.12	0.83	2.06	3.85
	Rural	0.12	2.93	7.42	1.06	2.02	4.83

Evening Peak Period							
Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	193.38	628.85	1327.08	2207.62	1532.93	4868.43
	Suburban	36.90	1132.23	2809.16	5252.97	3419.59	12445.64
	Rural	157.95	1447.76	2750.12	6597.77	3992.60	10132.47
CO	Urban	0.83	2.69	5.67	9.43	6.55	20.80
	Suburban	0.16	4.84	12.00	22.45	14.61	53.18
	Rural	0.67	6.19	11.75	28.19	17.06	43.30
NO_x	Urban	0.31	1.01	2.13	3.54	2.46	7.80
	Suburban	0.06	1.81	4.50	8.41	5.48	19.94
	Rural	0.25	2.32	4.41	10.57	6.40	16.23
PM_{10}	Urban	0.01	0.04	0.08	0.14	0.10	0.31
	Suburban	0.00	0.07	0.18	0.33	0.21	0.78
	Rural	0.01	0.09	0.17	0.41	0.25	0.64
$PM_{2.5}$	Urban	0.01	0.04	0.08	0.13	0.09	0.28
	Suburban	0.00	0.06	0.16	0.30	0.20	0.71
	Rural	0.01	0.08	0.16	0.38	0.23	0.58
SO_2	Urban	0.00	0.00	0.01	0.02	0.01	0.04
	Suburban	0.00	0.01	0.02	0.04	0.03	0.10
	Rural	0.00	0.01	0.02	0.05	0.03	0.08
THC	Urban	0.09	0.29	0.60	1.00	0.70	2.21
	Suburban	0.02	0.51	1.28	2.39	1.55	5.65
	Rural	0.07	0.66	1.25	3.00	1.81	4.60
VOC	Urban	0.09	0.28	0.58	0.97	0.67	2.14
	Suburban	0.02	0.50	1.24	2.31	1.50	5.47
	Rural	0.07	0.64	1.21	2.90	1.76	4.46

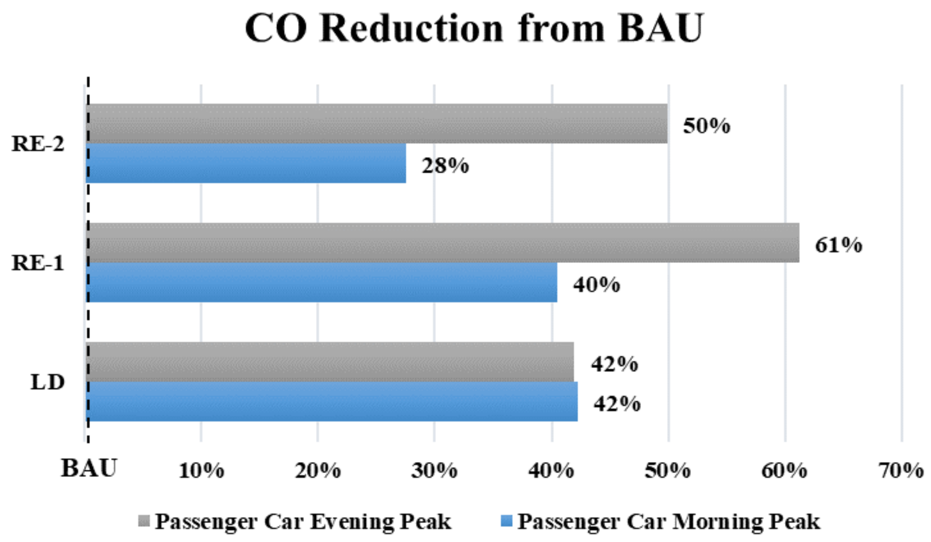
d) Reopening Scenario - 2

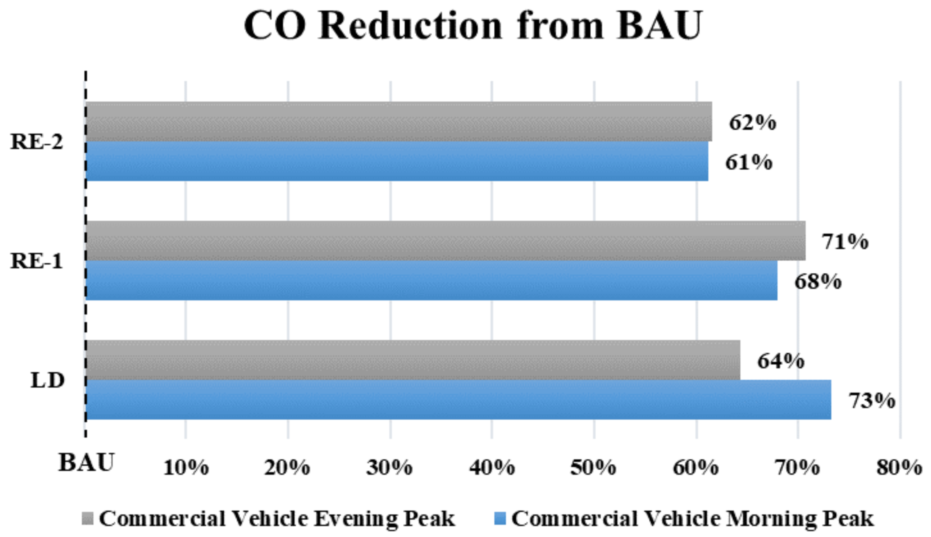
Morning Peak Period							
Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	250.80	1988.09	6313.98	815.57	2863.11	1721.12
	Suburban	47.86	4434.94	16141.03	1468.41	6812.70	3643.27
	Rural	204.85	5178.09	13141.03	1877.63	8556.80	3566.69
CO	Urban	1.02	8.09	25.71	3.32	11.66	7.01
	Suburban	0.19	18.06	65.71	5.98	27.74	14.83
	Rural	0.83	21.08	53.50	7.64	34.84	14.52
NO_x	Urban	0.36	2.87	9.10	1.18	4.13	2.48
	Suburban	0.07	6.39	23.27	2.12	9.82	5.25
	Rural	0.30	7.47	18.95	2.71	12.34	5.14
PM_{10}	Urban	0.02	0.14	0.45	0.06	0.20	0.12
	Suburban	0.00	0.32	1.15	0.10	0.49	0.26
	Rural	0.01	0.37	0.94	0.13	0.61	0.25
$PM_{2.5}$	Urban	0.02	0.13	0.41	0.05	0.19	0.11
	Suburban	0.00	0.29	1.05	0.10	0.44	0.24
	Rural	0.01	0.34	0.86	0.12	0.56	0.23
SO_2	Urban	0.00	0.02	0.05	0.01	0.02	0.01
	Suburban	0.00	0.03	0.13	0.01	0.05	0.03
	Rural	0.00	0.04	0.10	0.01	0.07	0.03
THC	Urban	0.12	0.94	2.98	0.39	1.35	0.81
	Suburban	0.02	2.10	7.63	0.69	3.22	1.72
	Rural	0.10	2.45	6.21	0.89	4.05	1.69
VOC	Urban	0.11	0.91	2.88	0.37	1.30	0.78
	Suburban	0.02	2.02	7.35	0.67	3.10	1.66
	Rural	0.09	2.36	5.99	0.86	3.90	1.62

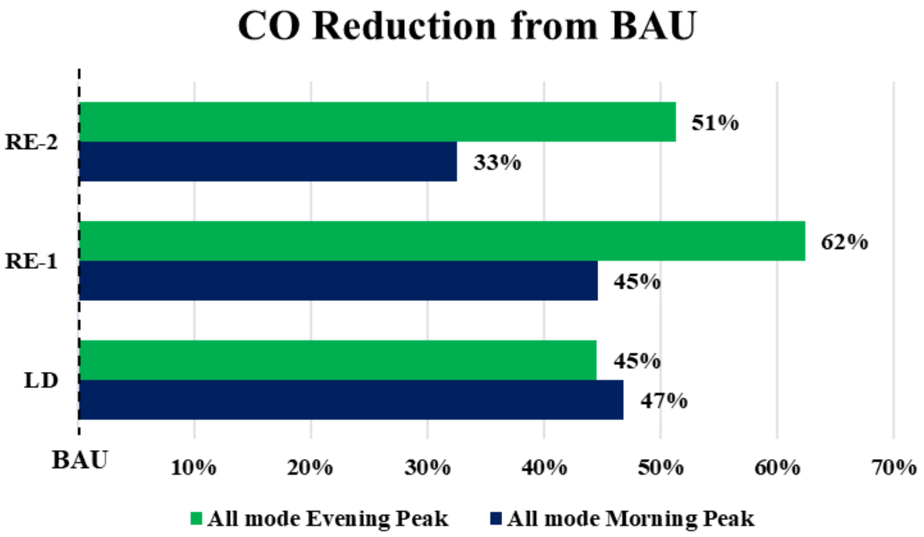
Evening Peak Period							
Pollutant	Region	Minimum (kg)	Average (kg)	Maximum (kg)	25th Percentile (kg)	Median (kg)	75th Percentile (kg)
GHG	Urban	218.65	1733.26	5504.67	711.03	1500.52	2496.13
	Suburban	41.73	3866.48	14072.13	1280.19	3176.29	5939.47
	Rural	178.59	4514.38	11456.66	1636.96	3109.52	7460.01
CO	Urban	0.67	5.32	16.90	2.18	4.61	7.66
	Suburban	0.13	11.87	43.19	3.93	9.75	18.23
	Rural	0.55	13.86	35.16	5.02	9.54	22.90
NO_x	Urban	0.31	2.48	7.87	1.02	2.15	3.57
	Suburban	0.06	5.53	20.12	1.83	4.54	8.49
	Rural	0.26	6.46	16.38	2.34	4.45	10.67
PM_{10}	Urban	0.01	0.11	0.36	0.05	0.10	0.16
	Suburban	0.00	0.25	0.92	0.08	0.21	0.39
	Rural	0.01	0.30	0.75	0.11	0.20	0.49
$PM_{2.5}$	Urban	0.01	0.10	0.33	0.04	0.09	0.15
	Suburban	0.00	0.23	0.85	0.08	0.19	0.36
	Rural	0.01	0.27	0.69	0.10	0.19	0.45
SO_2	Urban	0.00	0.01	0.04	0.01	0.01	0.02
	Suburban	0.00	0.03	0.11	0.01	0.02	0.05
	Rural	0.00	0.04	0.09	0.01	0.02	0.06
THC	Urban	0.07	0.52	1.67	0.22	0.45	0.76
	Suburban	0.01	1.17	4.26	0.39	0.96	1.80
	Rural	0.05	1.37	3.47	0.50	0.94	2.26
VOC	Urban	0.06	0.50	1.60	0.21	0.43	0.72
	Suburban	0.01	1.12	4.08	0.37	0.92	1.72
	Rural	0.05	1.31	3.32	0.47	0.90	2.16

Appendix E Changes in Emissions of Major Pollutants during Pandemic Scenarios

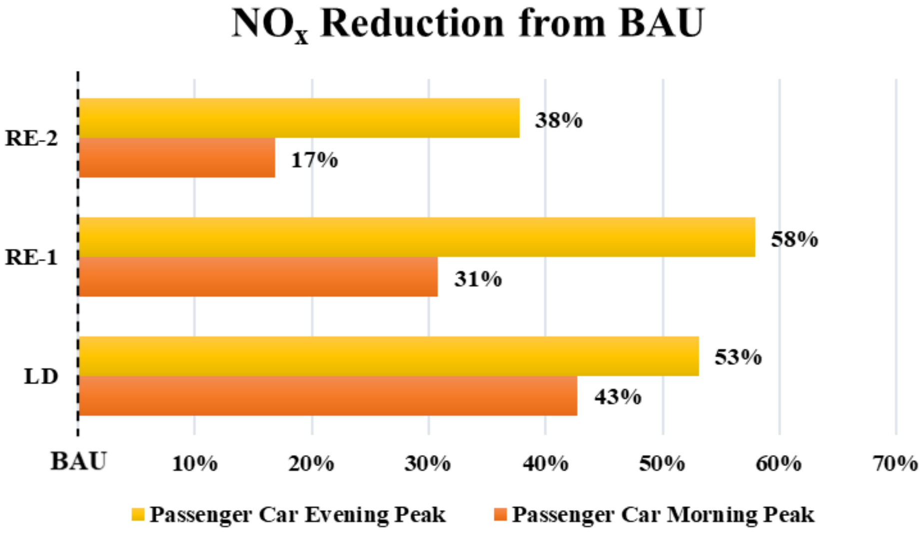
a) Change in CO Emission

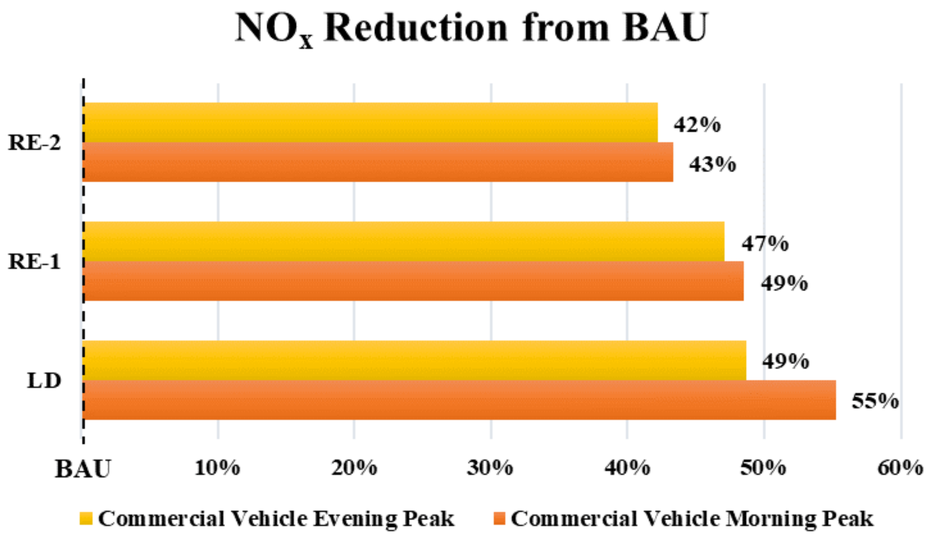


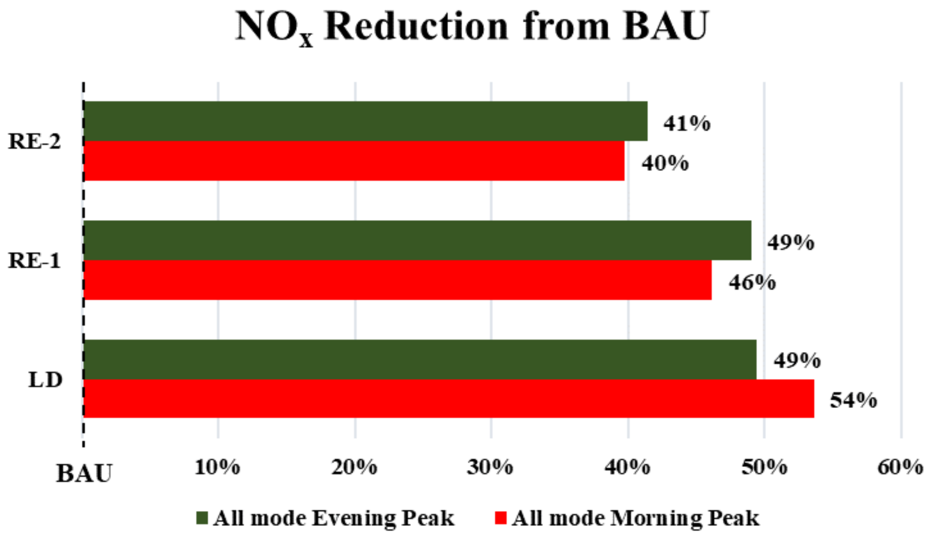




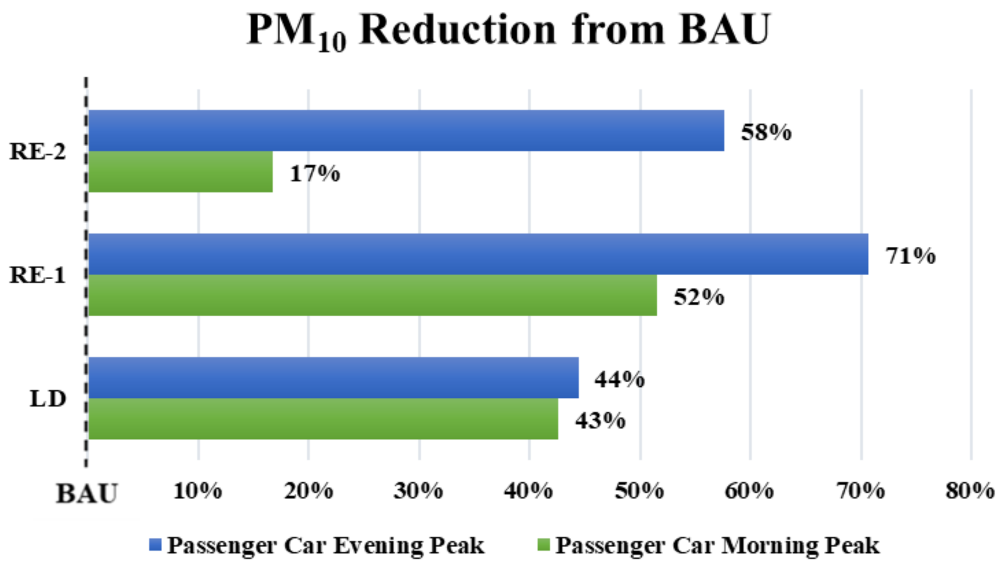
b) Change in NO_x Emission

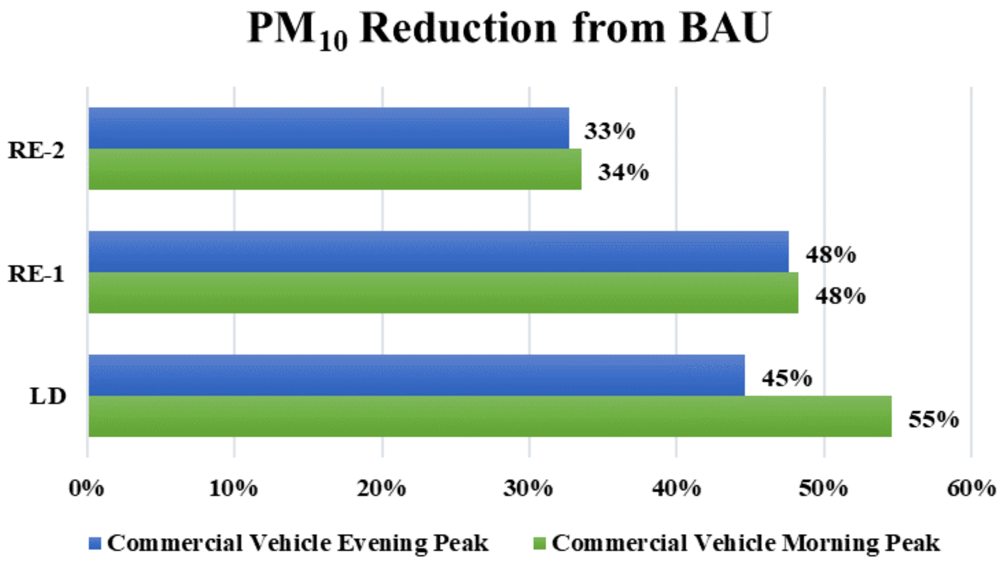


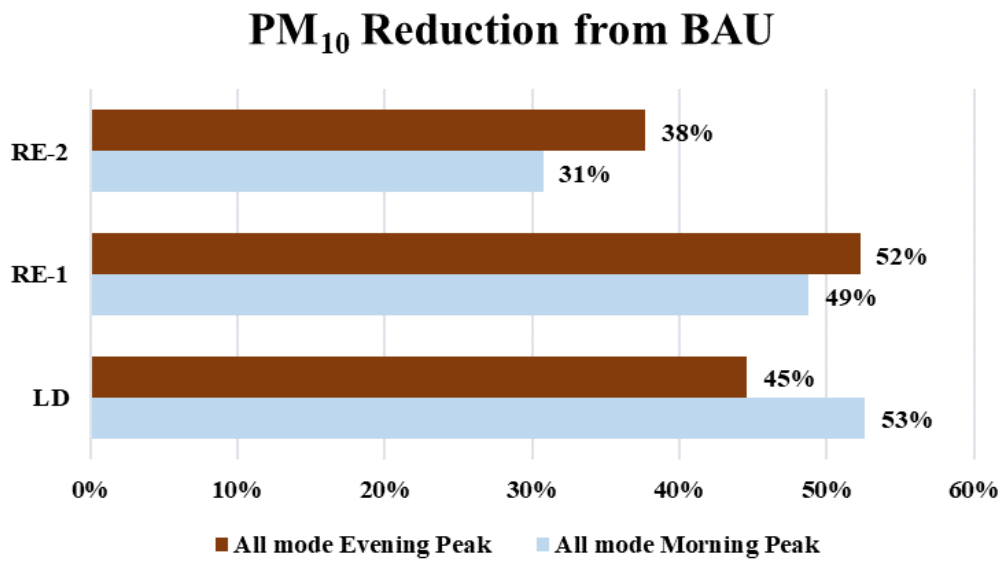

NOx Reduction from BAU
RE-2
42%
43%
RE-1
47%
49%
LD
49%
55%
BAU
10%
20%
30%
40%
50%
60%
Commercial Vehicle Evening Peak
Commercial Vehicle Morning Peak


NOx Reduction from BAU
RE-2
41%
40%
RE-1
49%
46%
LD
49%
54%
BAU
10%
20%
30%
40%
50%
60%
All mode Evening Peak
All mode Morning Peak

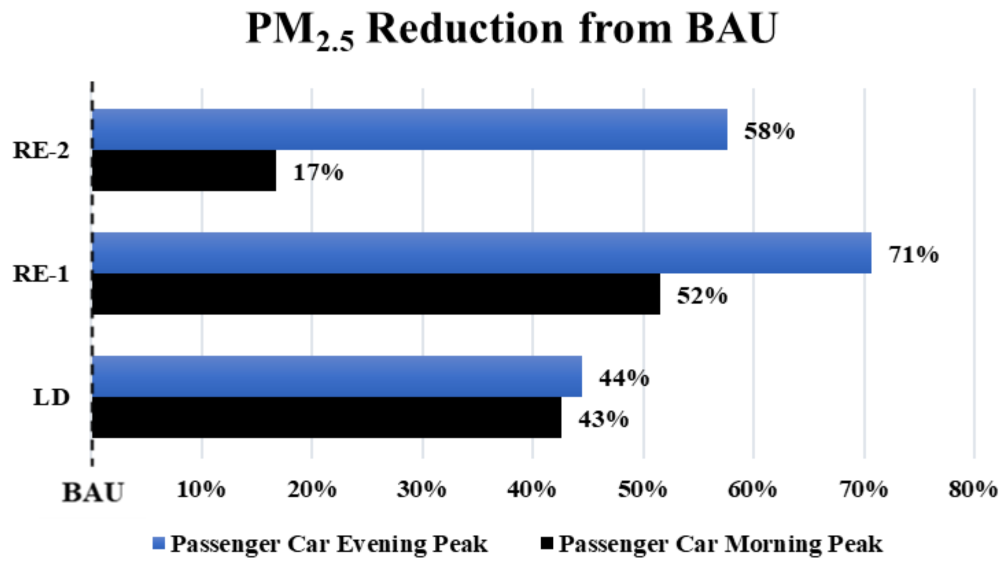
c) Change in PM$_{10}$ Emission

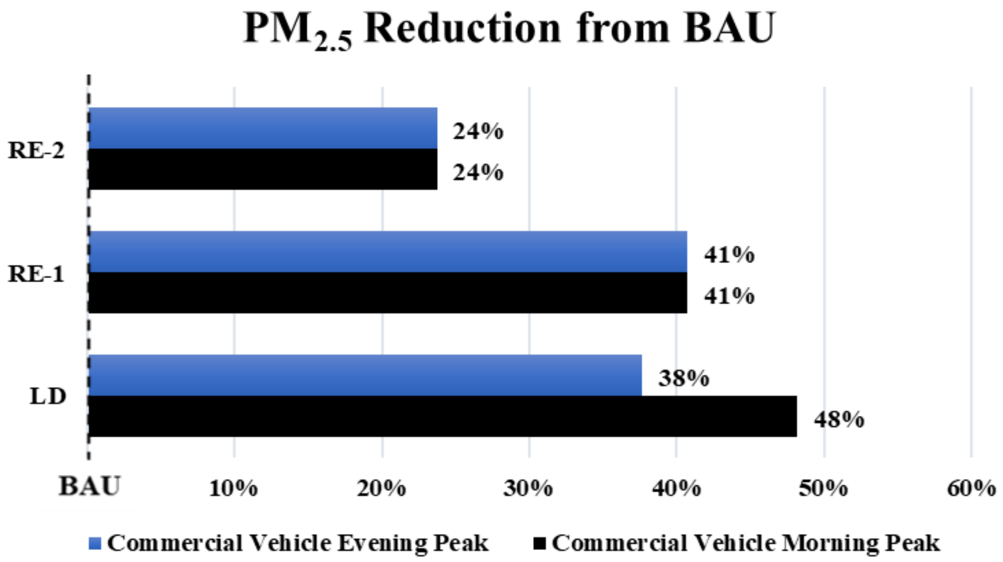


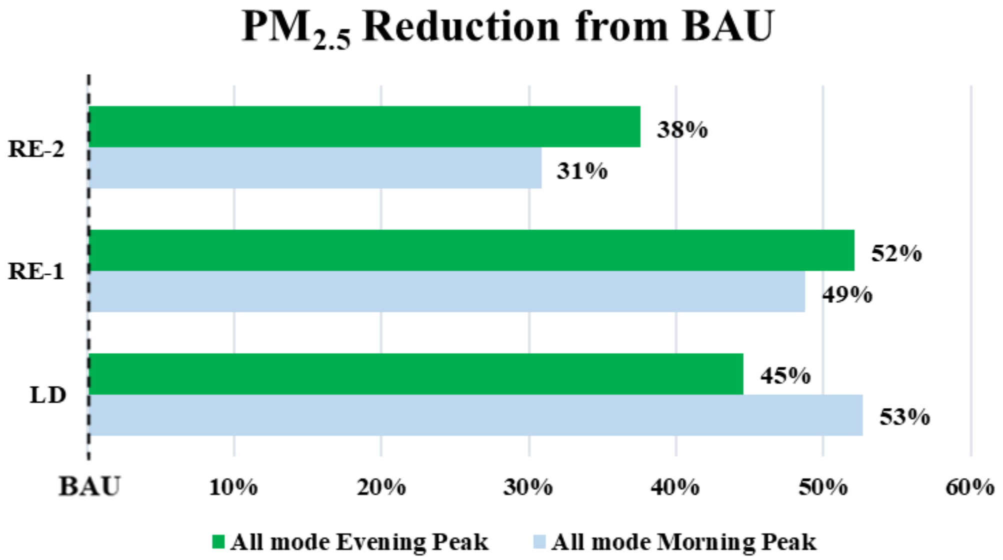




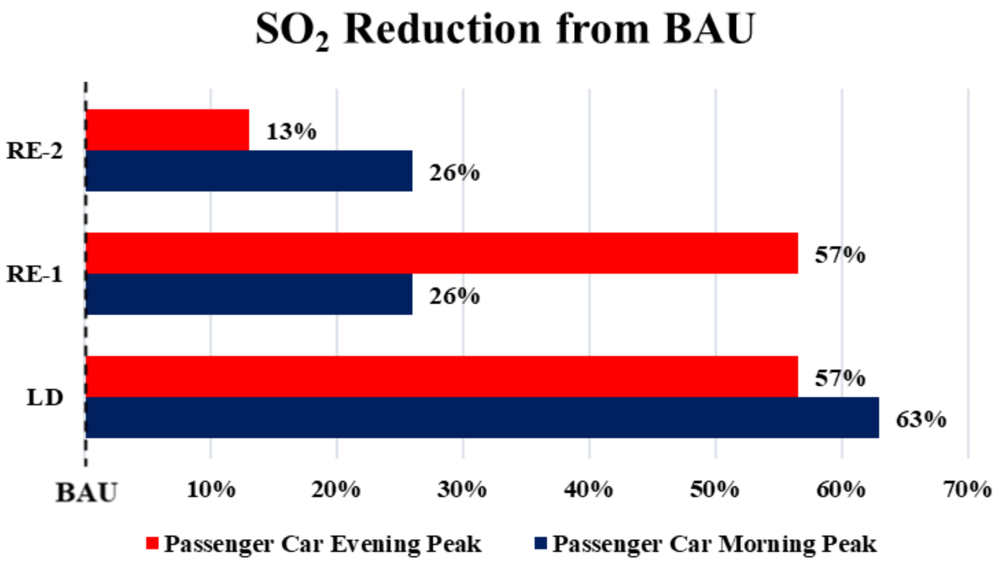
d) Change in PM$_{2.5}$ Emission

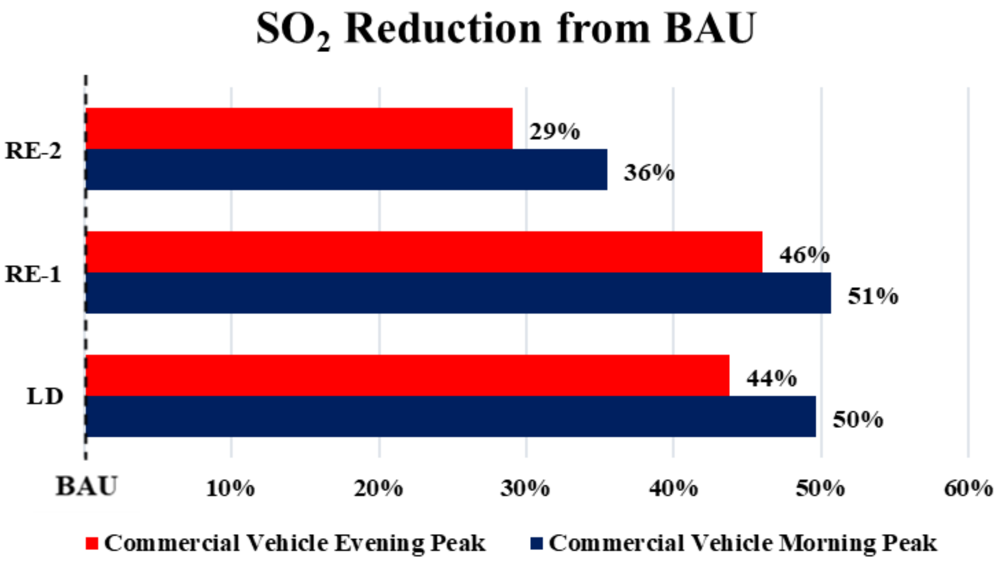


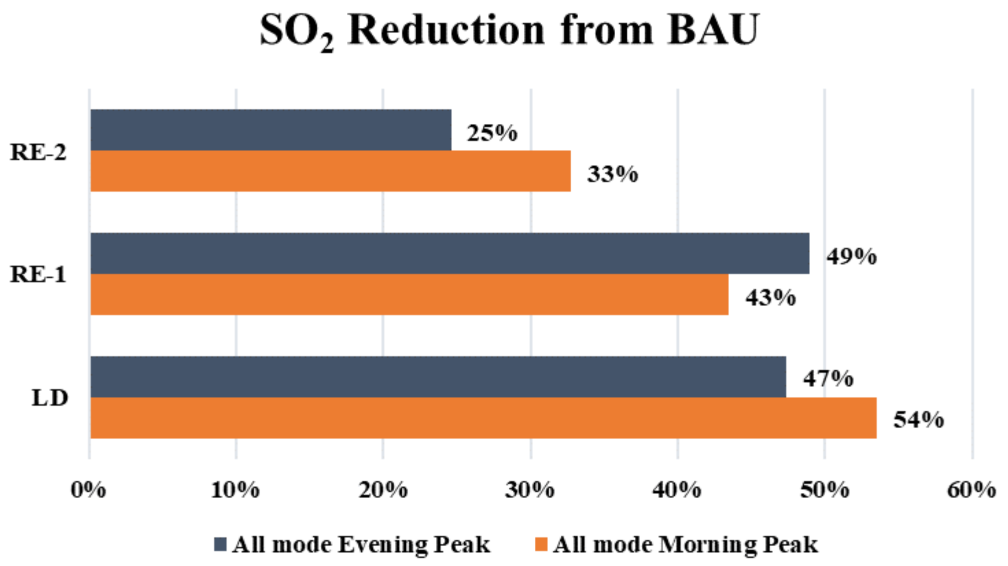

PM$_{2.5}$ Reduction from BAU
RE-2
24%
24%
RE-1
41%
41%
LD
38%
48%
BAU
10%
20%
30%
40%
50%
60%
Commercial Vehicle Evening Peak
Commercial Vehicle Morning Peak


PM$_{2.5}$ Reduction from BAU
RE-2
38%
31%
RE-1
52%
49%
LD
45%
53%
BAU
10%
20%
30%
40%
50%
60%
All mode Evening Peak
All mode Morning Peak

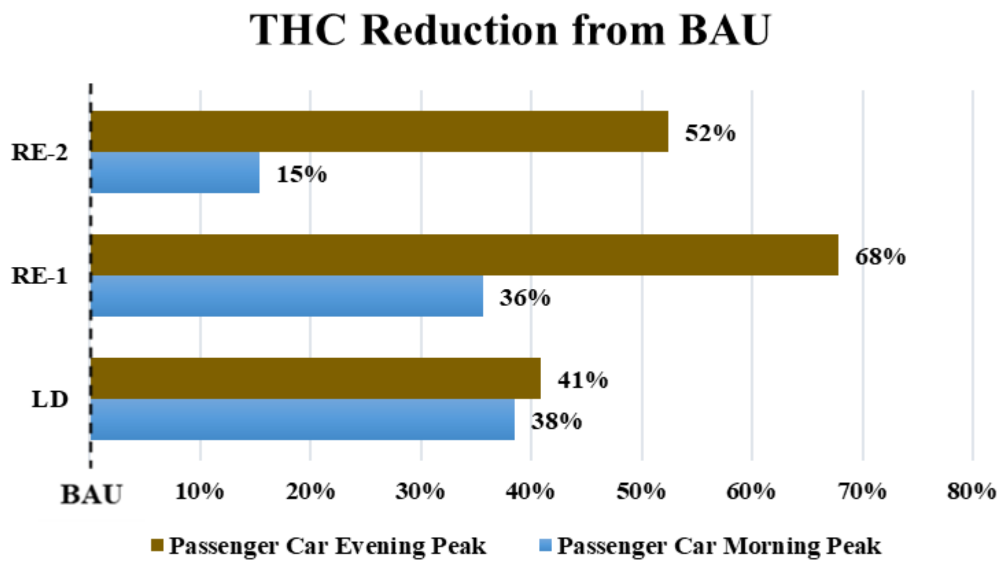
e) Change in SO_2 Emission

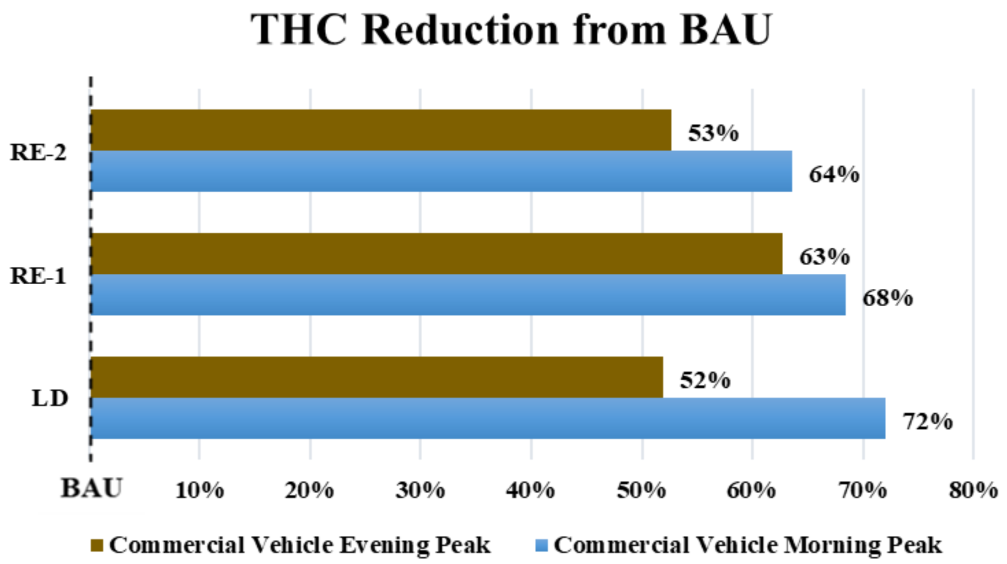


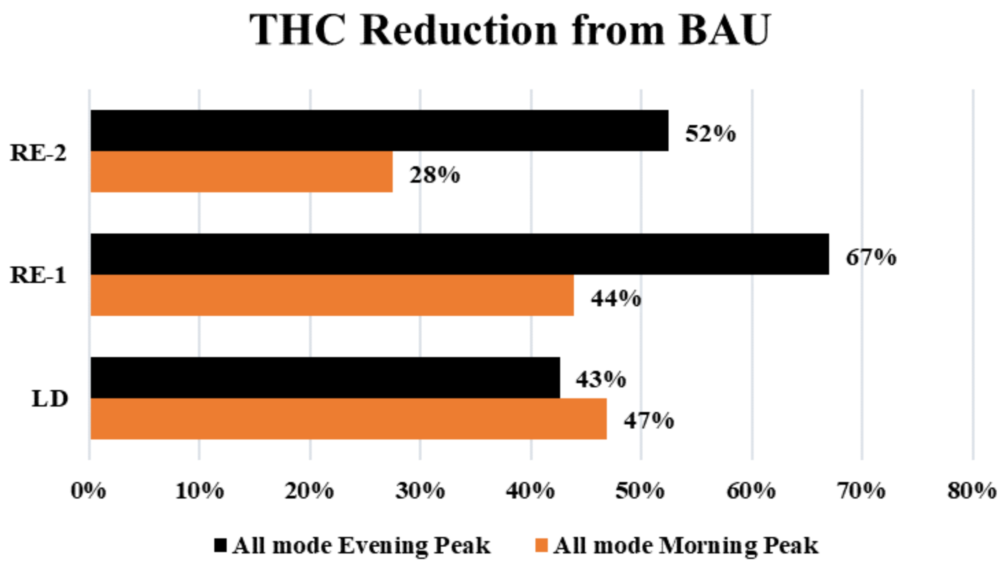




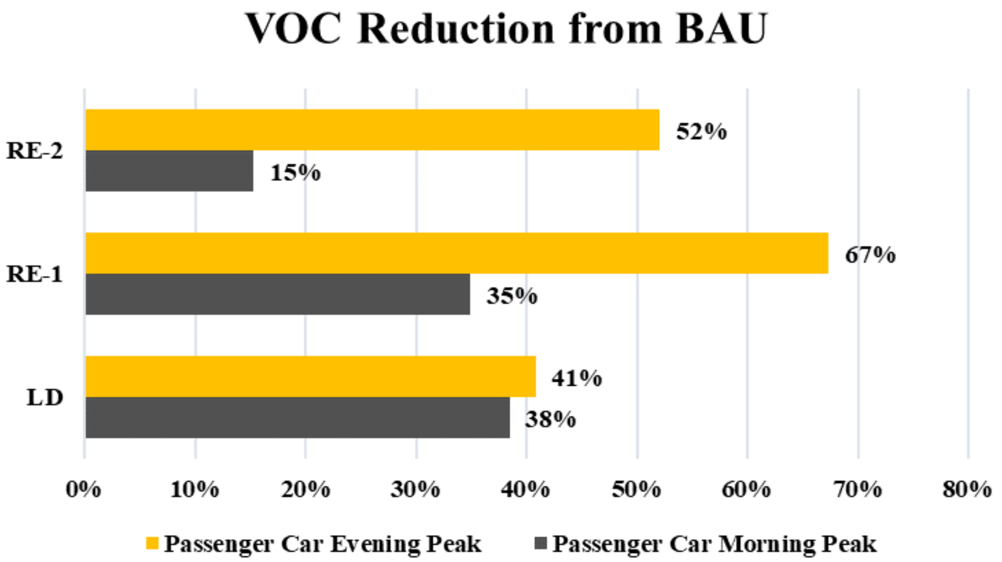
f) Change in THC Emission

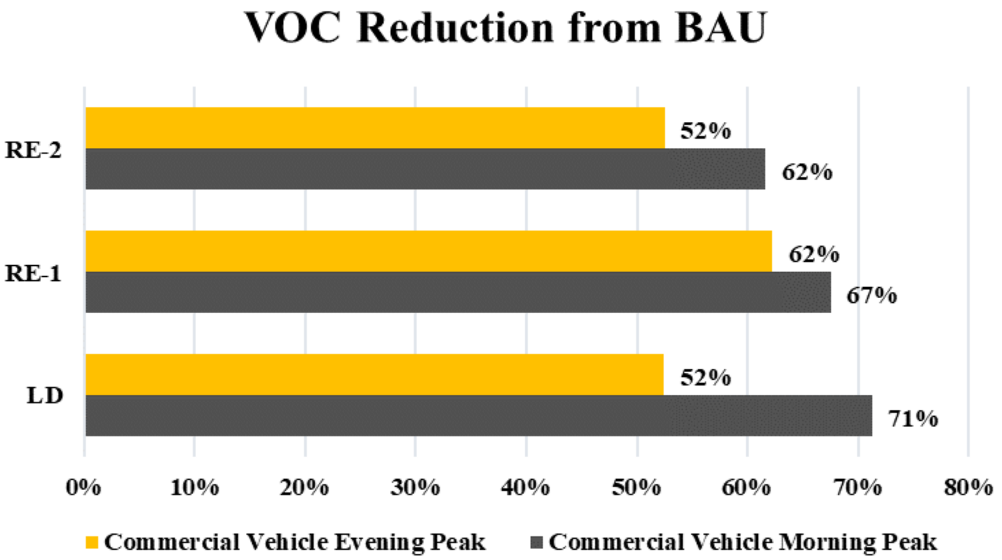


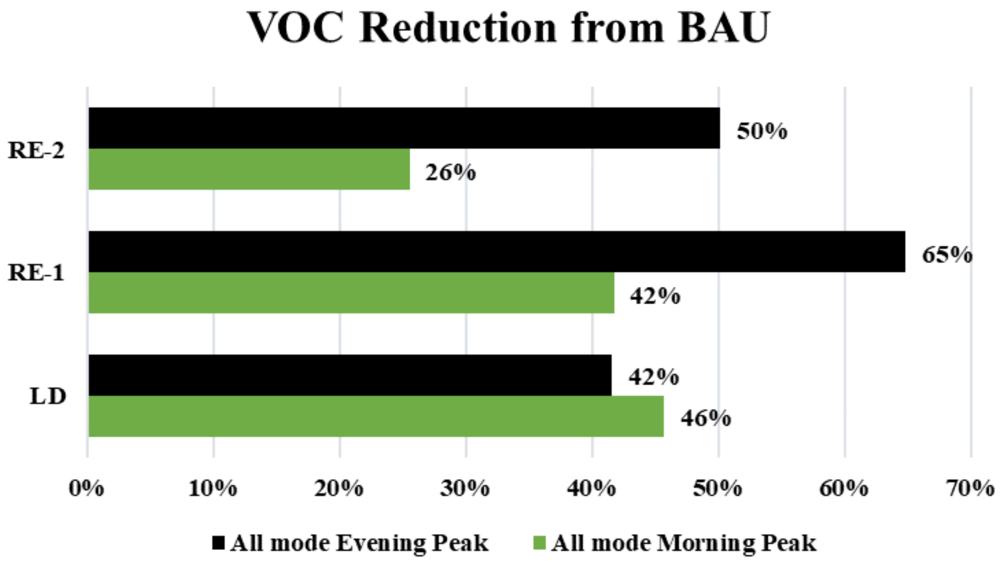

THC Reduction from BAU
RE-2
RE-1
LD
53%
64%
63%
68%
52%
72%
BAU
10%
20%
30%
40%
50%
60%
70%
80%
Commercial Vehicle Evening Peak
Commercial Vehicle Morning Peak


THC Reduction from BAU
RE-2
RE-1
LD
52%
28%
67%
44%
43%
47%
0%
10%
20%
30%
40%
50%
60%
70%
80%
All mode Evening Peak
All mode Morning Peak

g) Change in VOC Emission

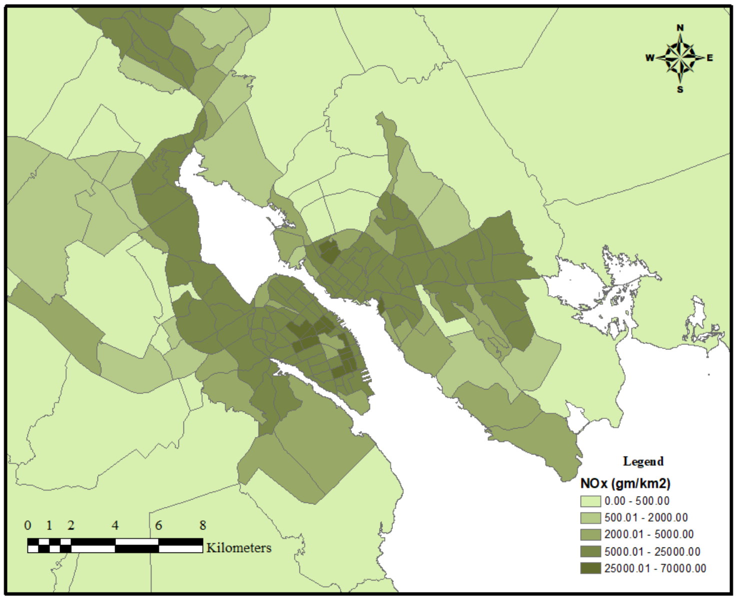




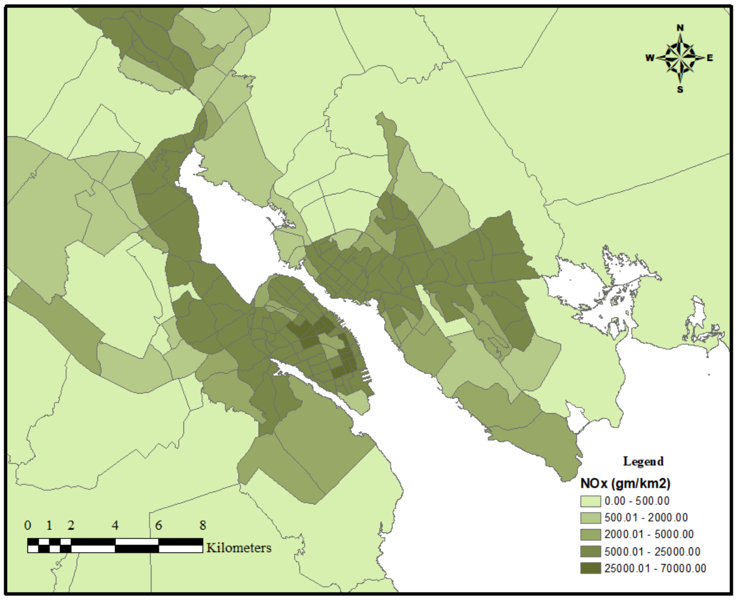

VOC Reduction from BAU
RE-2
50%
26%
RE-1
65%
42%
LD
42%
46%
0%
10%
20%
30%
40%
50%
60%
70%
■ All mode Evening Peak
🟩 All mode Morning Peak

Appendix F Spatial Distribution of Major Pollutants during Pandemic Scenarios

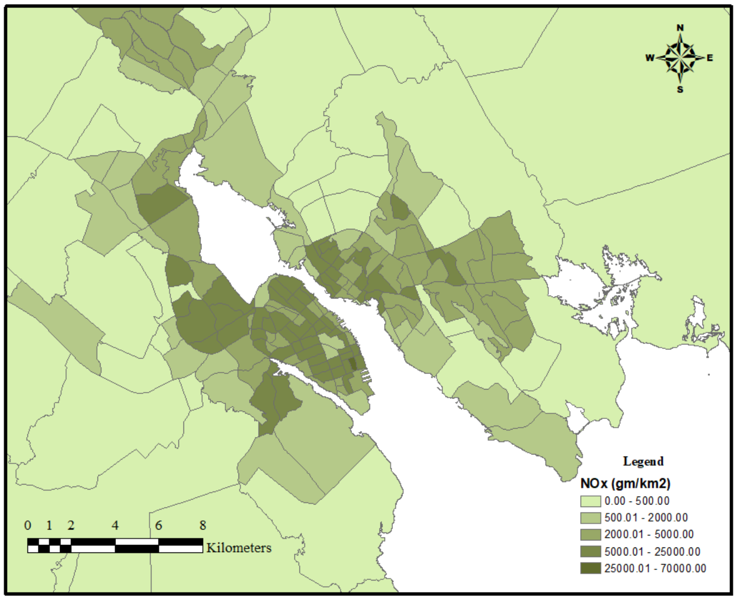
a) NO_x Emission Density Distribution



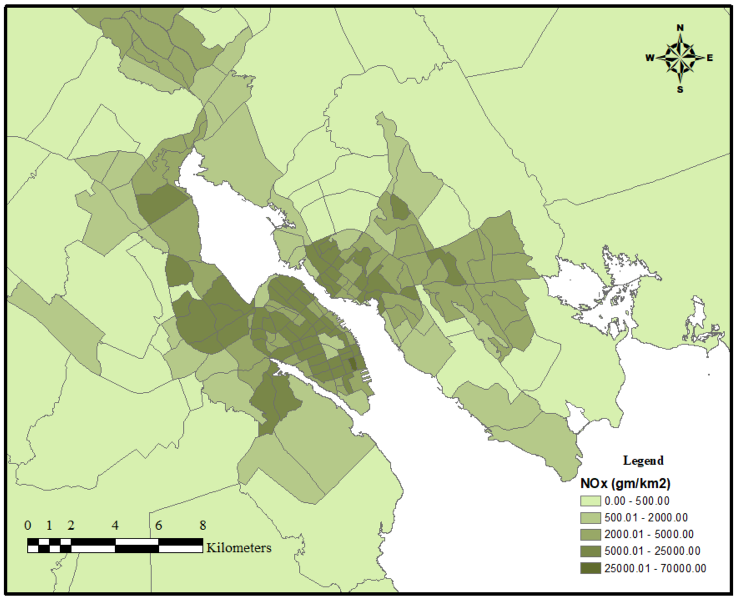
Business-as-Usual Scenario (Morning Peak Period)



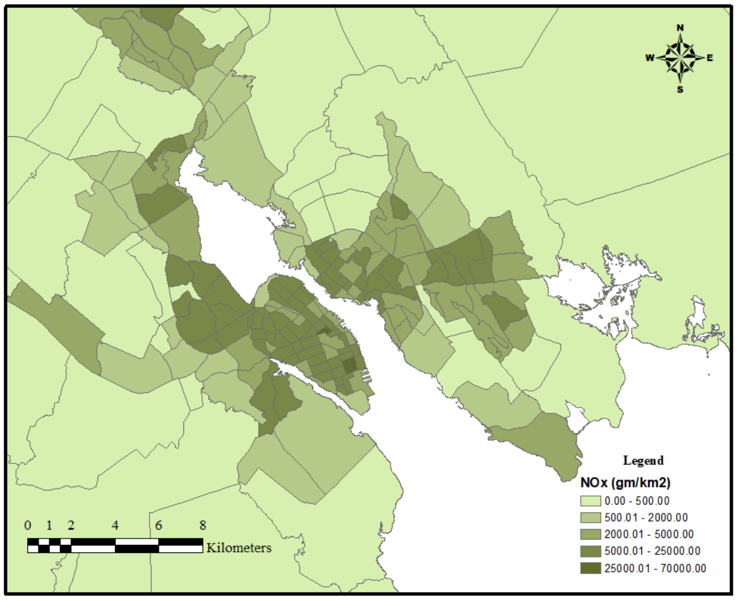
Business-as-Usual Scenario (Evening Peak Period)



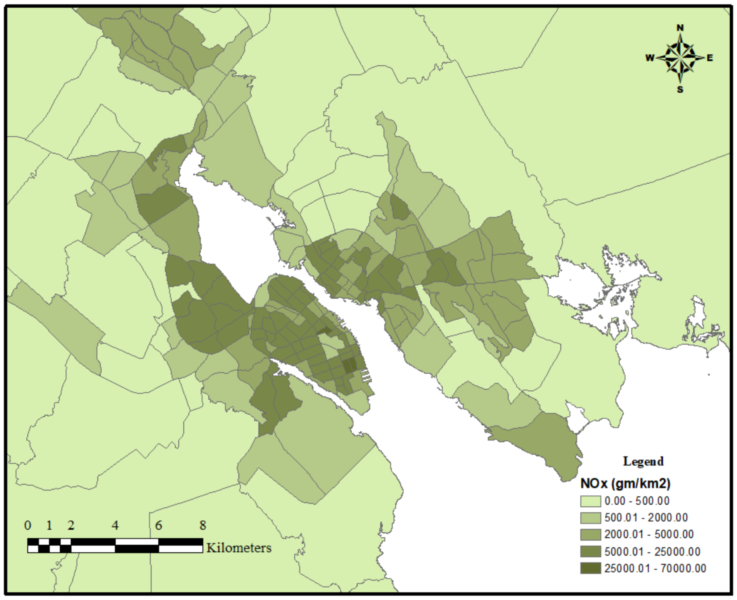
Lockdown Scenario (Morning Peak Period)



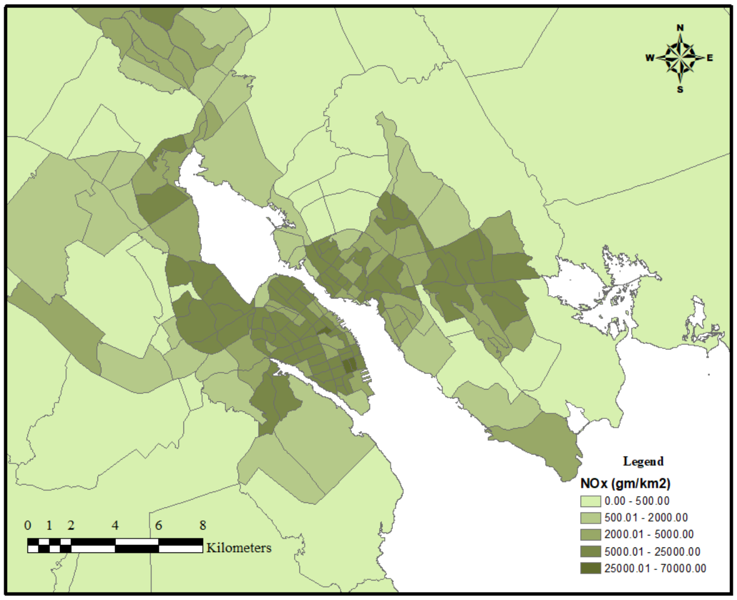
Lockdown Scenario (Evening Peak Period)



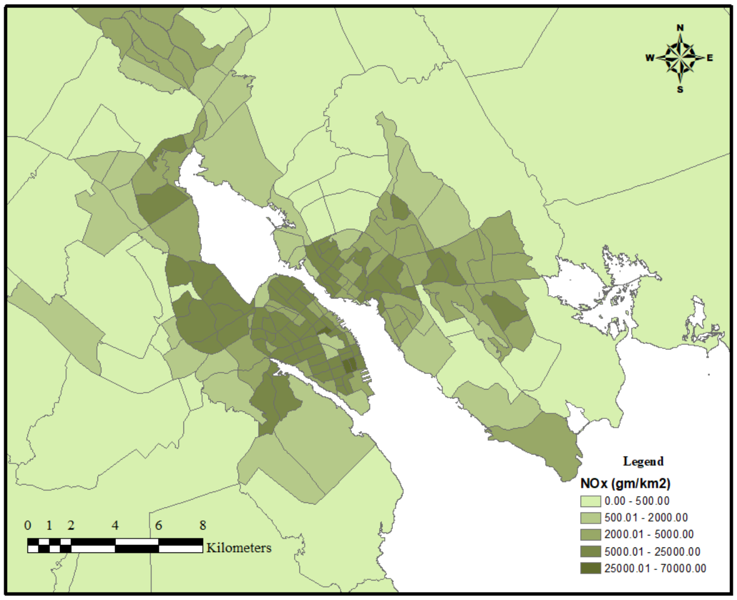
Reopening Scenario - 1 (Morning Peak Period)



Reopening Scenario - 1 (Evening Peak Period)

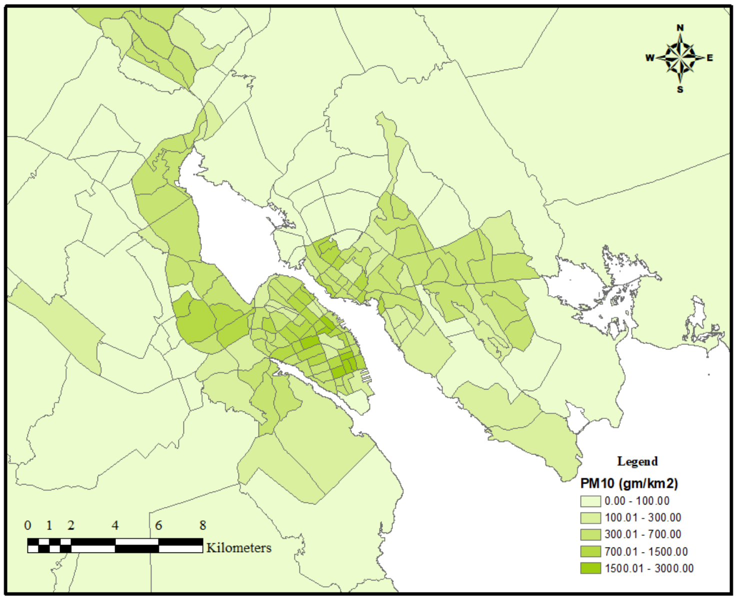


Reopening Scenario - 2 (Morning Peak Period)

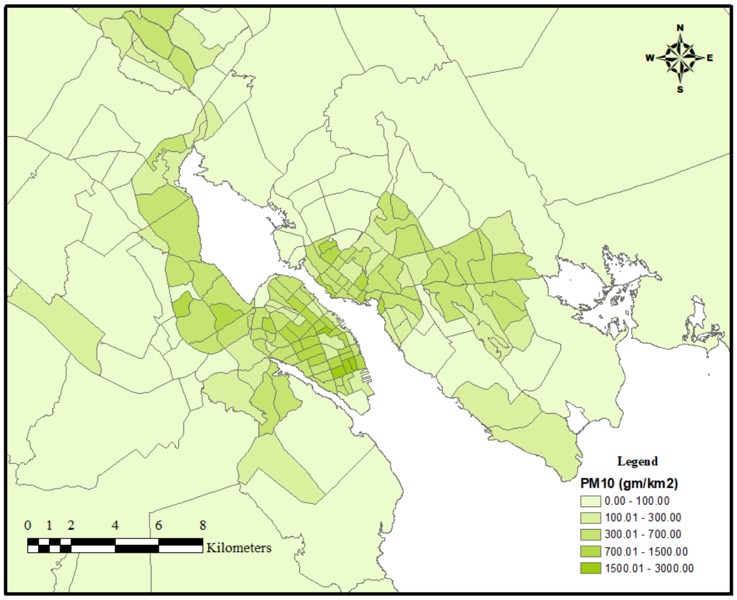


Reopening Scenario - 2 (Evening Peak Period)

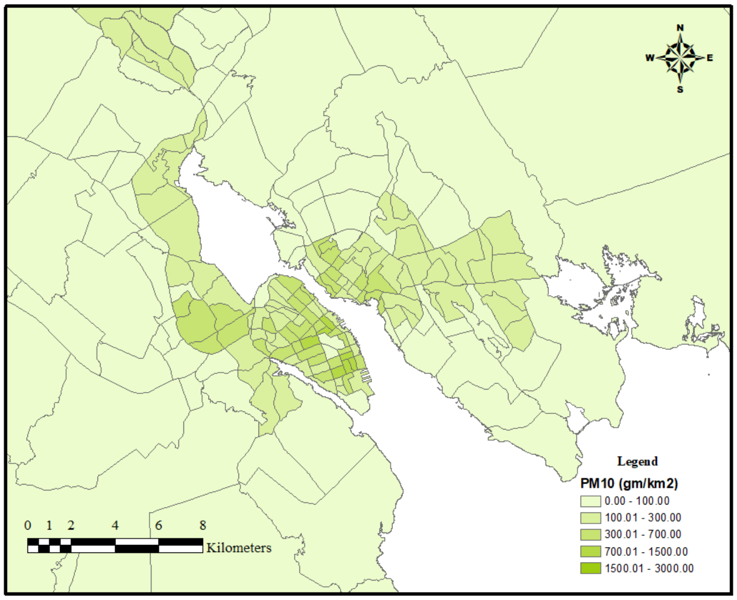
b) PM_{10} Emission Density Distribution



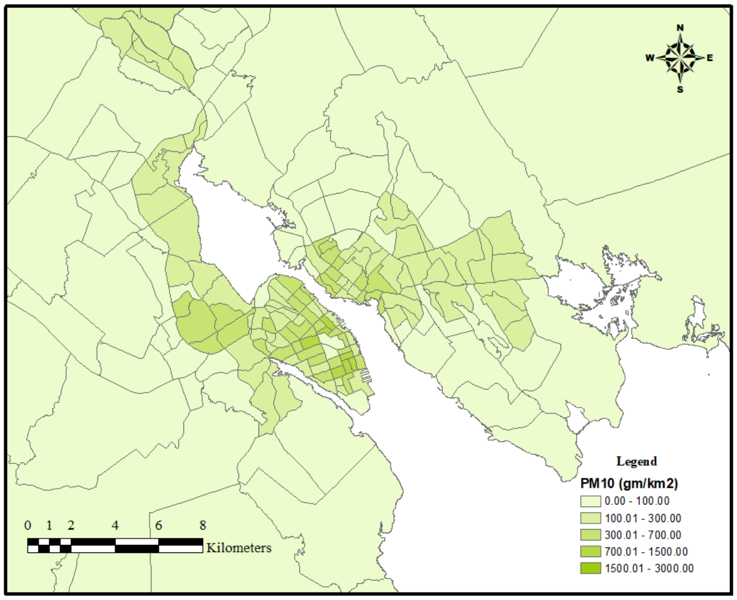
Business-as-Usual Scenario (Morning Peak Period)



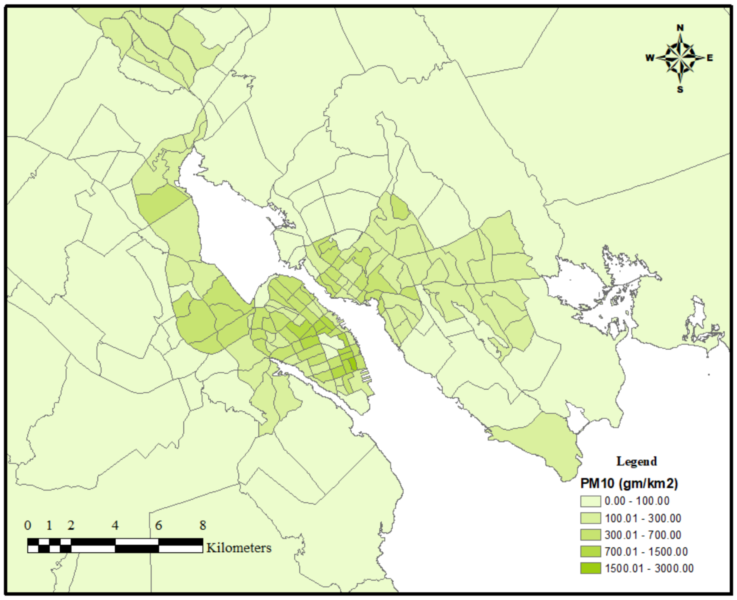
Business-as-Usual Scenario (Evening Peak Period)



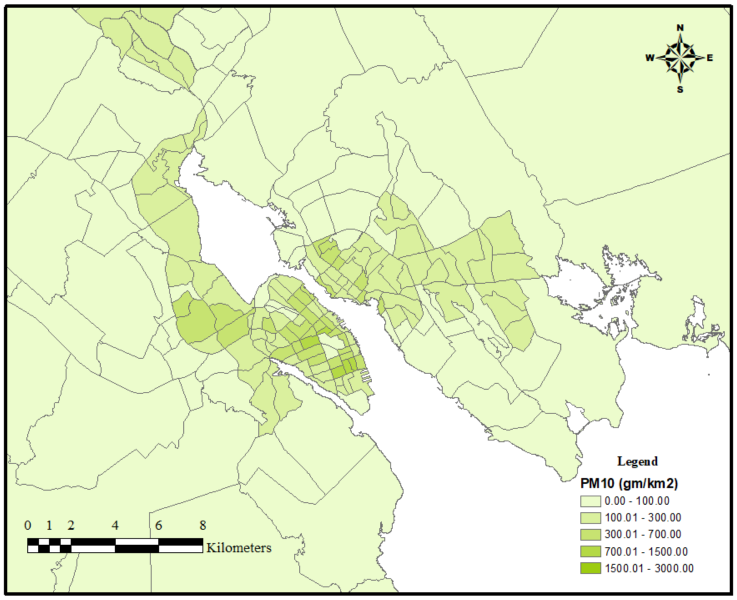
Lockdown Scenario (Morning Peak Period)



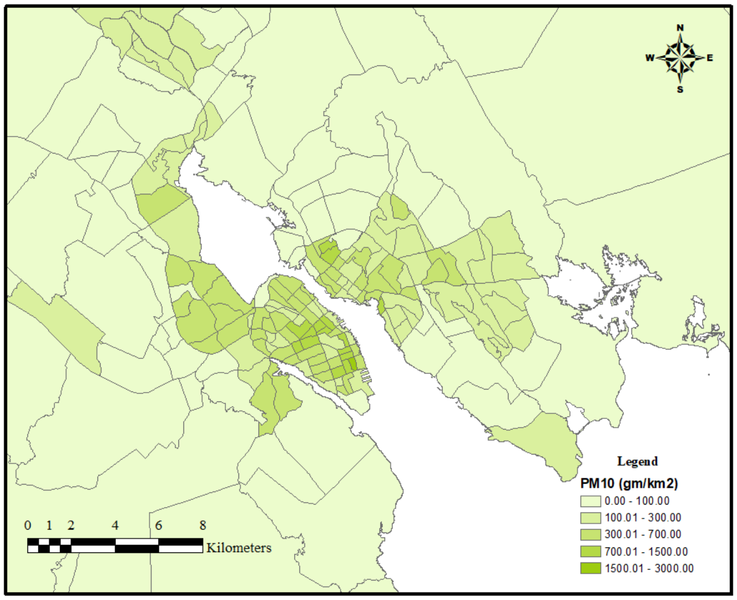
Lockdown Scenario (Evening Peak Period)



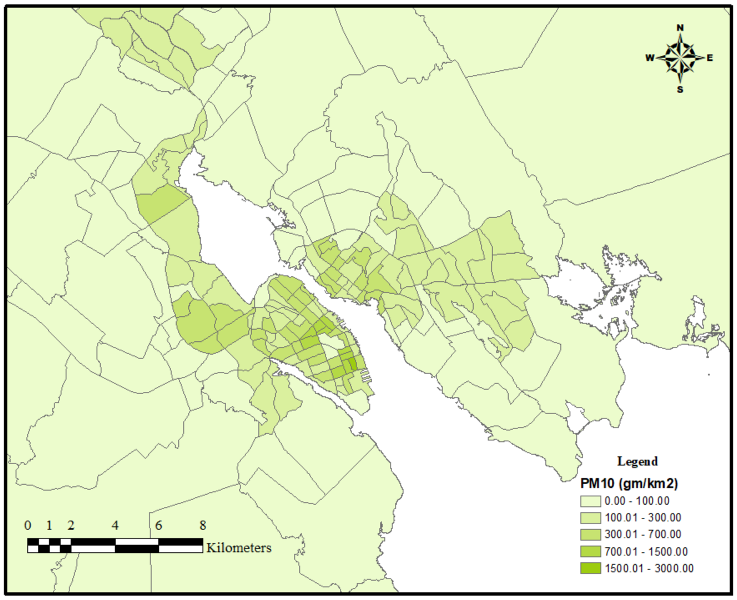
Reopening Scenario - 1 (Morning Peak Period)



Reopening Scenario - 1 (Evening Peak Period)

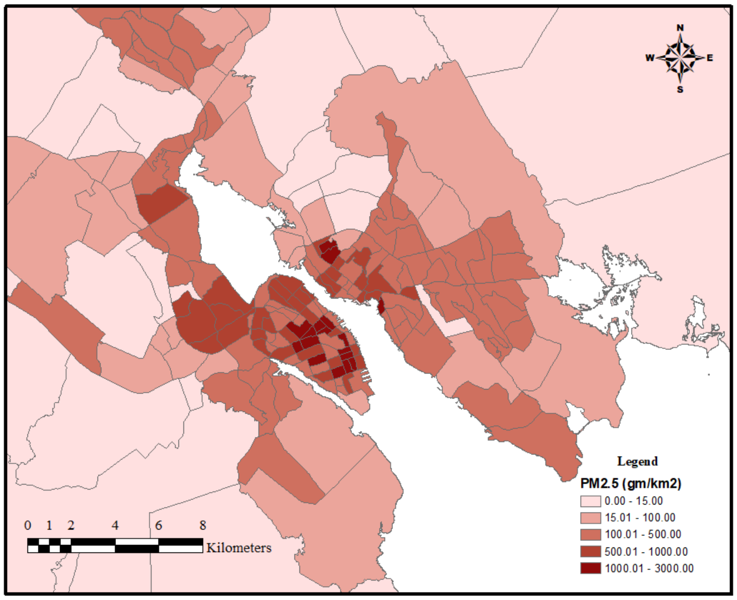


Reopening Scenario - 2 (Morning Peak Period)

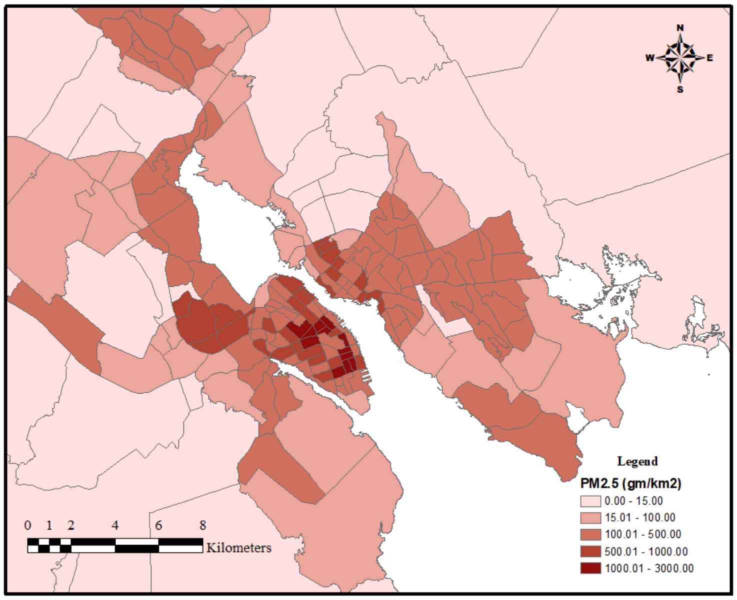


Reopening Scenario - 2 (Evening Peak Period)

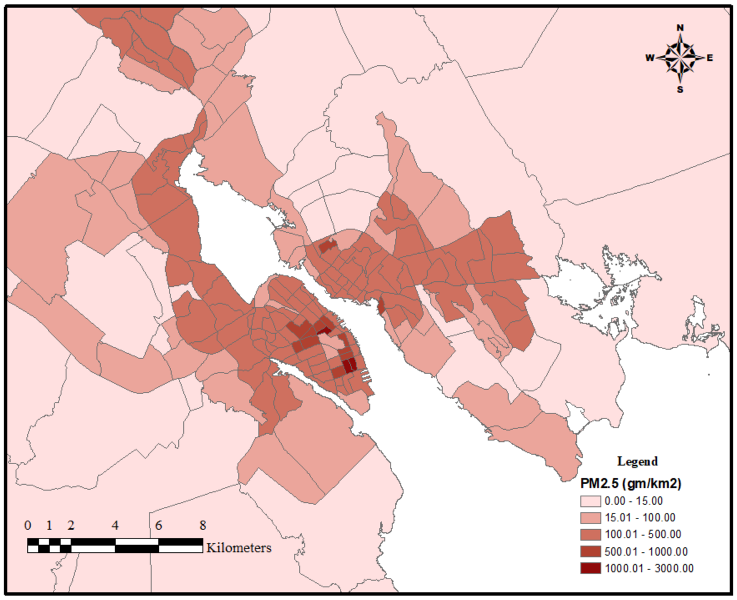
c) PM$_{2.5}$ Emission Density Distribution



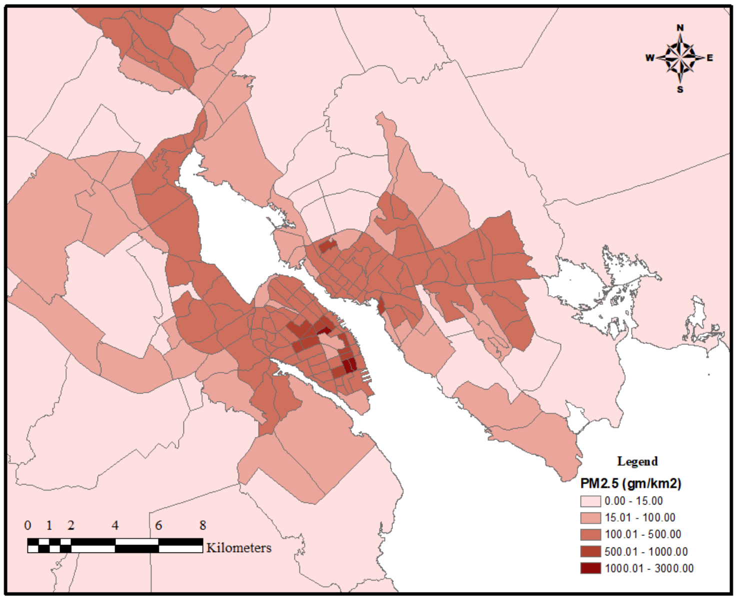
Business-as-Usual Scenario (Morning Peak Period)



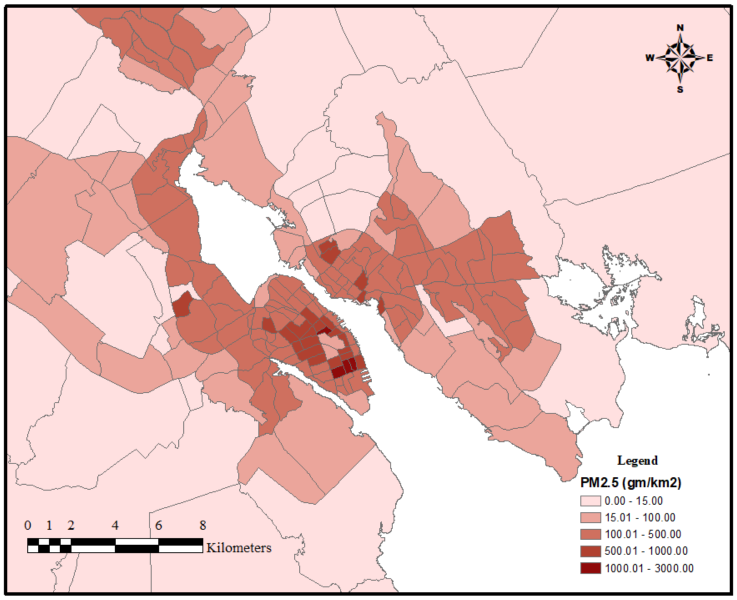
Business-as-Usual Scenario (Evening Peak Period)



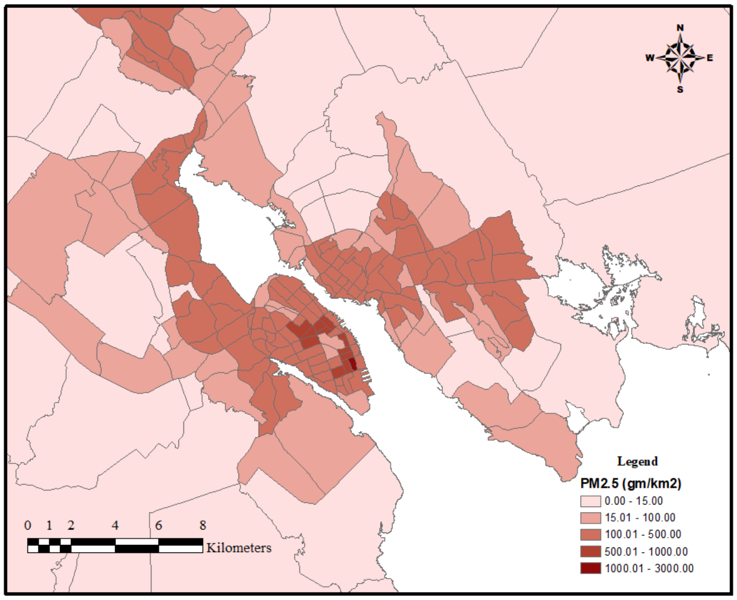
Lockdown Scenario (Morning Peak Period)



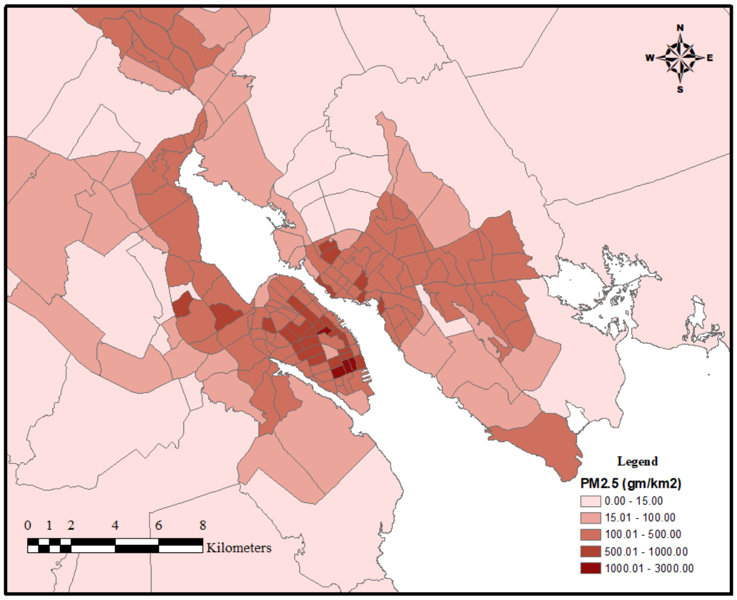
Lockdown Scenario (Evening Peak Period)



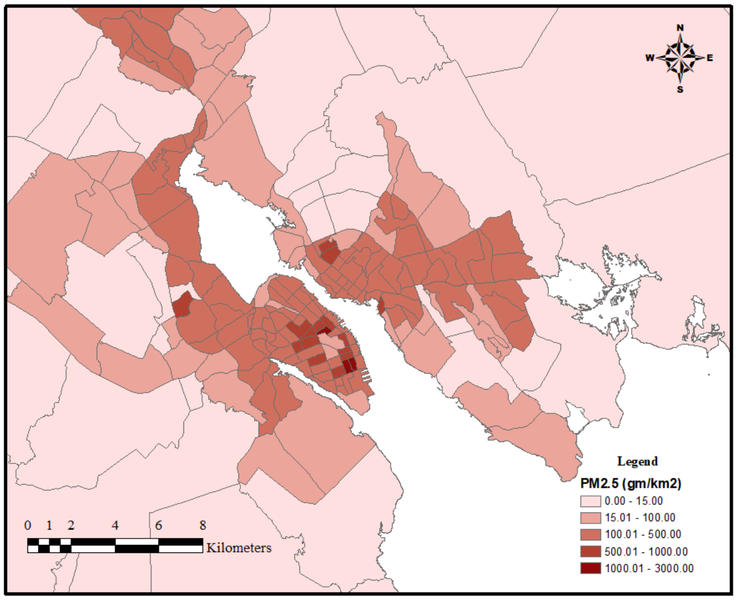
Reopening Scenario - 1 (Morning Peak Period)



Reopening Scenario – 1 (Evening Peak Period)

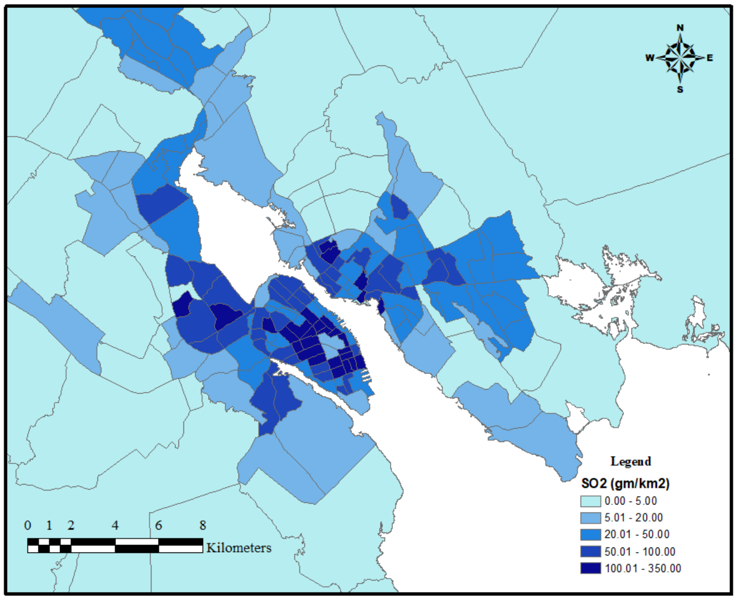


Reopening Scenario - 2 (Morning Peak Period)

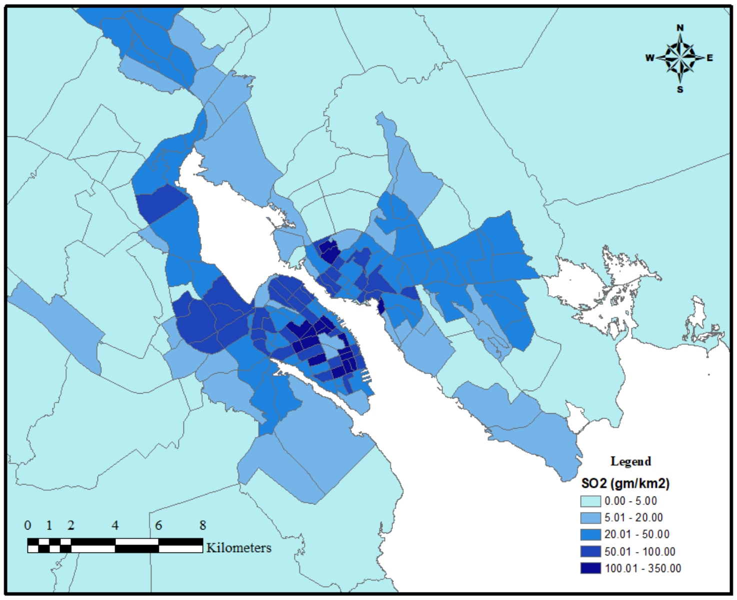


Reopening Scenario - 2 (Evening Peak Period)

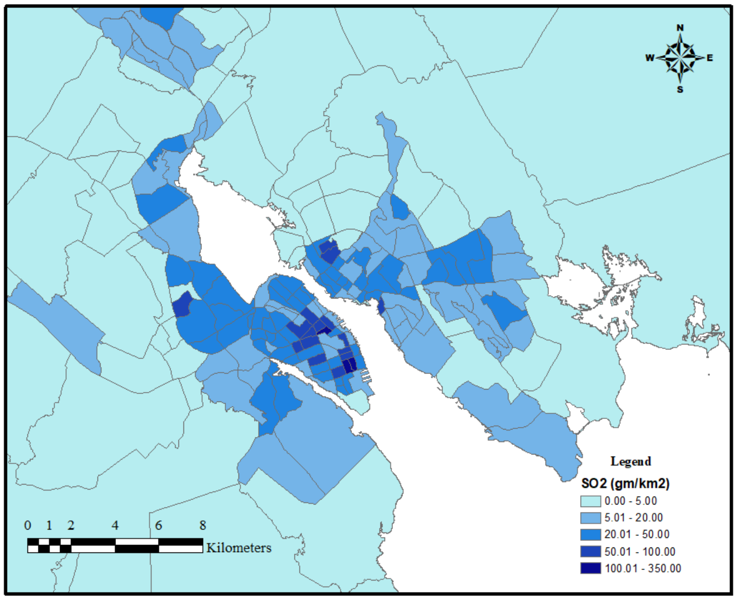
d) SO_2 Emission Density Distribution



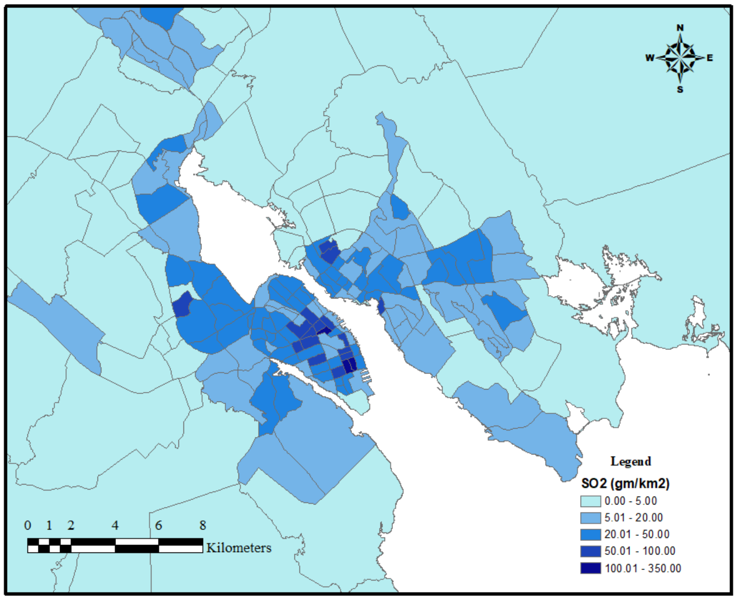
Business-as-Usual Scenario (Morning Peak Period)



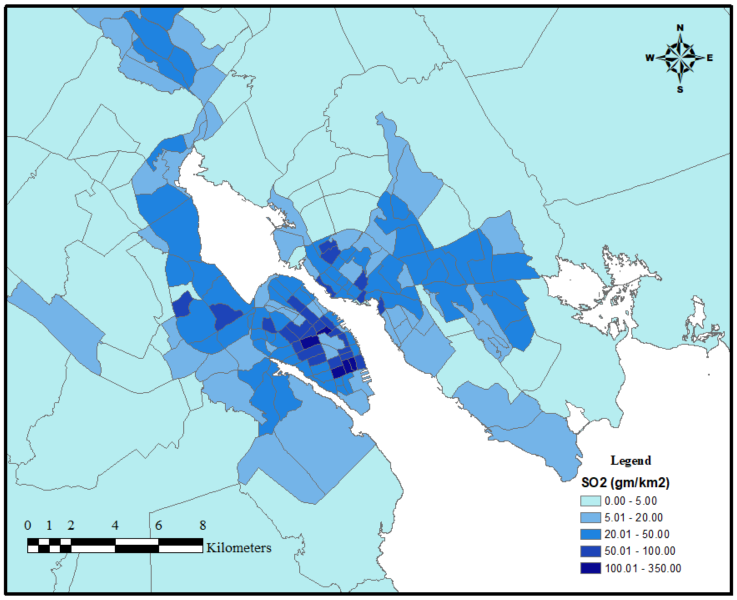
Business-as-Usual Scenario (Evening Peak Period)



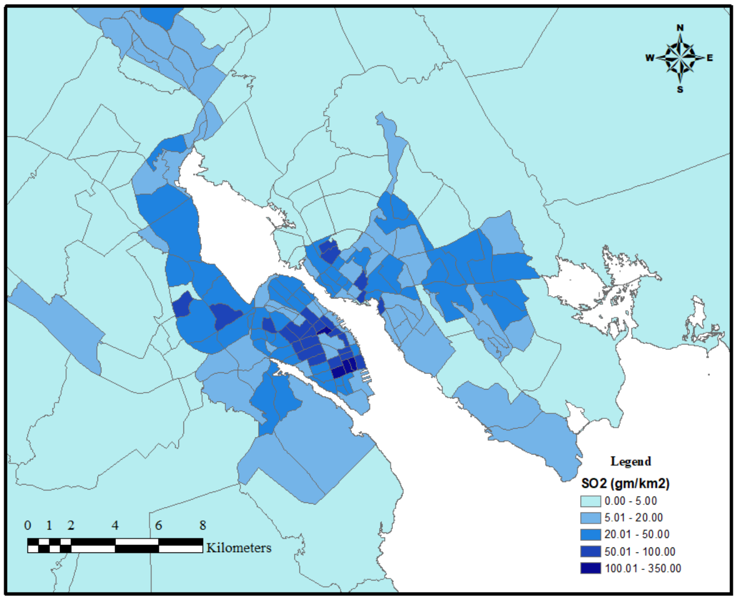
Lockdown Scenario (Morning Peak Period)



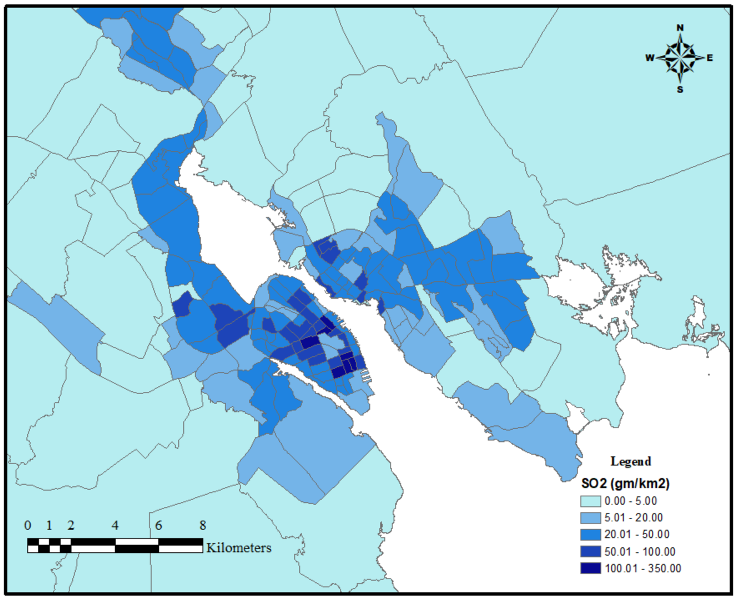
Lockdown Scenario (Evening Peak Period)



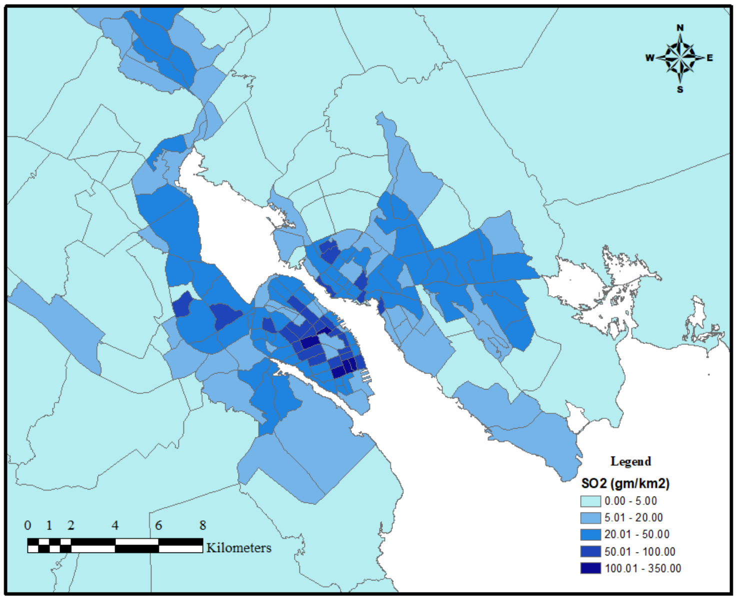
Reopening Scenario - 1 (Morning Peak Period)



Reopening Scenario - 1 (Evening Peak Period)

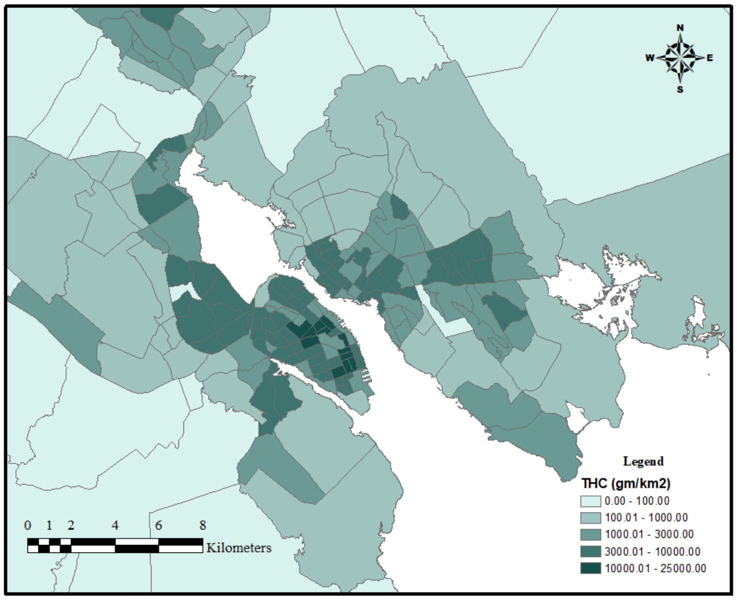


Reopening Scenario - 2 (Morning Peak Period)

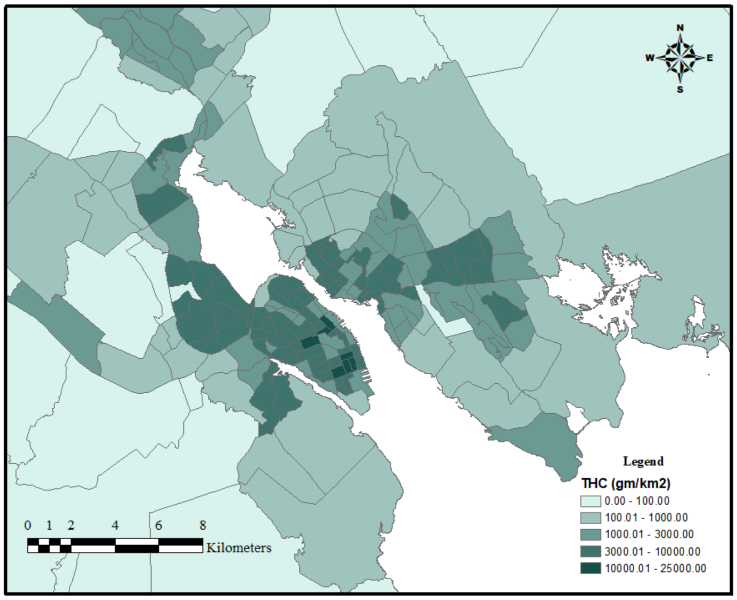


Reopening Scenario - 2 (Evening Peak Period)

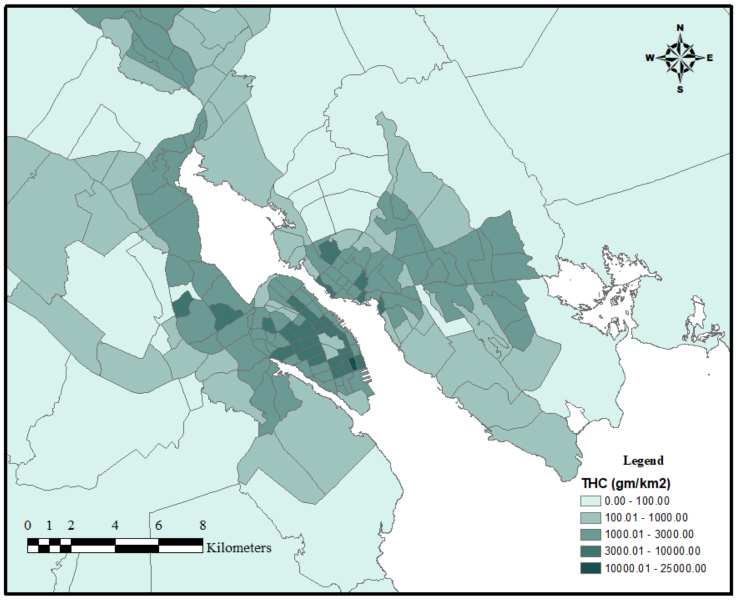
e) THC Emission Density Distribution



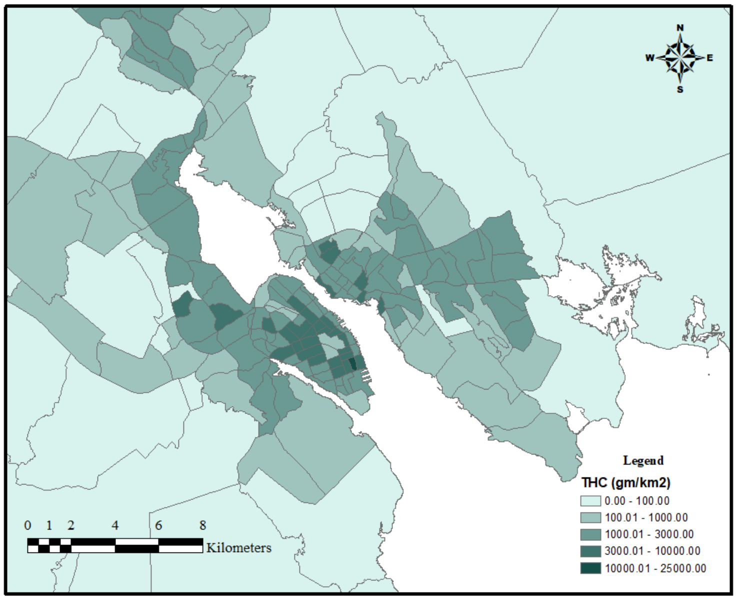
Business-as-Usual Scenario (Morning Peak Period)



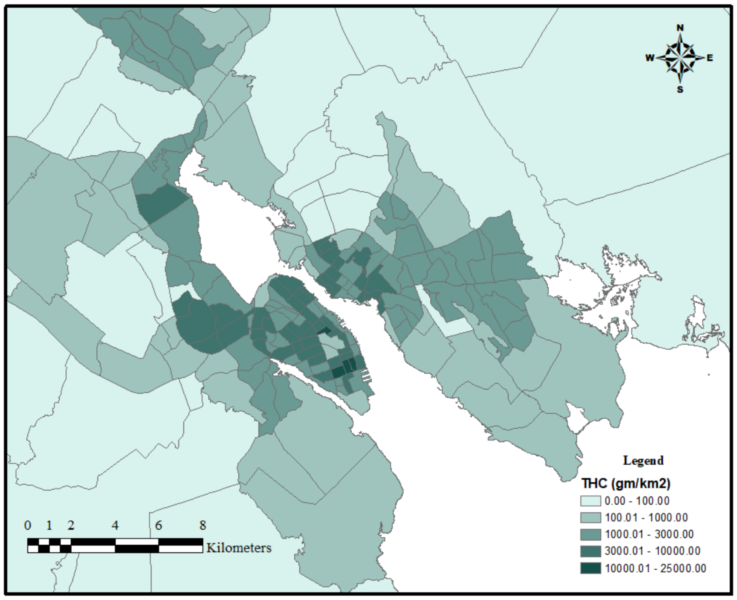
Business-as-Usual Scenario (Evening Peak Period)



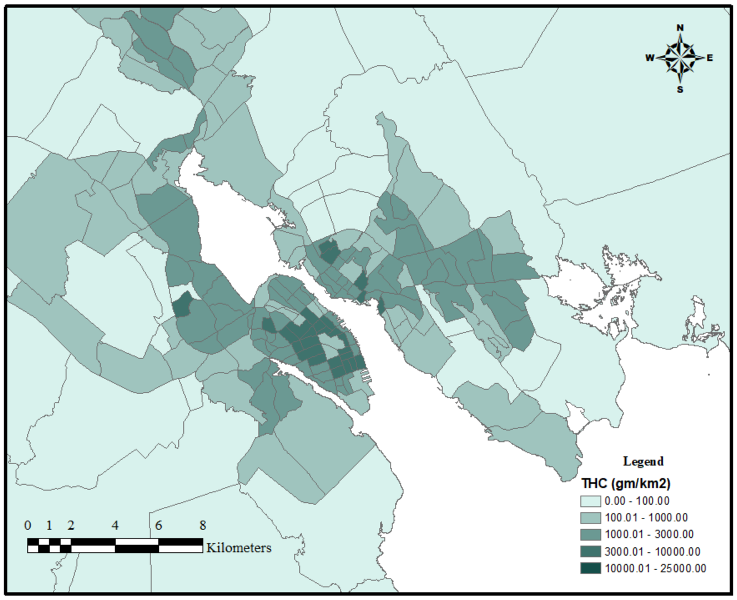
Lockdown Scenario (Morning Peak Period)



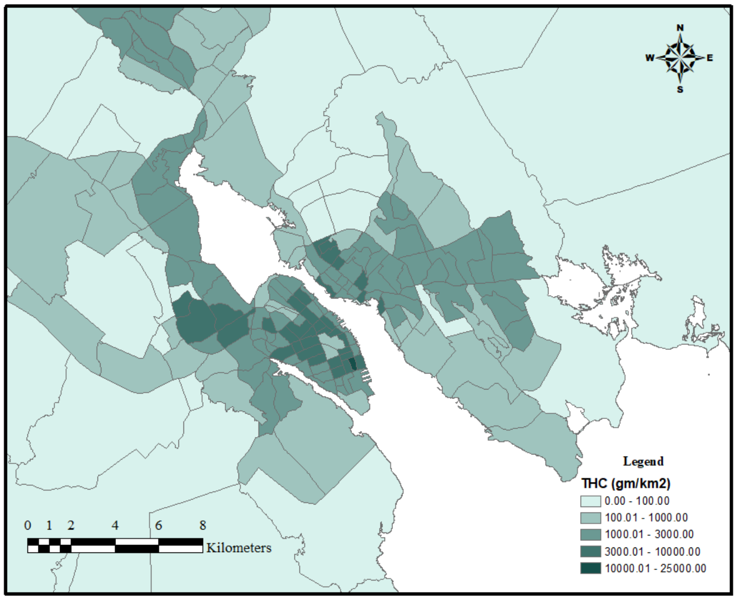
Lockdown Scenario (Evening Peak Period)



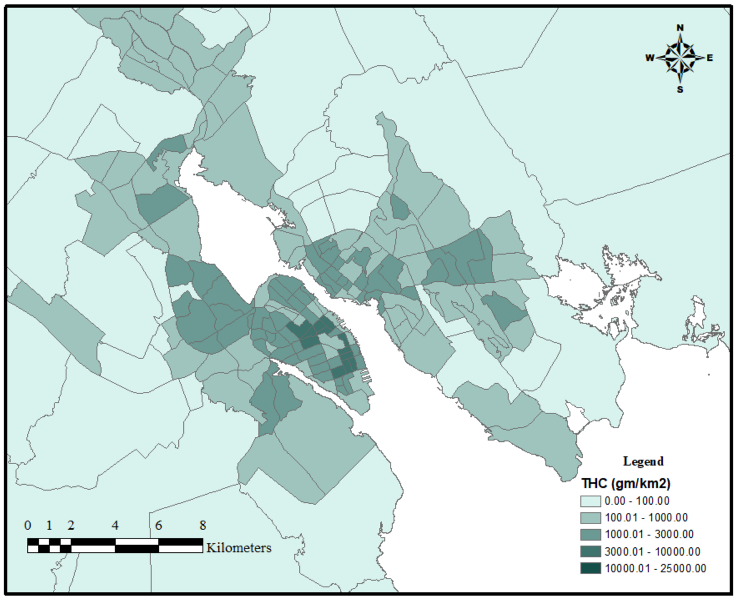
Reopening Scenario - 1 (Morning Peak Period)



Reopening Scenario - 1 (Evening Peak Period)

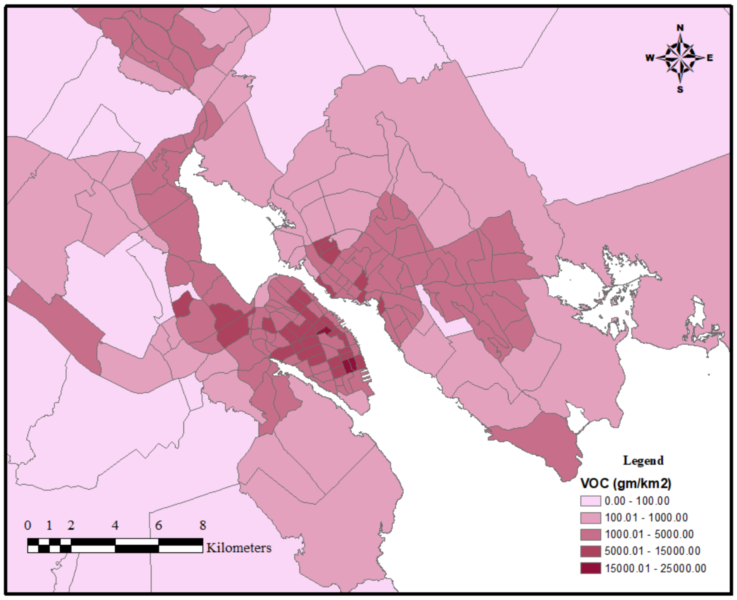


Reopening Scenario - 2 (Morning Peak Period)

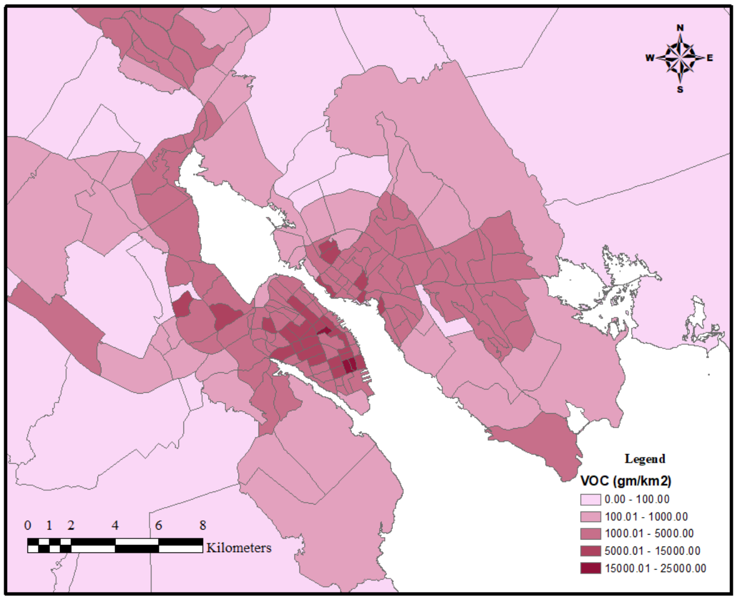


Reopening Scenario - 2 (Evening Peak Period)

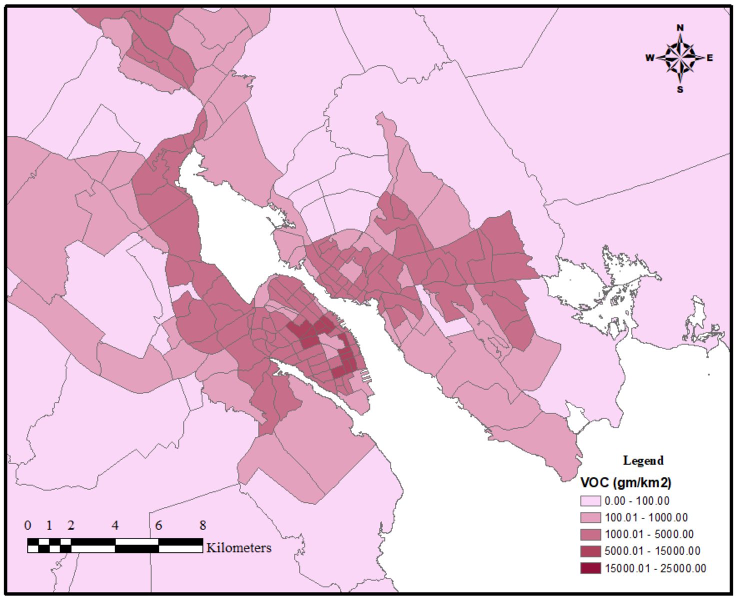
f) VOC Emission Density Distribution



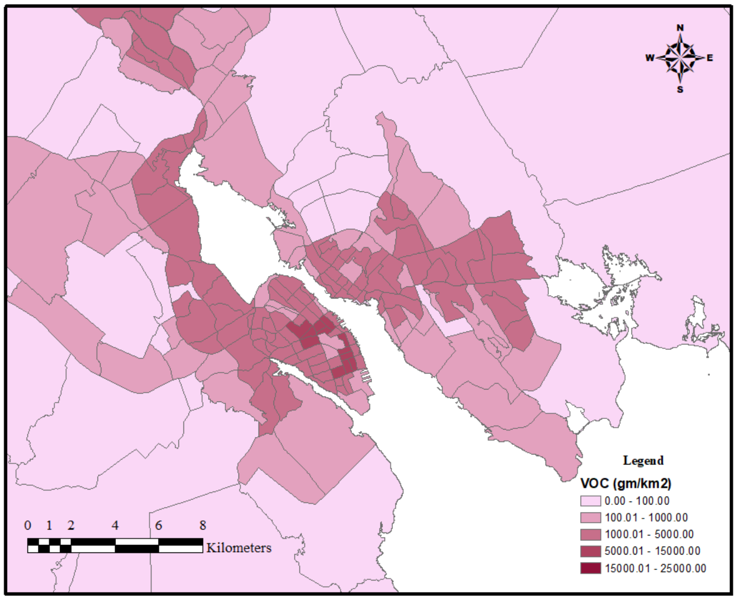
Business-as-Usual Scenario (Morning Peak Period)



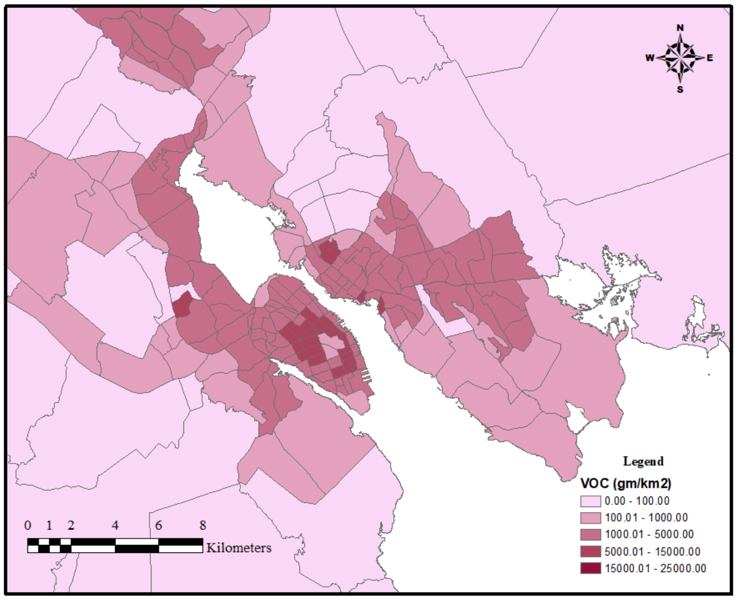
Business-as-Usual Scenario (Evening Peak Period)



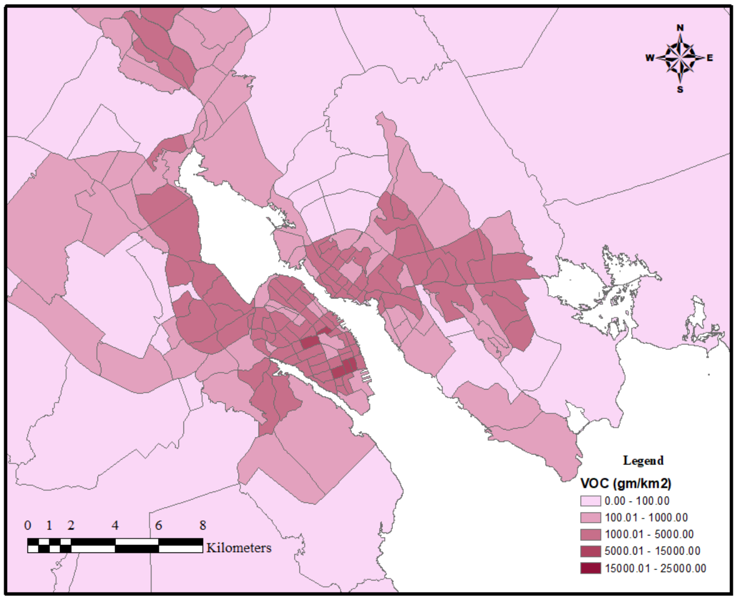
Lockdown Scenario (Morning Peak Period)



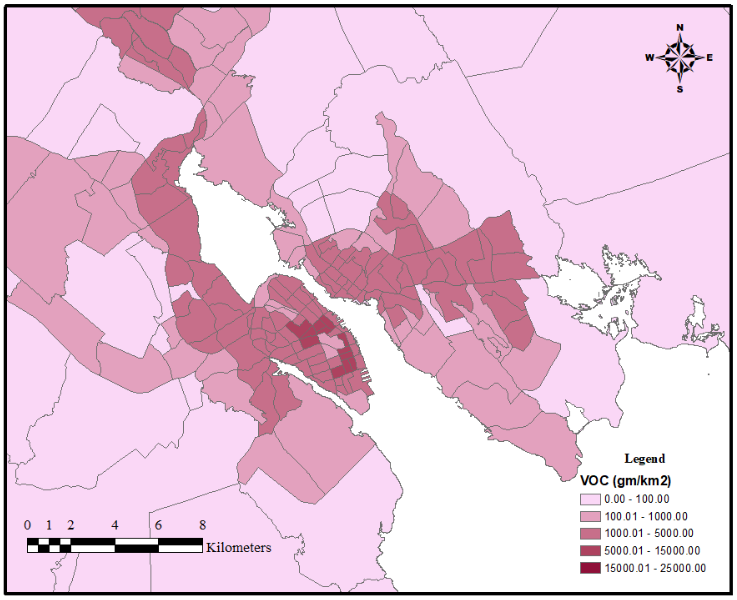
Lockdown Scenario (Evening Peak Period)



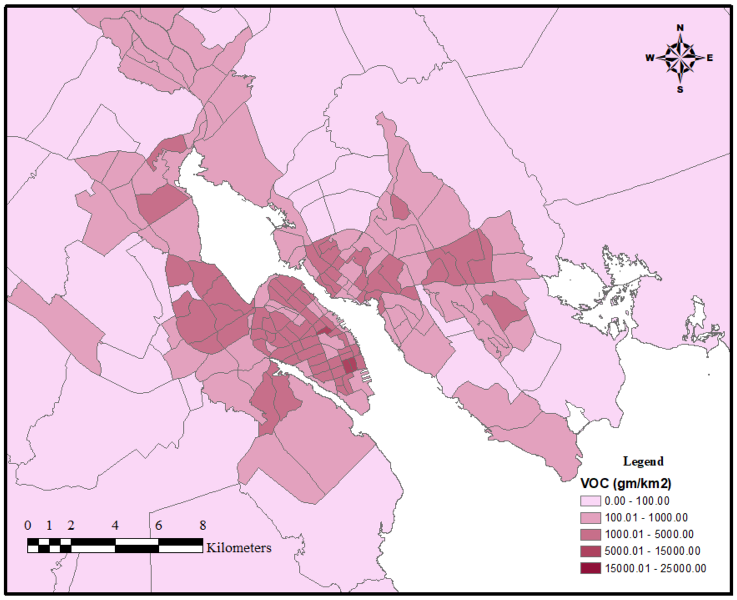
Reopening Scenario - 1 (Morning Peak Period)



Reopening Scenario - 1 (Evening Peak Period)

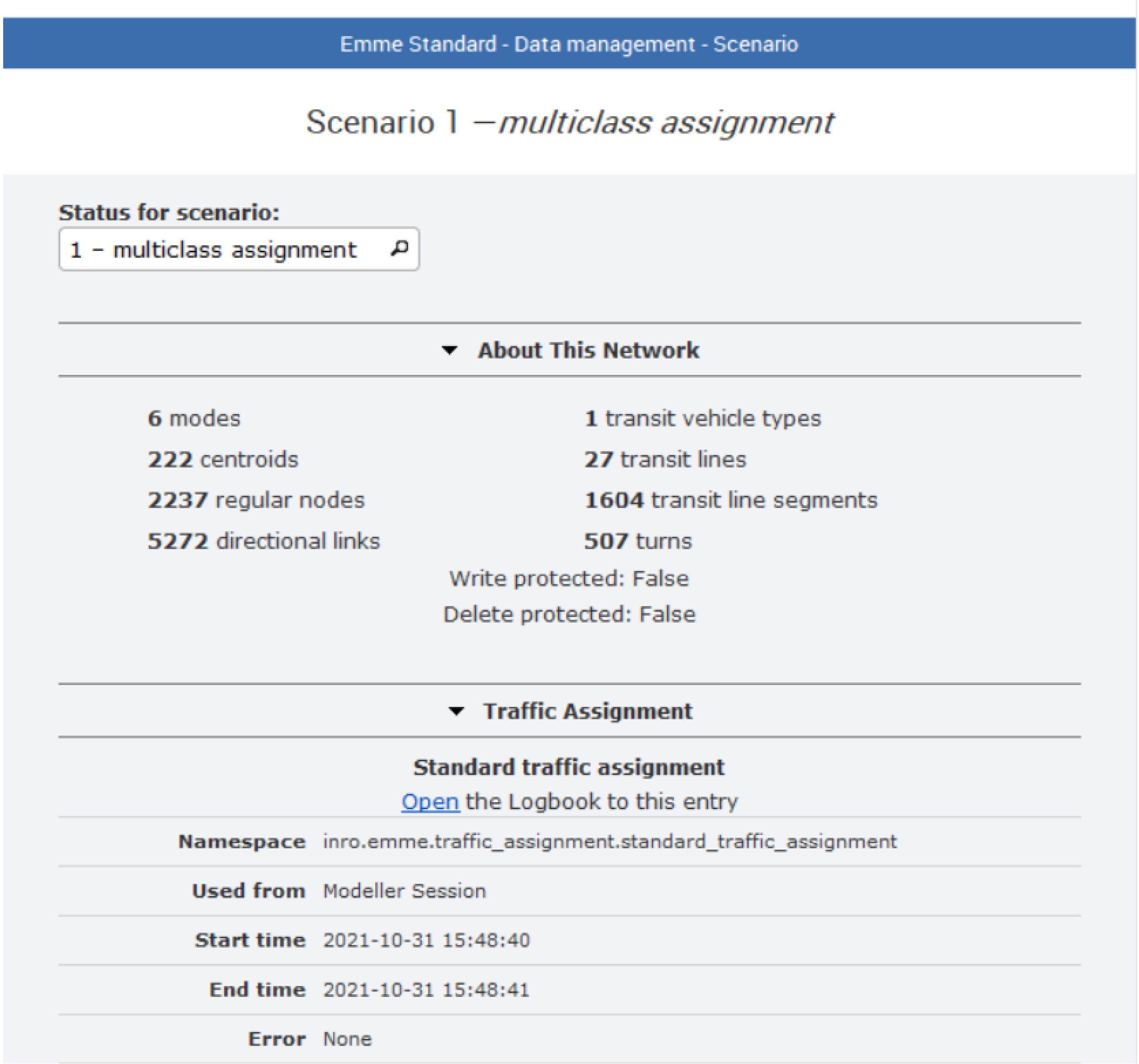


Reopening Scenario - 2 (Morning Peak Period)



Reopening Scenario - 2 (Evening Peak Period)

Appendix G Multiclass Traffic Assignment Model in EMME



Scenario 1 —*multiclass assignment*

Status for scenario:
1 – multiclass assignment

About This Network

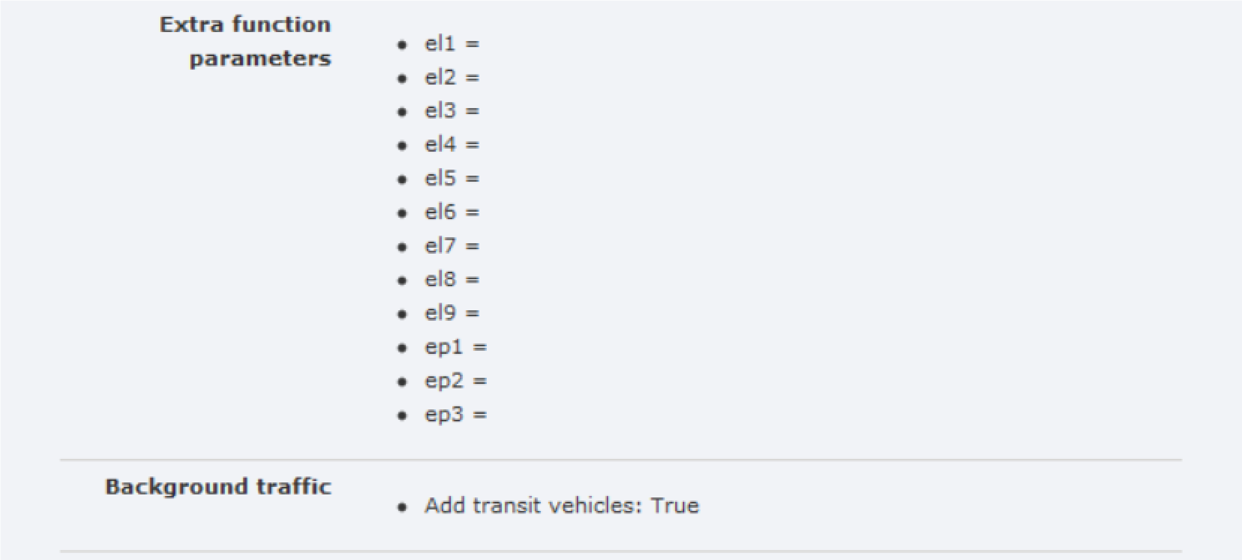
6 modes	**1** transit vehicle types
222 centroids	**27** transit lines
2237 regular nodes	**1604** transit line segments
5272 directional links	**507** turns

Write protected: False
Delete protected: False

Traffic Assignment

Standard traffic assignment
Open the Logbook to this entry

Namespace	inro.emme.traffic_assignment.standard_traffic_assignment
Used from	Modeller Session
Start time	2021-10-31 15:48:40
End time	2021-10-31 15:48:41
Error	None

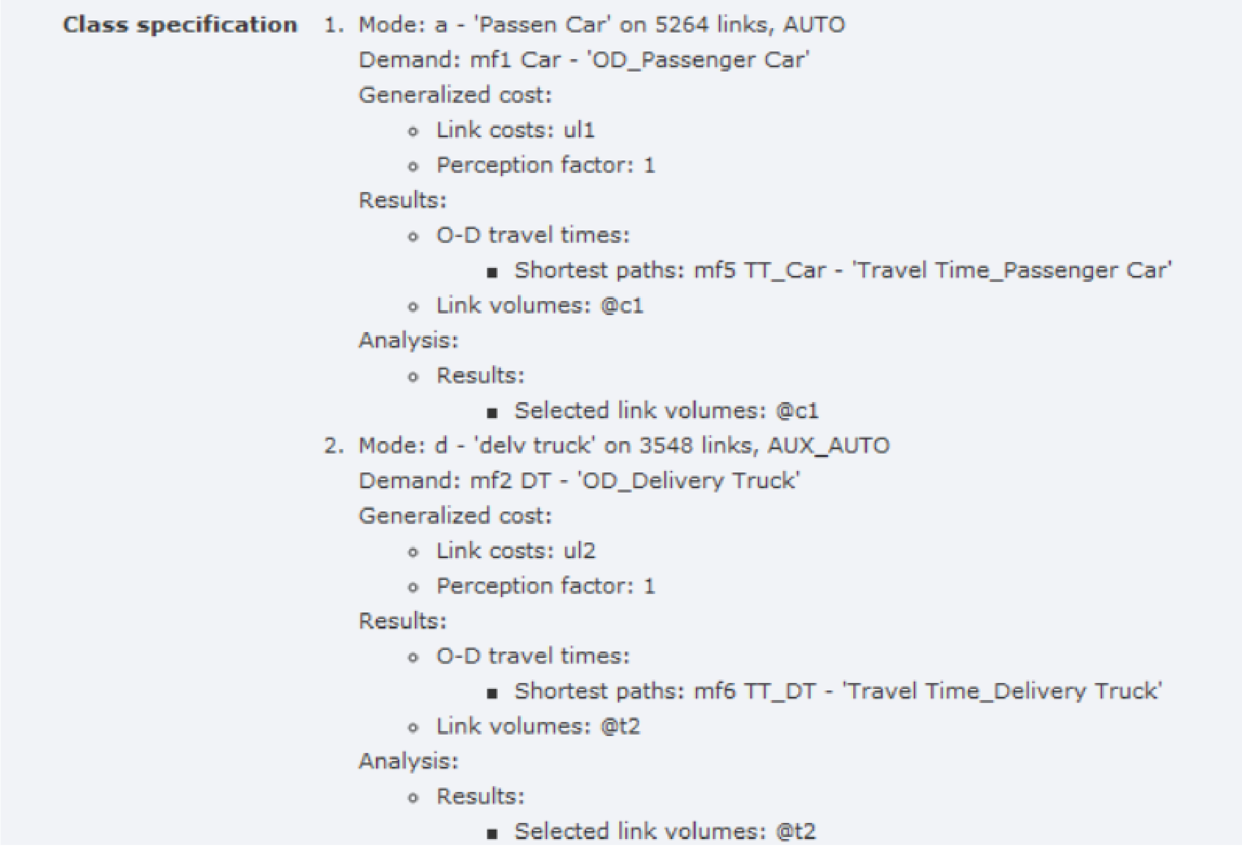


Extra function parameters

- el1 =
- el2 =
- el3 =
- el4 =
- el5 =
- el6 =
- el7 =
- el8 =
- el9 =
- ep1 =
- ep2 =
- ep3 =

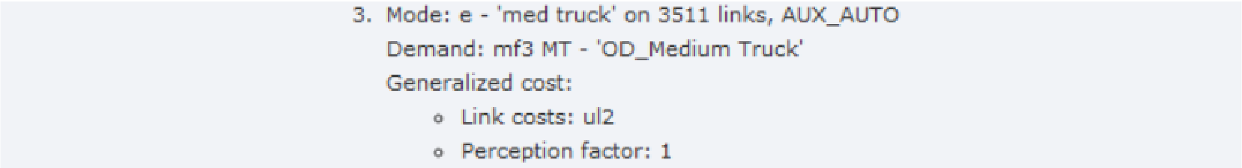
Background traffic

- Add transit vehicles: True

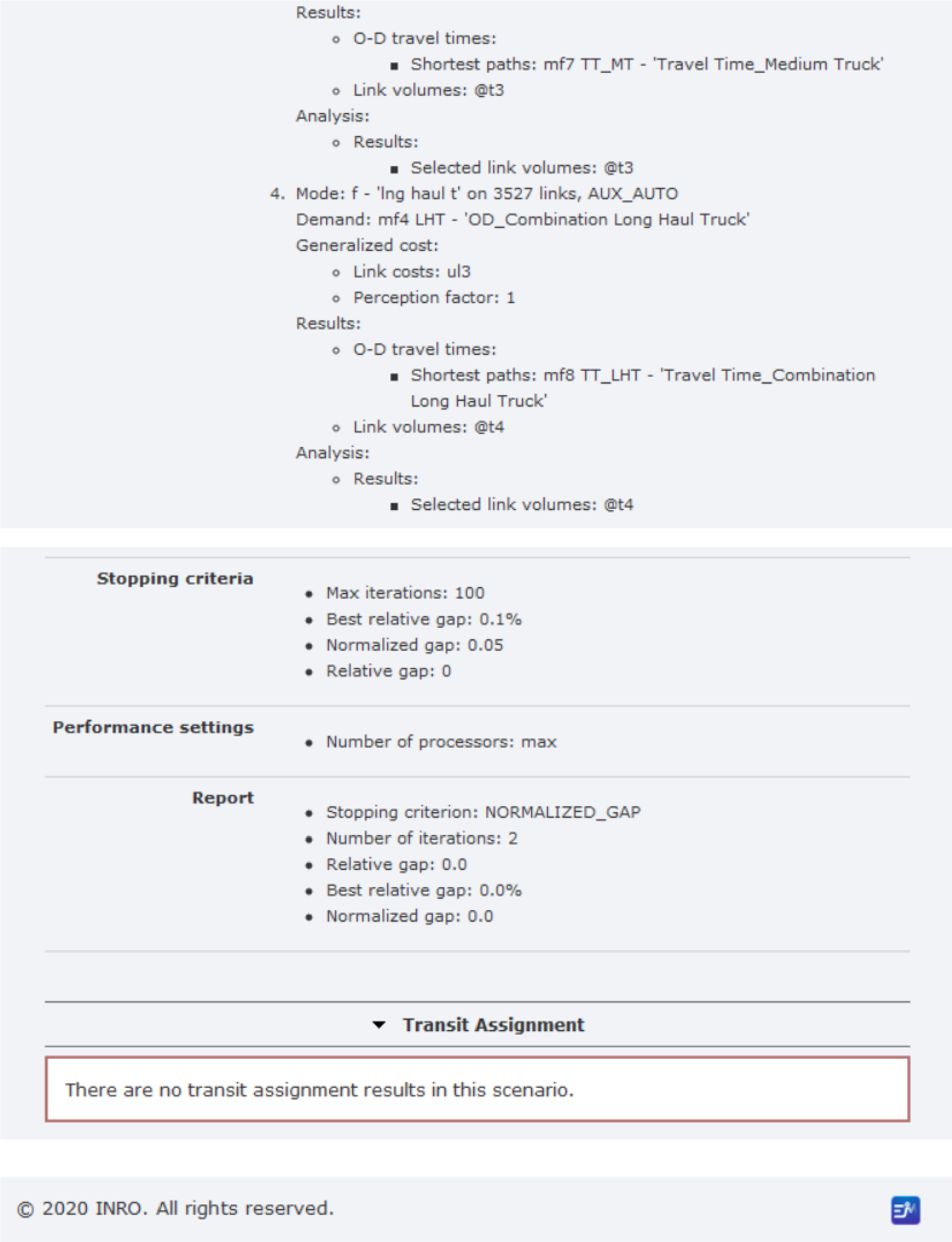


Class specification

1. Mode: a - 'Passen Car' on 5264 links, AUTO
   Demand: mf1 Car - 'OD_Passenger Car'
   Generalized cost:
    - Link costs: ul1
    - Perception factor: 1
   Results:
    - O-D travel times:
        - Shortest paths: mf5 TT_Car - 'Travel Time_Passenger Car'
    - Link volumes: @c1
   Analysis:
    - Results:
        - Selected link volumes: @c1
2. Mode: d - 'delv truck' on 3548 links, AUX_AUTO
   Demand: mf2 DT - 'OD_Delivery Truck'
   Generalized cost:
    - Link costs: ul2
    - Perception factor: 1
   Results:
    - O-D travel times:
        - Shortest paths: mf6 TT_DT - 'Travel Time_Delivery Truck'
    - Link volumes: @t2
   Analysis:
    - Results:
        - Selected link volumes: @t2



3. Mode: e - 'med truck' on 3511 links, AUX_AUTO
   Demand: mf3 MT - 'OD_Medium Truck'
   Generalized cost:
    - Link costs: ul2
    - Perception factor: 1



Results:
  - O-D travel times:
    - Shortest paths: mf7 TT_MT - 'Travel Time_Medium Truck'
  - Link volumes: @t3

Analysis:
  - Results:
    - Selected link volumes: @t3

4. Mode: f - 'lng haul t' on 3527 links, AUX_AUTO
   Demand: mf4 LHT - 'OD_Combination Long Haul Truck'
   Generalized cost:
     - Link costs: ul3
     - Perception factor: 1

   Results:
     - O-D travel times:
       - Shortest paths: mf8 TT_LHT - 'Travel Time_Combination Long Haul Truck'
     - Link volumes: @t4

   Analysis:
     - Results:
       - Selected link volumes: @t4

Stopping criteria

- Max iterations: 100
- Best relative gap: 0.1%
- Normalized gap: 0.05
- Relative gap: 0

Performance settings

- Number of processors: max

Report

- Stopping criterion: NORMALIZED_GAP
- Number of iterations: 2
- Relative gap: 0.0
- Best relative gap: 0.0%
- Normalized gap: 0.0

▾ Transit Assignment

There are no transit assignment results in this scenario.

Appendix H Sample Output of Transport Network Model in EMME

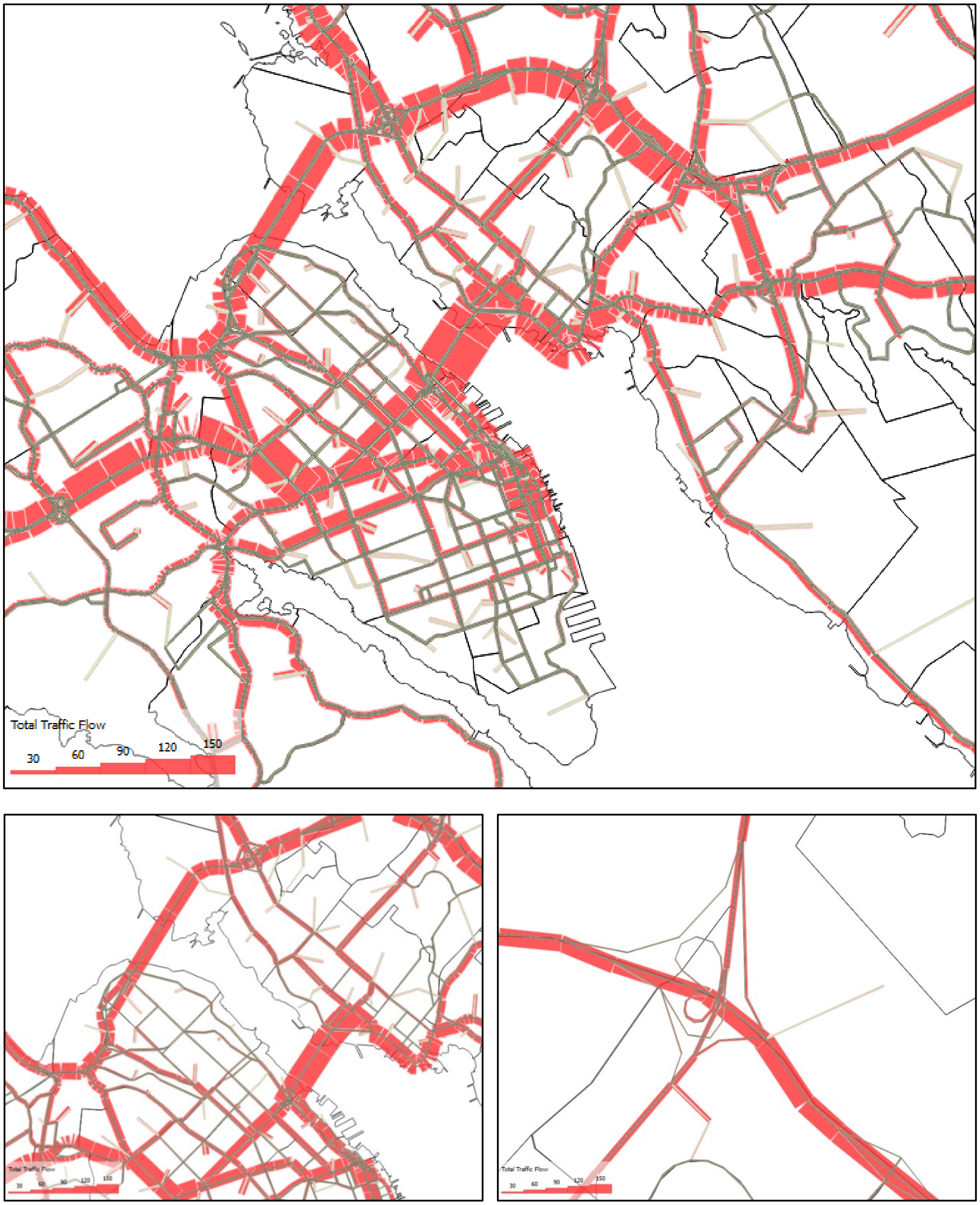
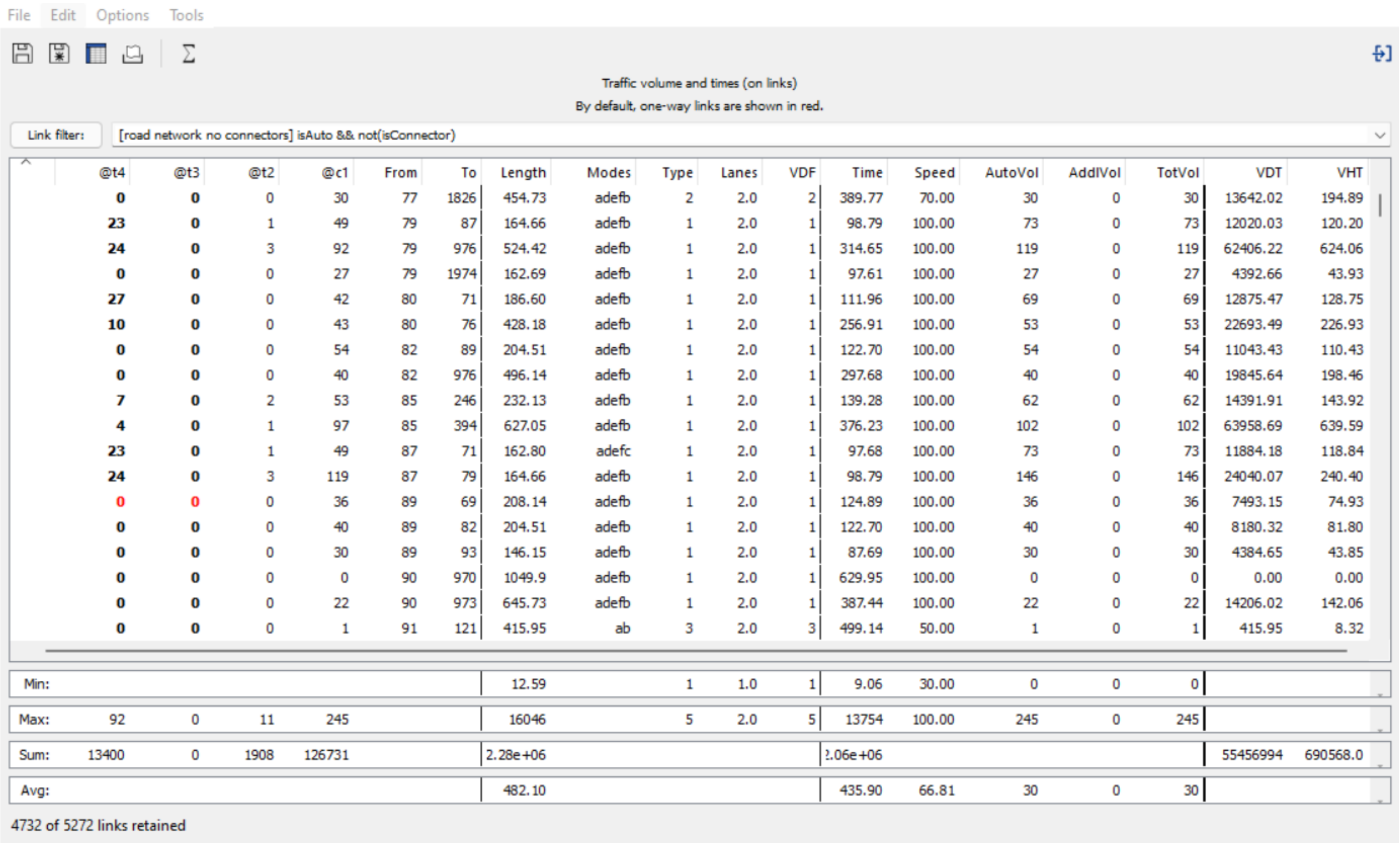


Figure H-1 Traffic Flow in the Transport Network Model



Traffic volume and times (on links)

By default, one-way links are shown in red.

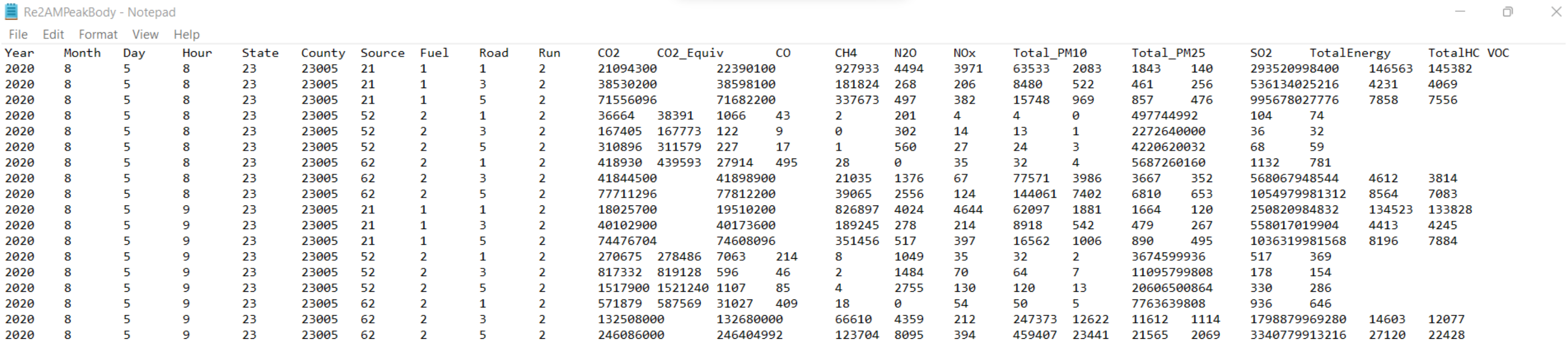
Link filter: [road network no connectors] isAuto && not(isConnector)

	@t4	@t3	@t2	@c1	From	To	Length	Modes	Type	Lanes	VDF	Time	Speed	AutoVol	AddlVol	TotVol	VDT	VHT
	0	**0**	0	30	77	1826	454.73	adefb	2	2.0	2	389.77	70.00	30	0	30	13642.02	194.89
	23	**0**	1	49	79	87	164.66	adefb	1	2.0	1	98.79	100.00	73	0	73	12020.03	120.20
	24	**0**	3	92	79	976	524.42	adefb	1	2.0	1	314.65	100.00	119	0	119	62406.22	624.06
	0	**0**	0	27	79	1974	162.69	adefb	1	2.0	1	97.61	100.00	27	0	27	4392.66	43.93
	27	**0**	0	42	80	71	186.60	adefb	1	2.0	1	111.96	100.00	69	0	69	12875.47	128.75
	10	**0**	0	43	80	76	428.18	adefb	1	2.0	1	256.91	100.00	53	0	53	22693.49	226.93
	0	**0**	0	54	82	89	204.51	adefb	1	2.0	1	122.70	100.00	54	0	54	11043.43	110.43
	0	**0**	0	40	82	976	496.14	adefb	1	2.0	1	297.68	100.00	40	0	40	19845.64	198.46
	7	**0**	2	53	85	246	232.13	adefb	1	2.0	1	139.28	100.00	62	0	62	14391.91	143.92
	4	**0**	1	97	85	394	627.05	adefb	1	2.0	1	376.23	100.00	102	0	102	63958.69	639.59
	23	**0**	1	49	87	71	162.80	adefc	1	2.0	1	97.68	100.00	73	0	73	11884.18	118.84
	24	**0**	3	119	87	79	164.66	adefb	1	2.0	1	98.79	100.00	146	0	146	24040.07	240.40
	0	**0**	0	36	89	69	208.14	adefb	1	2.0	1	124.89	100.00	36	0	36	7493.15	74.93
	0	**0**	0	40	89	82	204.51	adefb	1	2.0	1	122.70	100.00	40	0	40	8180.32	81.80
	0	**0**	0	30	89	93	146.15	adefb	1	2.0	1	87.69	100.00	30	0	30	4384.65	43.85
	0	**0**	0	0	90	970	1049.9	adefb	1	2.0	1	629.95	100.00	0	0	0	0.00	0.00
	0	**0**	0	22	90	973	645.73	adefb	1	2.0	1	387.44	100.00	22	0	22	14206.02	142.06
	0	**0**	0	1	91	121	415.95	ab	3	2.0	3	499.14	50.00	1	0	1	415.95	8.32
Min:							12.59		1	1.0	1	9.06	30.00	0	0	0		
Max:	92	0	11	245			16046		5	2.0	5	13754	100.00	245	0	245		
Sum:	13400	0	1908	126731			2.28e+06					2.06e+06					55456994	690568.0
Avg:							482.10					435.90	66.81	30	0	30		

4732 of 5272 links retained

Figure H-2 Link Based Traffic Volume and Other Attributes in the Transport Network Model

Appendix I Sample Output of Emission Model in MOVES



```
Year    Month   Day     Hour    State   County  Source  Fuel    Road    Run     CO2     CO2_Equiv       CO      CH4     N2O     NOx     Total_PM10      Total_PM25      SO2     TotalEnergy     TotalHC VOC
2020    8       5       8       23      23005   21      1       1       2       21094300        22390100        927933  4494    3971    63533   2083    1843    140     293520998400    146563  145382
2020    8       5       8       23      23005   21      1       3       2       38530200        38598100        181824  268     206     8480    522     461     256     536134025216    4231    4069
2020    8       5       8       23      23005   21      1       5       2       71556096        71682200        337673  497     382     15748   969     857     476     995678027776    7858    7556
2020    8       5       8       23      23005   52      2       1       2       36664   38391   1066    43      2       201     4       4       0       497744992       104     74
2020    8       5       8       23      23005   52      2       3       2       167405  167773  122     9       0       302     14      13      1       2272640000      36      32
2020    8       5       8       23      23005   52      2       5       2       310896  311579  227     17      1       560     27      24      3       4220620032      68      59
2020    8       5       8       23      23005   62      2       1       2       418930  439593  27914   495     28      0       35      32      4       5687260160      1132    781
2020    8       5       8       23      23005   62      2       3       2       41844500        41898900        21035   1376    67      77571   3986    3667    352     568067948544    4612    3814
2020    8       5       8       23      23005   62      2       5       2       77711296        77812200        39065   2556    124     144061  7402    6810    653     1054979981312   8564    7083
2020    8       5       9       23      23005   21      1       1       2       18025700        19510200        826897  4024    4644    62097   1881    1664    120     250820984832    134523  133828
2020    8       5       9       23      23005   21      1       3       2       40102900        40173600        189245  278     214     8918    542     479     267     558017019904    4413    4245
2020    8       5       9       23      23005   21      1       5       2       74476704        74608096        351456  517     397     16562   1006    890     495     1036319981568   8196    7884
2020    8       5       9       23      23005   52      2       1       2       270675  278486  7063    214     8       1049    35      32      2       3674599936      517     369
2020    8       5       9       23      23005   52      2       3       2       817332  819128  596     46      2       1484    70      64      7       11095799808     178     154
2020    8       5       9       23      23005   52      2       5       2       1517900 1521240 1107    85      4       2755    130     120     13      20606500864     330     286
2020    8       5       9       23      23005   62      2       1       2       571879  587569  31027   409     18      0       54      50      5       7763639808      936     646
2020    8       5       9       23      23005   62      2       3       2       132508000       132680000       66610   4359    212     247373  12622   11612   1114    1798879969280   14603   12077
2020    8       5       9       23      23005   62      2       5       2       246086000       246404992       123704  8095    394     459407  23441   21565   2069    3340779913216   27120   22428
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Figure I-1 Emissions of Major Pollutants during the Morning Peak Period (7:59 am- 8:59 am) of May 2020