DEVELOPMENT OF TRAFFIC MICROSIMULATION AND EMISSION MODELLING SYSTEM FOR EVALUATING MAJOR TRANSPORTATION PLANNING DECISIONS

by

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Submitted in partial fulfillment of the requirements
for the degree of Master of Applied Science

at

Dalhousie University
Halifax, Nova Scotia
November 2015

DEDICATION

To My Mother, Sharifa Jahan

&

My Husband, Mahmudur Rahman Fatmi (Sunny)

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Abstract

The first objective of this thesis is to develop an emission modelling framework to estimate vehicular emissions of a major truck route in the downtown Halifax and examine alternative policy scenarios for emission reduction. The key findings from the first objective suggest that traffic microsimulation model is required to generate vehicle trajectory for a better temporal and spatial resolution of emission estimation. Therefore, the second objective is to develop a sequential microscopic traffic simulation and emission modelling framework to estimate vehicular emissions. The study evaluates the impacts of a major infrastructure renewal plan focusing on re-building a part of the expressway in the Halifax Downtown Core. The study also assesses the sensitivity of different traffic attributes along with their isolated and combined effects on emission variation. Finally, a land use regression model is developed to examine the potential effect of land use and built environment attributes on emissions.

List of Abbreviations Used

ACC	Adaptive Cruise Control
CAC	Criteria Air Contaminants
CFM	Car Following Speed Measuring Method
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DA	Dissemination Area
DEM	Digital Elevation Model
DMTI	Desktop mapping Technologies Inc.
EPOI	Enhanced Point of Interest
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GPS	Global Positioning Systems
HC	Hydrocarbons
HDDVs	Heavy-Duty Diesel Vehicles
HPA	Halifax Port Authority
HRM	Halifax Regional Municipality
ITEM	Integrated Traffic Emission Model
iTLE	integrated Transportation, Land Use, and Energy Modelling System
Link	A Segment of Road Connecting Two Adjacent Intersections
Link Grade	Slope of the Link
MLs	Managed Lanes
MOVES	Motor Vehicle Emission Simulator
Multi-grade	Roadway at different Elevations
NOx	Nitrogen Oxides
PM_{10}	Particulate Matter less than or equal to 10 Microns
$PM_{2.5}$	Particulate Matter less than or equal to 2.5 Microns
RMSE	Root Means Square Error
ROW	Right Of Way
SI	International System of Units
SO_2	Sulphur Dioxide
THC	Tetrahydrocannabinol
TSP	Transit Signal Priority
USEPA	US Environmental Protection Agency
VKT	Vehicle Kilometer Travelled
VMT	Vehicle Miles Travelled
VOCs	Volatile Organic Compounds
VSP	Vehicle Specific Power

Acknowledgements

This thesis would not have been possible without the help of many individuals. My special thanks to Dr. Muhammad Ahsanul Habib, my supervisor for giving me the opportunity to work in this research area. I would like to express my enormous gratitude to Dr. Habib for his valuable guidance, moral advice and continuous support throughout the program. I would like to thank him from the bottom of my heart for assisting me in solving technical issues, and collaborating with other students in the laboratory.

I would also like to thank Dr. Nouman Ali, and Dr. Alireza Ghasemi for their valuable contribution in the supervisory committee.

I would like to acknowledge Roddy Maclntyre, Traffic Services Supervisor of Halifax Regional Municipality (HRM), for providing the necessary data required to complete the study. My heartfelt thanks to my colleagues at Dalhousie Transportation Collaboratory (DalTRAC) for their cooperation and support throughout my journey. I would also like to thank the discussants, other researchers, and venders; while I was presenting my work in multiple international conferences.

Most importantly, I would also like to express my sincere appreciation to my Mom, husband (Sunny), sisters (Nipa, Nisha), and brother (Sumon) for all their endless support, and love and giving me the confidence to pursue my Masters. Finally, I would like to thank Allah, the most gracious and merciful, for giving me the capability to accomplish my graduate program.

A special thanks to the funding agencies, Natural Sciences and Engineering Research Council (NSERC)-Discovery Grant Program, and the Nova Scotia Department of Energy for providing the financial support to conduct this research.

Chapter 1

Introduction

1.1 Background and Motivation

The impact of the urban transportation related air pollution is becoming an increasing concern since majority of people resides in busy urban area experiencing significant air pollution. In Canada, 82% of total employee commute by car, while only 12% take public transit, and 6% use active transportation (*Turcotte, 2011*). Therefore, transportation has become a major source of Criteria Air Contaminants (CAC) such as, Carbon Monoxide (CO), Nitrogen Oxides (NOx), Sulfur Dioxide (SOx), Particulate Matter (PM_{10} and $PM_{2.5}$) and Volatile Organic Compounds (VOCs). According to Environment Canada (*2015a*), transportation is responsible for the 33.7 % of the total CO emissions, 43.1% of the total NOx emissions, 4.7 % of the total SOx emissions, 2.2 % of the total $PM_{2.5}$ emissions, 1.7 % of the total NH_3 emissions, and 10 % of the total VOCs emissions in Canada in 2013. This statistics also reveals that transportation sector is the largest contributor of CO and NOx emissions among all sectors. Moreover, Environment Canada (*2015b*) reveals that transportation (including passenger, freight, and off-road transportation) is responsible for almost quarter (23%) of total Greenhouse Gas (GHG) emissions in Canada among all the sectors. The distribution of GHG emissions by economic sectors in Canada, 2013 is presented in Figure 1-1. According to Environment Canada, the amount of Canada's GHG emissions is 1.6% of global GHG emissions in 2011. It is also found that Global GHG emissions have increased by 42% between 1990 and 2011, with Canada's GHG emissions increasing by 19% during that period (*Environment Canada, 2015c*).

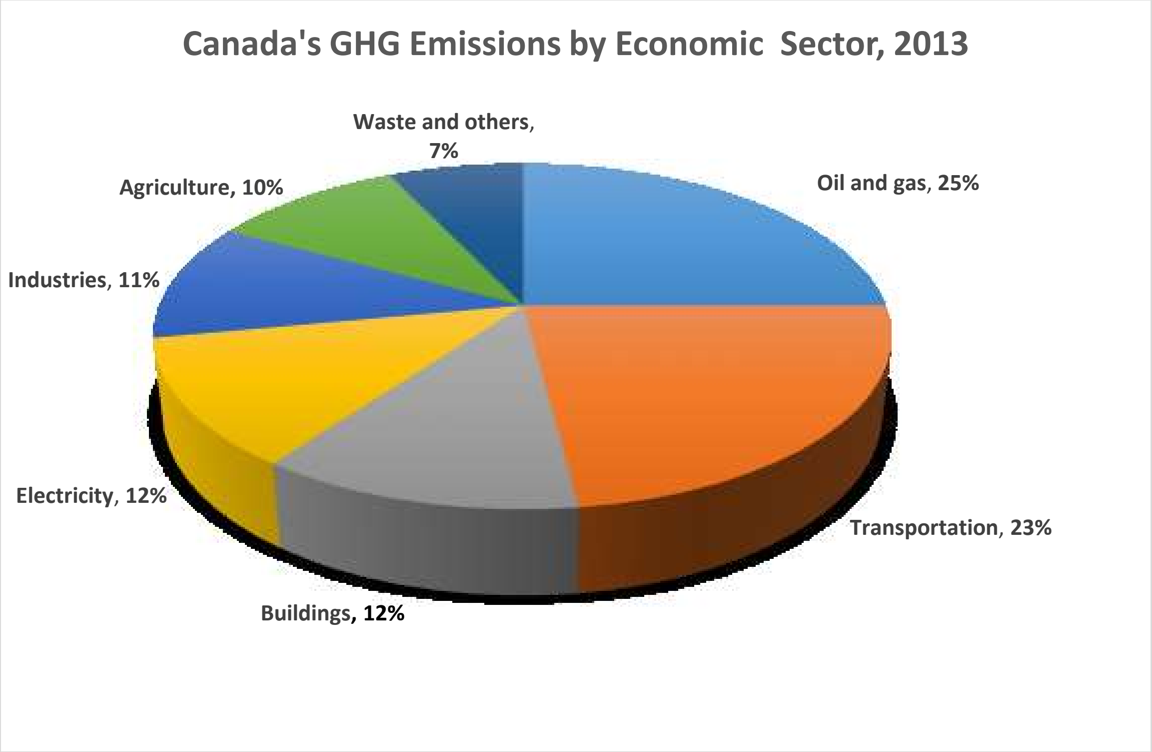

Figure 1-1 Distribution of GHG Emissions by Economic Sector in Canada, 2013 (*Environment Canada, 2015b*)

Vehicular emissions are significantly related with various health effects including respiratory (*Suresh et al., 2000; Preutthipan et al., 2004*) and cardiovascular diseases (*Brunekreef et al., 2009*), asthma (*Preutthipan et al., 2004*), lung damage (*Suresh et al., 2000*), premature mortality (*Künzli et al., 2000*), and other chronic health disorders. As a result, transportation engineers and planners have shown considerable interest in transportation emission modelling.

Nowadays, due to the urban sprawl, one of the major focuses of transport researchers is to improve traffic operation systems and develop alternative strategies to enhance road network efficiency and safety as well as to promote sustainable transportation. It is a challenge to apply these operational strategies and reduce traffic emission concurrently. Moreover, air pollution becomes a major public concern in cases when trucks run through densely populated urban downtown cores, such as truck route through Halifax Downtown Core. Therefore, it is necessary to develop emission inventory models to investigate the potential of different transportation planning strategies for emission mitigation.

In the case of emission modelling, US and European countries have developed emission estimation tools, such as MOVES, EMFAC, and COPERT based on their local context. There are some emission estimation tools developed in Canada such as, GHGenius, and UTEC; however, these tools estimate emissions at macro scale. There is no such model in Canada to capture instantaneous traffic operational changes and associate emission variation at micro scale. Among all the above mentioned emission estimation tools, MOVES (developed by US Environmental Protection Agency, USEPA) is broadly used in Canada. It is the USEPA's latest version of previous emission estimation tools such as MOBILE 6.2. MOVES can be used to estimate emissions at macro, meso, and micro scales. MOVES offers the opportunity to estimate emissions of a wide range of transportation related air pollutants for different vehicle types considering various vehicle model years, fuel types, meteorology, and road types. However, the embedded driving characteristics in MOVES is based on USA context. Vehicular emissions are significantly influenced by local traffic situation (such as vehicle class, and vehicle age distribution), road type, driving behaviour, meteorology, and topographic condition. Hence, the use of the embedded driving characteristics based on US cities causes underestimation or overestimation of emissions in a local Canadian context. Therefore, it is essential to develop a modelling framework to estimate emissions at both aggregate and disaggregate levels based on local Canadian context.

Although emission modelling has emerged as a key component of transportation research, limited studies assessed the environmental impact of major infrastructure renewal plan at the micro scale. In this line of research, few studies have evaluated the impact using field traffic data or applying modelling techniques to investigate emissions prior and after the implementation of renewal plan at the macro scale. However, one of the major limitations of these macro models is their inability to capture the effects of instantaneous speed and traffic volume variation on emissions. There is a growing body of research in traffic microsimulation modelling, which offers the potential to estimate emissions at a finer resolution with higher accuracy.

Thus, it is required to develop a sequential microscopic emission model that combines a traffic simulation model with emission estimation tool to estimate emissions at a finer spatial and temporal resolution.

Therefore, the motivation for this thesis is to develop a sequential microscopic emission modelling framework to evaluate different policy scenarios and major infrastructure renewal plan by predicting emissions at both aggregate and disaggregate level. The sequential emission modelling tool can be spatially transferred to other regions to evaluate planning projects.

1.2 Research Goal

The main objective of the thesis is to develop a modelling framework to estimate vehicular emissions at a finer resolution to capture the effect of truck operation and a major infrastructure renewal plan in the Halifax downtown core.

1.2.1 Specific Objectives

The research objective of this thesis is divided into four specific objectives:

1. Develop an emission modelling framework for a major truck route in downtown core of Halifax.

2. Develop a comprehensive, sequential microsimulation-based traffic and emission model for the assessment of a major renewal plan in Halifax downtown core.

3. Evaluate emissions at aggregate and disaggregate levels under different policy scenarios in both cases.

4. Assess the effects of network attributes and land use effects on vehicular emissions.

1.3 Research Significance

The major contribution of this research involves demonstration of an innovative and comprehensive emission modelling framework that combines a microscopic traffic simulation model with an emission estimation tool. This study aims to estimate vehicular emissions and emission rates at both link level and network level by generating instantaneous driving cycle profiles and by considering local geographic condition and state of traffic. The emission model developed in this study captures the isolated and combined effect of network attributes on emissions. Particularly, this study investigates the impact of roadway grades and instantaneous speed variations on emissions due to a major infrastructure renewal plan, which is limited in the existing literature. The research also develops a land use regression model to examine the potential effects of built environment characteristics on emissions. The discussion about the land use factors on emissions also brings a new prospective that land use factors cannot be captured in details unless the driving cycling factors are considered as well. This research has substantial policy implication since it explores the network attributes and built environment attributes responsible for emission rise, which helps transportation engineers and planners in making decision on policy implementation and evaluating the potential of emission mitigation strategies. Moreover, the land use regression model can be applied in other areas to predict emissions with limited instantaneous speed information.

1.4 Organization of the Thesis

This thesis is presented in five main chapters. The **first** chapter defines the problem and presents the research objectives and the outline of the thesis. The **second** chapter presents an analysis of link-based emissions for a major truck routes in the downtown Halifax Canada. This chapter describes a review of literature on emission modelling, modelling approach, diurnal variation of emissions, contribution of different transportation mode in emissions, and scenario evaluation to identify the best option for reducing emissions. The **third** chapter presents a microsimulation-based emission model for Halifax downtown core. This chapter describes a review of literature, demonstrates microscopic emission modelling framework showing detailed procedure to combine microscopic traffic simulation model with emission estimation tool, and evaluates the effect of network attributes and a major infrastructure renewal plan on emissions at a finer resolution. This chapter also presents land use regression model for each pollutant. These models focus on the examination of the influence of land use and built environment attributes along with street and traffic attributes on emissions. The **forth** chapter summarizes the major findings of the thesis including policy implications, limitations and recommends for the future work of the research.

1.5 Note on Units Used in the Thesis

This thesis uses both International System of Units (SI) and Imperial units to remain faithful to the convention of the MOVES (MOtor Vehicle Emission Simulator) model used in this research. Note that MOVES model uses grams as unit of emission and miles as unit of distance. Moreover, it also helps to make the research results consistent with other emission studies in the literature.

Chapter 2

Emission Model for Downtown Halifax Truck Route [1]

2.1 Chapter Overview

Air quality degradation due to vehicular emissions in urban areas poses a growing threat to human health. The objective of this study is to estimate vehicular emissions of a major truck route in the downtown core of Halifax, Canada and examine alternative policy scenarios for emission reduction. The study proposes an emission estimation framework that utilizes information from field surveys and uses a simulation platform, the Motor Vehicle Emission Simulator (MOVES). The study focuses on major air pollutants, including: carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM_{10} and $PM_{2.5}$) that are estimated for the time periods of AM peak, midday, off peak, PM peak and overnight. In total, thirty simulation runs were conducted for the 20.768 km (12.9 mile) long route to estimate link-based emissions in both directions. Moreover, this study estimates variations in emission rates with time and vehicle type. Two alternative strategies (i.e. limiting truck for the entire day, and restricting truck for the AM peak, midday, and PM peak periods) are tested in order to reduce emissions from the route.

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[1] This Chapter is partially based on the **peer-reviewed conference paper,** Irin, S., and Habib, M.A. "Estimation of Link-Based Emission for a Truck Route in the Downtown Halifax, Canada", presented at 94th Annual Meeting of the Transportation Research Board, Washington, D.C., U.S.A., No. 15-5946, January 11-15, 2015.

This chapter begins with an introduction and brief literature review of relevant vehicular emission studies, followed by a brief description of data and methodology. Next, the results of this study are presented and discussed. The chapter ends with a conclusion including a summary of contributions, the practical applications of the research as well as suggestions for future work.

2.2 Introduction

Vehicles are a significant source of pollution (*Sivanandan et al., 2008*) that contributes to the deterioration of air quality (*Mahmod et al., 2010*). Approximately 63 percent of total air pollution comes from vehicular emissions (*Davis and Truett, 2003*). It is found that chronic exposure to pollutants is correlated with long-term health effects including cardiovascular disease and lung cancer (*Gan et al., 2012*), as well as other immediate health problems (*Bodin et al., 2009*). Freight transport is a critical source of air pollution that is becoming a major public issue in cases where trucks run through densely populated urban cores (*HEI, 2010*). Particularly, it raises concerns of the impending health effects for urban populations and the escalating severity of related illnesses (*HEI, 2010*). As a result, emission reduction strategies are vital to decrease pollution and associated negative health effects of vehicular emissions.

Inventories of vehicle emissions play a significant role in selecting appropriate traffic emission reduction strategies (*Sharma and Khare, 2001; Rakha et al., 2003; Abo-Qudais and Qdais, 2005*). Increased pressure has been placed on decision makers to mitigate air quality issues, greenhouse gas (GHG) emissions and other environmental degradation. The in-depth investigation on the nature and extent of the pollutants, both for traffic routes and hot spots, allows informed decision-making regarding emission abatement techniques.

The objective of this study is to examine vehicular emissions of a critical truck route in Halifax (Figure 2-1) that connects the port of Halifax and its hinterland. The Halifax peninsular truck route is of particular interest as it passes through a variety of commercial, institutional, cultural and residential districts. Potentially truck emits more emissions compared to passenger car, and the area surrounding the truck route in Halifax Downtown has a higher population density. Therefore, this truck route running through the downtown core has the potential of a higher emission exposer for such densely populated and mixed land-use neighbourhoods. Alternatives to this truck route for freight movements exist including a rail option. Recently, transportation engineers and planners are exploring innovative solutions for redirecting truck traffic on the rail tracks, of which its' capacity is being vastly under-utilized. Given the importance of the issue to the public and decision makers, this study attempts to evaluate alternative strategies in terms of their performance in reducing vehicular emissions. The study proposes an emission estimation framework based on the Motor Vehicle Emission Simulator (MOVES) 2010b, developed by the US Environmental Protection Agency (EPA).This study focuses on the emission rates of four major criteria pollutants: Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Particulate Matter (PM_{10} and $PM_{2.5}$) to assess the current status of the vehicular emissions along the truck route and evaluate alternative options for truck traffic.

2.3 Literature Review

Air quality has been a topic of study for well over a century and has since become a critical issue worldwide (*Abou-Senna and Radwan, 2014a*). Pollution from vehicles is one of the major contributors for climate change, which affects the economic, social, health and environmental aspects of human life. In Canada, 25 percent of emissions (*Canadian Government Climate Change Website*) are attributed solely to the transportation sector. Globally, many studies determine the emission rates of a specified area within a set period of time (*Frey et al., 2008; Hatzopoulou et al., 2008; Sivanandan et al., 2008; Choi and Frey, 2010; Farzaneh and Zietsman, 2012; Sider et al., 2014; Abou-Senna and Radwan, 2014a; Abou-Senna and Radwan, 2014b).* Numerous types of pollutants are investigated, including: Nitrogen Oxides (NOx), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Hydrocarbons (HC), THC, and Particulate Matter (PM_{10} and $PM_{2.5}$) (*Frey et al., 2008; Hatzopoulou et al., 2008; Sivanandan et al., 2008; Choi and Frey, 2010; Mahmod et al., 2010; Farzaneh and Zietsman, 2012; Sider et al., 2014; Abou-Senna and Radwan, 2014a; Abou-Senna and Radwan, 2014b; Alam et al., 2014c*). Some pollutants such as NOx and CO are found in highest concentrations near roadways, and are considered to be one of the most effective indicators of traffic congestion (*Alam et al., 2014c*). Particulate Matter (PM) emissions are released mainly by transport vehicles and are found to cause cardiovascular, respiratory and autoimmune diseases (*Kappos et al., 2004*). Additionally, long-term exposure to $PM_{2.5}$ has been linked to early death (*COMEAP, 2010; US Environmental Protection Agency, 2011).* High levels of diesel traffic lead to high PM concentrations, which is becoming a major health concern (*Vallamsundar and Lin, 2012*). For the abovementioned reasons, this study focuses on the emissions of NOx, CO, PM_{10} and $PM_{2.5}$ from different types of transportation vehicles including diesel-based truck traffic mix in the Halifax region, Canada.

The concentration of NOx and PM in the atmosphere is significantly related to emissions from Heavy-Duty Diesel Vehicles (HDDVs) (*Gajendran and Clark, 2003*). An inventory of on-road vehicle emissions in 2002 shows that HDDVs release approximately 46 percent and 54 percent of the total NOx and PM emissions in the United States (*US Environmental Protection Agency, 2005*). The amount of pollutant emissions from HDDVs is influenced by fuel type, driving cycle, vehicle class and weight (*Clark et al., 2002; Brodrick et al., 2004*). Moreover, these large trucks release 30 to 100 times more PM pollutants than personal cars (*Kanaroglou et al., 2000*). NOx emissions from HDDVs may be up to five times higher than from single-unit gasoline fueled trucks (*Miller et al., 2003*). Additionally, vehicle weight may increase NOx emission rates, particularly during acceleration (*Brodrick et al., 2004*).

Many scenarios have been tested in the literature for reducing emissions (*Kitwiroon et al., 2007; Sivanandan et al., 2008; Mahmod et al., 2010; Farzaneh and Zietsman, 2012; Alam et al., 2014c*). In general, vehicle pollution is found to be reduced after the introduction of traffic control measures (*Mahmod et al., 2010*). Traffic control measures can be used to reduce overall vehicle use or alter traffic flow conditions. Creating fewer stoppages, dedicated bus lanes, banning HDDVs, reducing speed limits and encouraging alternative work hours can also reduce emissions. Previous studies investigate the aforementioned scenarios to simulate reductions in harmful emissions from vehicles, particularly in densely populated urban areas. A study in India determines that introducing lane restrictions for different vehicle types is an effective way of significantly reducing vehicular emissions (*Sivanandan et al., 2008*). Similarly, a study in the Netherlands concludes that reducing heavy-duty vehicles and traffic volume leads to a large reduction in pollutant emissions (*Mahmod et al., 2010*). A study by Kitwiroon et al., (*2007*) shows that a 20 percent reduction in number of HDDVs decreases NOx and PM_{10} emissions by 9 percent and 11 percent respectively. Farzaneh and Zietsman

(2012) observe roadway emissions in Texas, and determine that speed limit enforcement has a complex impact on total emissions; however, the reduction in exceeding speed limit decreases NOx emissions as well as traffic noise and accidents. A study in Montreal, Canada, concludes that the best way to reduce vehicular emissions is by restricting through traffic in an urban neighbourhood (*Alam et al., 2014c*).

The study uses the Motor Vehicle Emission Simulator (MOVES) 2010b platform which replaced an earlier version of EPA's emissions model, MOBILE (*Chamberlin et al., 2011*). The MOVES applies new capabilities such as adjustment for temperature, air conditioning and fuel effects to emission rates for estimating the total emissions (*Vallamsundar and Lin, 2012*; *US Environmental Protection Agency, 2009*). The MOVES utilizes a binning approach and classifies vehicles into source bins (*Bai et al., 2009*). Vehicle class, model year group, vehicle weight, engine size and technology, and fuel type are defined in source bins to describe unique combinations (*US Environmental Protection Agency, 2004*). The resulting binned activities are given an emission rate (*Vallamsundar and Lin, 2012*) that can be analyzed on its own, or combined to present a total emission rate.

In addition to the estimation of key pollutants this study generates hot spots for the NOx, CO, PM_{10} and $PM_{2.5}$ emissions. The separation of emissions by vehicle types and location allows for spatial hot spots to be determined (*Hatzopoulou et al., 2008*). Hot spots are areas where local pollution concentrations exceed the set standards (*US Environmental Protection Agency, 2010*). Local hot spots can be used to visually represent problem areas in the study area. Often, such analysis could be useful for transportation planners, engineers and decision makers. Finally, two alternative scenarios are tested to evaluate their performances in reducing emissions: (a) a ban on all trucks along the route assuming that the goods from port can be transported via rail tracks, and (b) restriction on truck operation by certain hours of the day.

2.4 Study Area, Data and Methodology

2.4.1 Study Area

The Halifax peninsular truck route spans from the tollgates at the Dartmouth approach to the A. Murray Mackay Bridge to the intersection of Inglis and Robie Streets that connects to the port of Halifax (Figure 2-1). The truck route is 20.768 kilometers (12.9 miles) in length, divided into 106 links. Inbound and outbound truck routes were modeled separately in this study. Four vehicle types are chosen for emissions analysis: passenger cars, light commercial trucks, single unit short-haul trucks, and combination long-haul trucks.

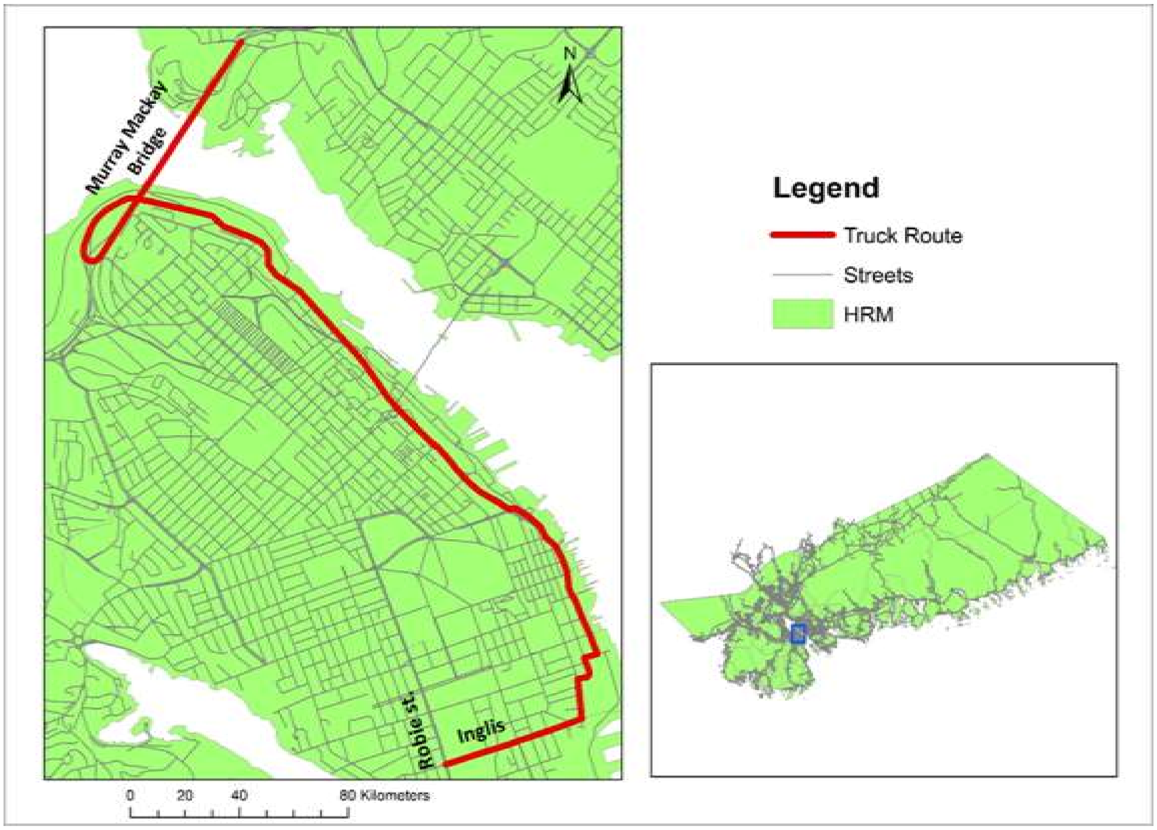

Figure 2-1 Truck Route in the Downtown Halifax

2.4.2 Data Used

The study uses project scale analysis in the MOVES platform, which allows the finest level of emission estimation for links, intersections, parking lots and highway corridors (*US Environmental Protection Agency, 2010*). Project level analysis also has the capacity to customize modelling input according to the modelling environment, making it highly valuable to international users (*Koupal et al., 2010*). Project scale analysis in MOVES requires information about roadway link characteristics, vehicular age distribution, fuel and meteorological data. The roadway link characteristics include: hourly link traffic volume, link length, link grade, and link speed. Hourly link traffic volume data is obtained from the traffic count data provided by the Halifax Regional Municipality's (HRM)'s Department of Transportation and Public Works representing a typical weekday of the month of July. In addition, this study supplemented the HRM data with a field survey. A day-long field survey was conducted in July (typical weekday) with 10 surveyors who counted all types of vehicles including the classification used for emissions analysis to get the traffic volumes at 10 specified segments in different time periods. This classification includes passenger cars, light commercial trucks, single unit short haul trucks and combination long haul trucks. The survey was designed to collect 15 minutes of traffic volume data twice in an hour based on Highway Capacity Manual. The length of the each link and link grade is calculated in ArcGIS 10.1 from the HRM spatial geodatabase. The link specific average speed data is used as a vehicle activity input, collected through the field survey. The speeds of each type of vehicles were measured using the car following speed measuring method (CFM). According to the CFM method, vehicles of each type were followed by a car, and their speeds were monitored from the odometer of the chasing car. It is widely used in urban areas and costs less than other surveying methods (*Feng and Gu, 2005*).

Data on vehicle age distribution was estimated from the Canadian Vehicle Survey. This study assumes that all passenger cars are gasoline fueled, and light commercial trucks, single unit short-haul trucks, and combination long-haul trucks are diesel fueled. Meteorological information such as hourly temperature and relative humidity data was provided by Environment Canada at the Halifax Naval Dockyard weather station, which is within the study route area.

2.4.3 Model Development and Estimation

The study develops an emission estimation framework based on the MOVES and available relevant information. The hourly emission rates (g/VMT) are derived for each roadway link for the inbound and outbound directions. The running emission rates are calculated based on the HRM and field survey data. The AM peak, midday, off peak, PM peak and overnight emission rates are estimated, as well as the total daily emissions for scenario comparisons. CO, NOx, PM_{10} and $PM_{2.5}$ emission inventories are also calculated to estimate link total emissions in grams. The emission rates (g/VMT) are calculated for a typical weekday in the month of July 2014. Five weekday hours; 8am to 9am, 12 pm to 1 pm, 2 pm to 3 pm, 3 pm to 4pm and 7pm to 8 pm are chosen to represent the AM peak, midday, off peak, PM peak and overnight periods. All the links in the Halifax peninsula truck route fall within the urban restricted and urban unrestricted categories. The hourly proportion of link traffic volume of each vehicle type is calculated from traffic count data by manual survey to get link source type fraction in each link. To develop the emission model in this study, a total of thirty unique simulation runs have been completed for three scenarios. A linear extrapolation technique was used to estimate the daily emission rates (g/VMT) for each link and the daily total emissions (g) in the truck route using the hourly emission rates.

Two policy scenarios (i.e. limiting truck for the entire day, and restricting truck for the AM peak, midday, and PM peak periods) were developed based on the Halifax-Trucking Options Study by the Halifax Port Authority (HPA) and Halifax Regional Municipality (HRM) in January 2006 (*Halifax Inland Terminal and Trucking Options Study, 2006*). They conducted a study to assess the impact of an Inland Terminal giving truck access to the rail cut, bypassing the downtown streets of Halifax. All truck traffic from the existing downtown terminals was recommended to be shifted to this new inland terminal near Rocky Lake. The objectives of this study was to reduce truck traffic and vehicular emissions through the HRM peninsula and also lessen congestion on Hollis and Lower Water Street.

In this study, base case Scenario 1 represents a business-as-usual truck route in the Halifax peninsula where all types of vehicles are allowed to run. Scenario 2 attempts to represent the study route where no trucks are allowed for the entire day (i.e. a ban on all trucks along the route assuming that the goods from the port can be transported via rail tracks). In this case, the goods transported by the trucks are assumed to be accommodated through an alternative mode which can be rails, which already exists in the same route or the existing truck route should be redesigned by avoiding the central business district of the Halifax peninsula. Scenario 3 represents the banning of light commercial trucks, single unit short-haul trucks and combination long-haul trucks for AM peak, midday and PM peak periods only (i.e. restriction on truck operation by certain hours of the day). First, emission rates for each link are calculated for the base case scenario 1. In the next step, new emission rates are calculated by implementing proposed transportation scenarios to compare the relative merits of restricting trucks in the route.

2.5 Results and Discussion

This section presents the estimated variations in link emission rates with time and vehicle type. Link emission rates (g/VMT) are calculated by dividing the corresponding link total emissions (g) with the link length (mile) and link traffic volume. Moreover, two policy scenarios are evaluated to assess their effectiveness in mitigating air pollution.

2.5.1 Diurnal Variation of Emissions

Table 2-1 demonstrates the summary statistics of the estimated hourly emission rates (g/VMT) of CO, NOx, PM_{10} and $PM_{2.5}$ during different periods in a day. The ratios of maximum to minimum emission rates for CO, NOx, PM_{10} and $PM_{2.5}$ are 2.279, 2.015, 2.30 and 2.398 respectively. This implies that emission rates vary for each link due to differences in proportion of vehicle types and overall traffic volume. Table 2-1 also shows that 50% of the total 106 links have emission rates at or below the average emission rates for the AM peak, midday, off peak, PM peak and overnight periods. On the other hand, 50% of the total links have higher emission rates relative to the average value, which offers the opportunity to identify hot spots representing higher emission concentration in the study area.

Figure 2-2 and Figure 2-3 shows the diurnal variation of emissions per vehicle mile travelled for all pollutants along the route. The model results demonstrate an increasing trend in the average emission rates during the AM peak, and PM peak period, with a declining trend in emission rates during the overnight period. The daily average emission rate for CO is 41.954 g/VMT. Table 2-2 displays relative difference in emission rates throughout the day. During the AM peak and PM peak period, the CO emission rates increase to 15.33 % above the daily average emission rate. Similarly, during the midday and off peak periods, the CO emission rates remain 9.81% higher than the daily average rate. Conversely, CO emission rates decline to 50.27 % below the daily average emission rate in the overnight period. This indicates that emission rates are significantly responsive to time of a day, as more people are driving in the peak hours of the day to commute and perform their daily activities.

Table 2-1 Summary Statistics of Hourly Emission Rates of Pollutants during Different Periods in a Day

Pollutant	**Time**	**Minimum**	**25 Percentile**	**Median**	**Average**	**75 Percentile**	**Maximum**
		(g/VMT)	(g/VMT)	(g/VMT)	(g/VMT)	(g/VMT)	(g/VMT)
CO	AM Peak	34.41814	43.97579	47.0889	48.38388	51.76111	73.42595
	Midday	31.40268	41.75865	44.40512	46.0696	49.12174	74.71351
	Off Peak	31.40272	41.75864	44.405	46.0696	49.12178	74.7133
	PM Peak	34.41802	43.97571	47.08887	48.38388	51.76109	73.42604
	Overnight	15.12089	18.32086	19.67383	20.86176	21.87295	35.89613
NOx	AM Peak	34.762	45.29971	47.63863	48.49232	51.38008	66.69766
	Midday	31.97289	42.53906	45.36819	46.46124	49.53718	66.76153
	Off Peak	32.34407	42.78008	45.84571	46.23289	49.53728	66.76155
	PM Peak	34.7619	45.29992	47.63873	48.49231	51.37998	66.69776
	Overnight	23.23289	29.74261	32.13159	33.35517	35.81735	48.45153
PM_{10}	AM Peak	4.412453	5.558456	5.934869	6.145018	6.527861	8.800013
	Midday	4.058694	5.227967	5.772638	6.005442	6.440514	9.917637
	Off Peak	4.06891	5.242103	5.789069	5.987501	6.459874	9.95941
	PM Peak	4.379223	5.51994	5.888306	6.094621	6.472454	8.70099
	Overnight	3.161917	4.111775	4.510751	4.786059	5.248586	8.320746
$PM_{2.5}$	AM Peak	3.981497	5.150563	5.434942	5.682662	6.039652	8.297266
	Midday	3.694852	4.893321	5.360037	5.610544	6.019098	9.412624
	Off Peak	3.704706	4.90758	5.375188	5.5937	6.036915	9.45108
	PM Peak	3.950886	5.109521	5.392068	5.636257	5.988638	8.206065
	Overnight	2.906367	3.850584	4.241925	4.513705	4.963195	7.937537

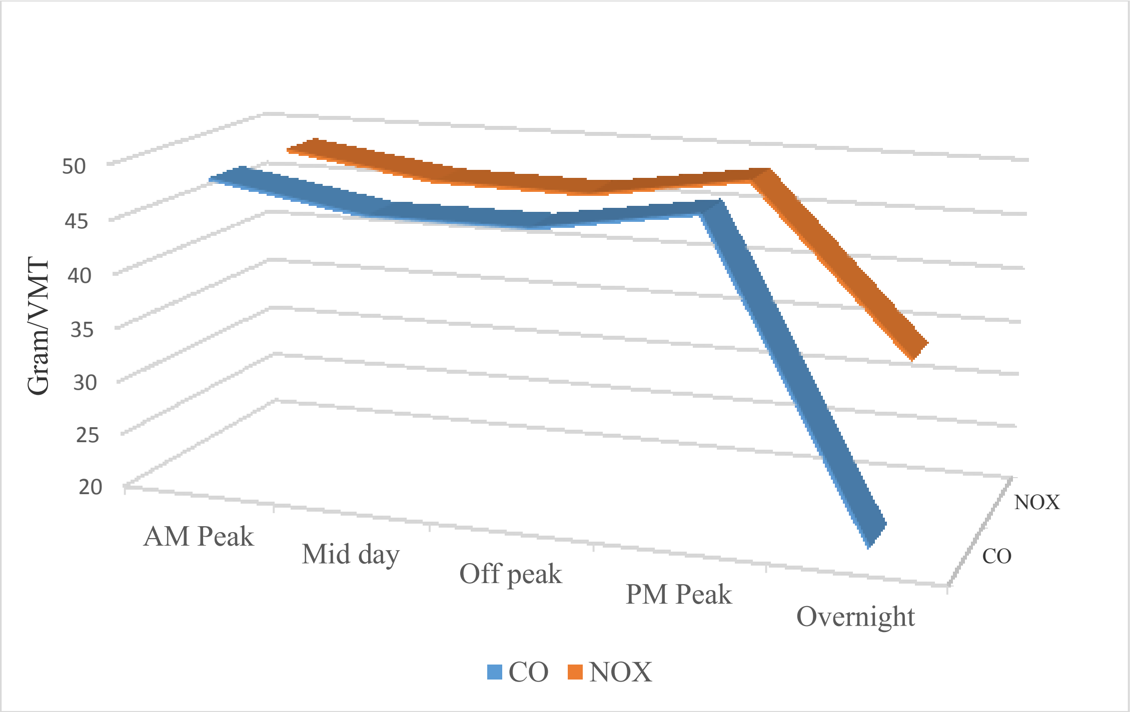

Figure 2-2 Diurnal Variation of Emissions per Vehicle Mile Travelled for CO and NOx

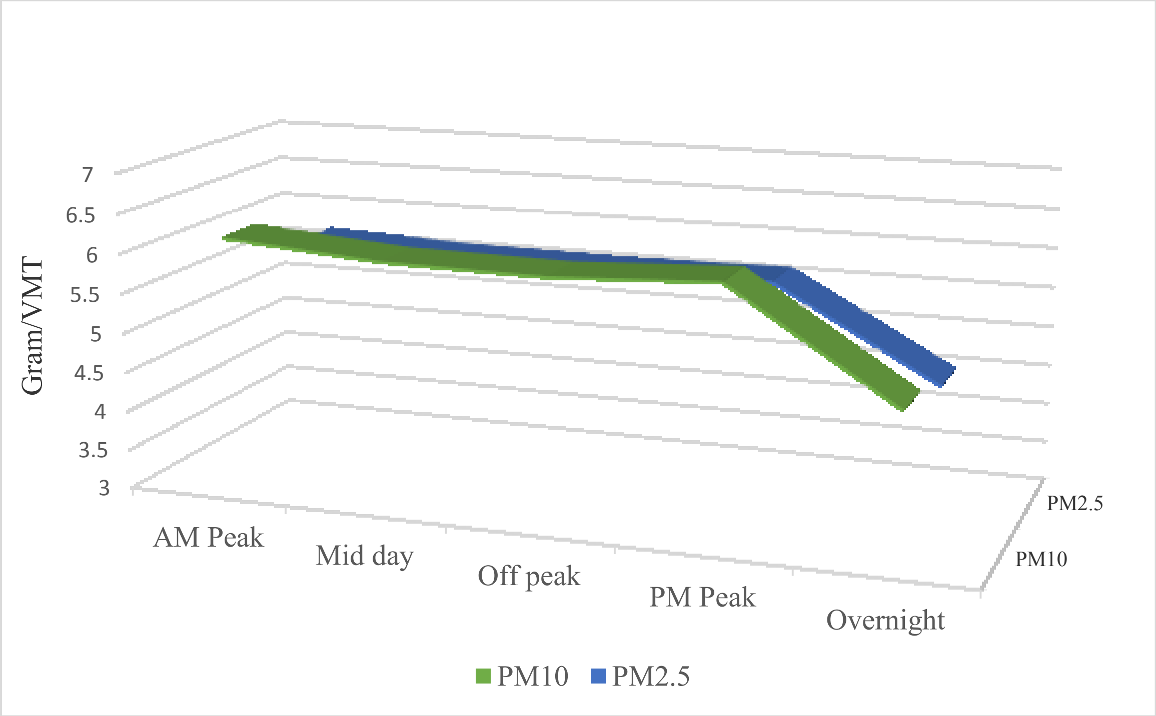

Figure 2-3 Diurnal Variation of Emissions per Vehicle Mile Travelled for PM_{10} and $PM_{2.5}$

Table 2-2 Relative Difference in Emission Rates in AM peak, Midday, Off Peak, PM Peak and Overnight Periods Compared to Daily Average Emission Rate

	Percentage (%) Difference in Emission Rates			
Time	**CO**	**NOx**	**PM_{10}**	**$PM_{2.5}$**
AM peak	15.327%	8.711%	5.881%	5.091%
Midday	9.810%	4.157%	3.476%	3.757%
Off peak	9.8105%	3.645%	3.166%	3.446%
PM peak	15.327%	8.711%	5.012%	4.233%
Overnight	-50.274%	-25.224%	-17.535%	-16.527%

** Positive and negative values indicate increase and decrease in emission rates with respect to daily average emission rate respectively

2.5.2 Contribution of Different Transportation Modes in Emissions

Figure 2-4 illustrates the hourly CO, NOx, PM_{10} and $PM_{2.5}$ emissions of different vehicle types in the AM peak, midday, off peak, PM peak and overnight time periods, normalized by link length. A significantly large percentage of pollutants are emitted daily from combination long-haul trucks, ranging from 12.84% to 13.99 % of total CO, 65.17% to 66.72% of total NOx, 70.09% to 73.56% of total PM_{10}, and 70.94% to 73.51% of total $PM_{2.5}$ emissions. Single unit short-haul trucks also contribute significantly to emissions, ranging from 50.30% to 51.30% of total CO, 25.89% to 27.45% of total NOx, 16.495% to 19.70% of total PM_{10}, and 17.30% to 19.42% of total $PM_{2.5}$ emissions. In comparison to emissions from trucks, passenger cars emit a lower amount of air pollutants (NOx, PM_{10} and $PM_{2.5}$), ranging from 3.79% to 5.21 % of total NOx, 5.39% to 7.09% of total PM_{10} and 5.23% to 6.32% of total $PM_{2.5}$ emissions. The model results suggest that NOx, PM_{10} and $PM_{2.5}$ are the most prevailing pollutants produced by the combination long-haul trucks. On the other hand, the highest amounts of CO are produced by the single unit short-haul trucks and passenger car compared to other modes.

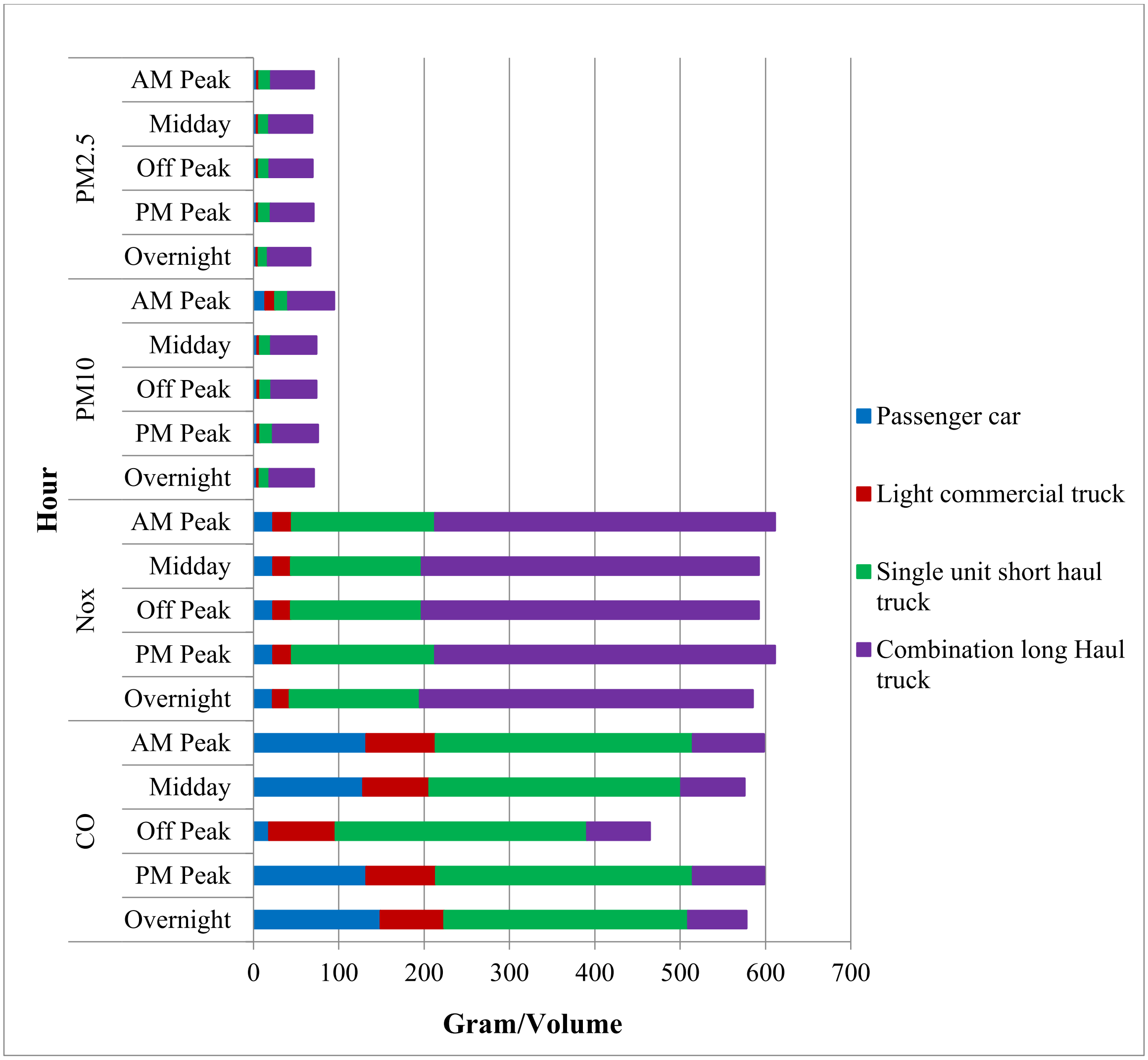

Figure 2-4 Hourly CO, NOx, PM10 and PM2.5 Emissions per Volume (g/volume) in AM peak, Midday, Off peak, PM peak and Overnight Periods

Overall, the emission model results indicate that trucks greatly contribute to the total emissions on the Halifax peninsular truck route as compared to other modes.

2.5.3 Results of Policy Scenario Testing

As trucks contribute the greatest proportion of total emissions, two policy scenarios are tested to determine the results of altering the truck access to the study route, as well as to identify the better policy scenario for reducing total emissions. In the base scenario 1, the study estimates a daily average emission rate of 41.954 g/VMT, 44.607g/VMT, 5.804 g/VMT, and 5.407 g/VMT for CO, NOx, PM_{10} and $PM_{2.5}$ respectively.

Figure 2-5 summarizes the relative reduction in air pollution in scenarios 2 and 3 (i.e. policy scenarios) in comparison to the base case scenario 1. It is evident that the strategy of a ban on all trucks if implemented (i.e. scenario 2), the amount of emissions is drastically reduced. In scenario 2, where trucks are restricted for 24 hours of the day, the route experiences a reduction of 51.733%, 54.096%, and 64.905% of PM_{10}, $PM_{2.5,}$ and NOx emissions respectively. This is because a large percentage of PM_{10}, $PM_{2.5,}$ and NOx emissions are produced from the running emissions of trucks compared to passenger cars. In the case of CO, the reduction percentage is 9.526 % in scenario 2, which is comparatively less than other pollutants.

In scenario 3, which assumes that trucks are banned from the route in AM peak, midday, and PM peak periods and allowed to run only in off peak and overnight periods till 9 pm, emission reduction percentages for PM_{10}, $PM_{2.5,}$ and NOx are 21.158%, 22.522%, and 27.207% respectively which is considered very significant.

Therefore, the results indicate that the policy of removing all trucks for the entire day achieves the best emission reductions for this specific study route. However, banning the trucks for entire day is quite extreme that might have economic impact; instead limiting trucks to certain period of the day may be a reasonable solution to reduce vehicular emissions along this route while avoiding much public discontent.

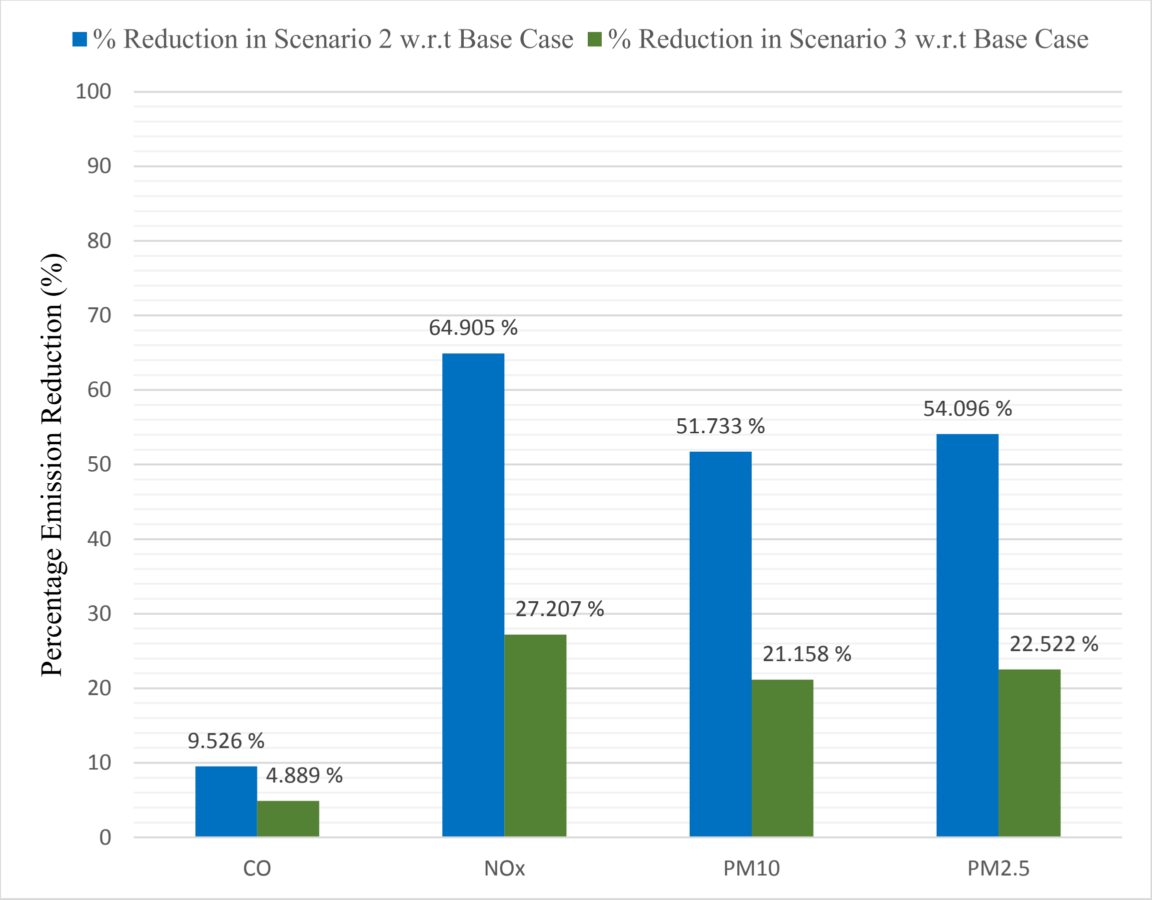

Figure 2-5 Percent Reduction of Daily Emissions in Scenario 2 and 3 from Base Case Scenario 1

Figure 2-6 to Figure 2-9 present the relative difference in emission rates from the link average emission rate of the Halifax peninsular truck route during the AM peak hour for CO, NOx, PM_{10} and $PM_{2.5}$. Emission rate patterns are found very similar in the AM peak and PM peak time periods. Moreover, in the midday and off peak periods, the emission rate patterns are almost same.

Relative difference in emission rates from link average emission rate in midday, off peak, PM peak and overnight periods are presented in Appendix A.

This study also focuses on identifying hot spots with the maximum concentration of pollutants. In this study, hot spots are defined as the links with relatively high emission rates compared to the link average emission rate. This study finds that 17% of total links in the route have considerably higher pollutant concentrations that may cause severe long-term health impacts to residents. The hot spots are located on Barrington Street between Africville Road and Glebe Street, Barrington Street between North Marginal Road and Devonshire Avenue, Barrington Street between Cornwallis Street and Cogswell Street to Upper Water Street via ramp Cogs-4A as identified in Figure 2-6 to Figure 2-9. It can be concluded from this study that priority steps should be taken to minimize the severity of air pollution in these hot spots.

Figure 2-6 Relative Difference in CO Emission Rates from Link Average Emission Rate in AM Peak

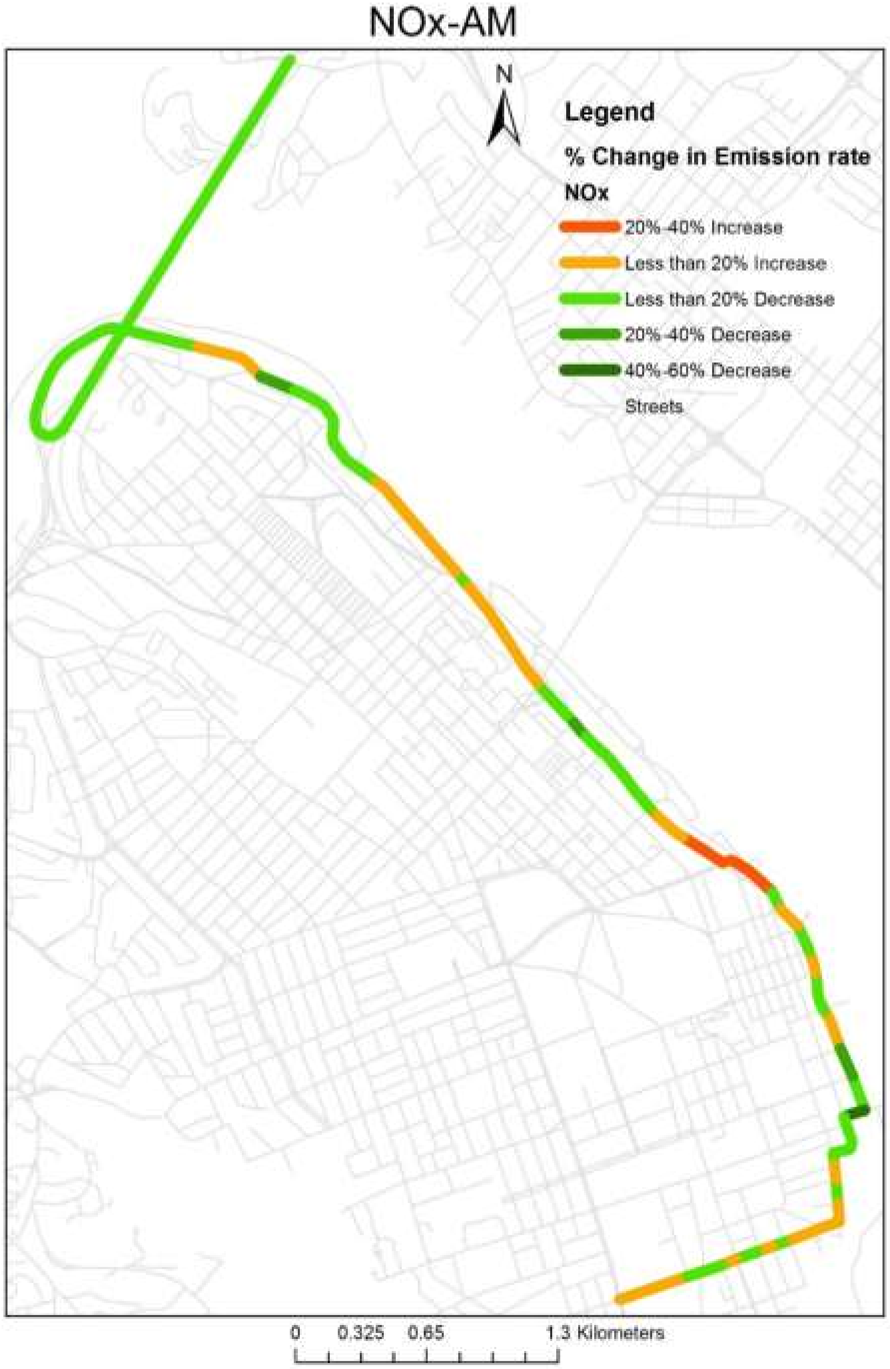

Figure 2-7 Relative Difference in NOx Emission Rates from Link Average Emission Rate in AM Peak

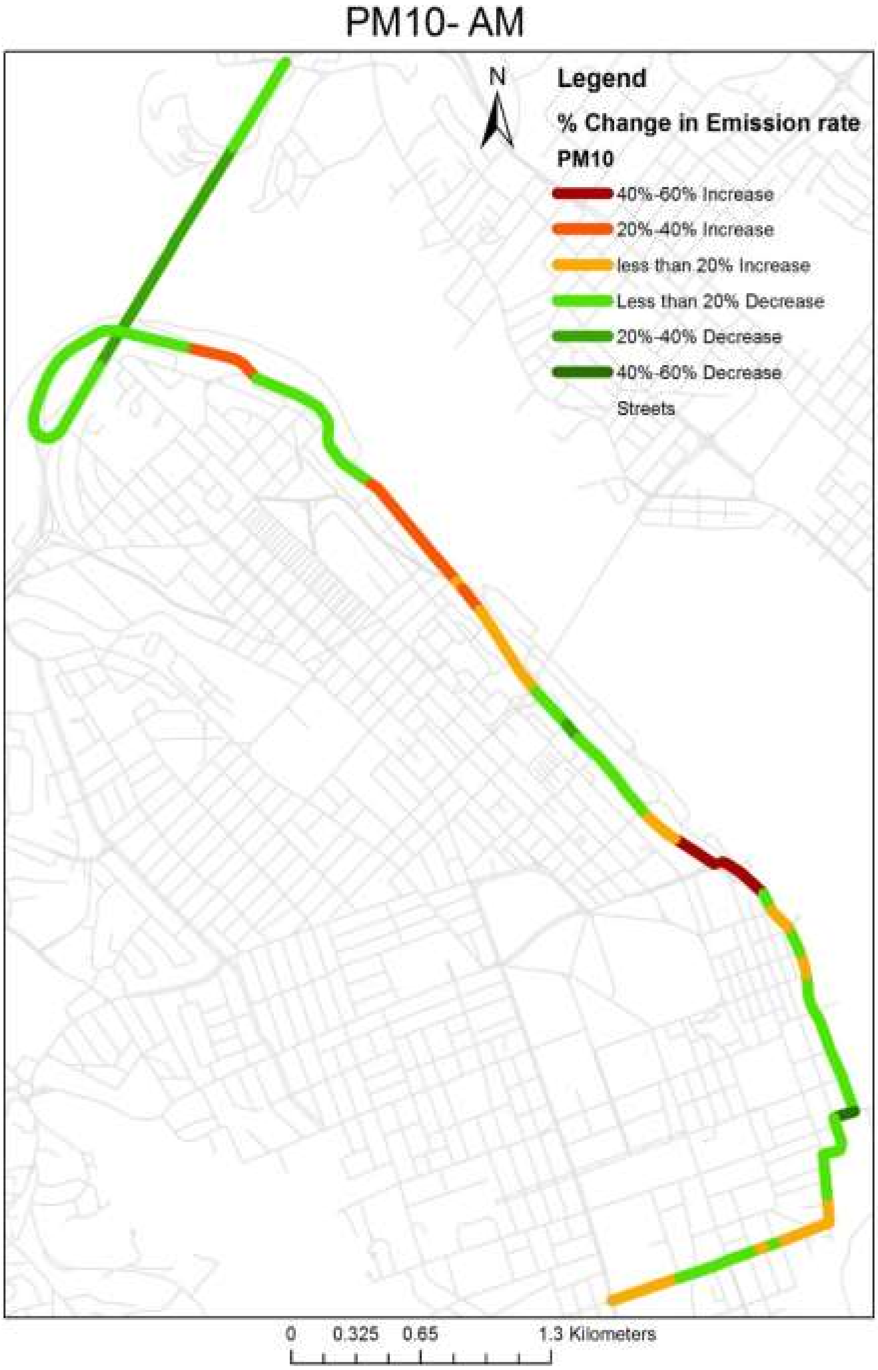

Figure 2-8 Relative Difference in PM_{10} Emission Rates from Link Average Emission Rate in AM Peak

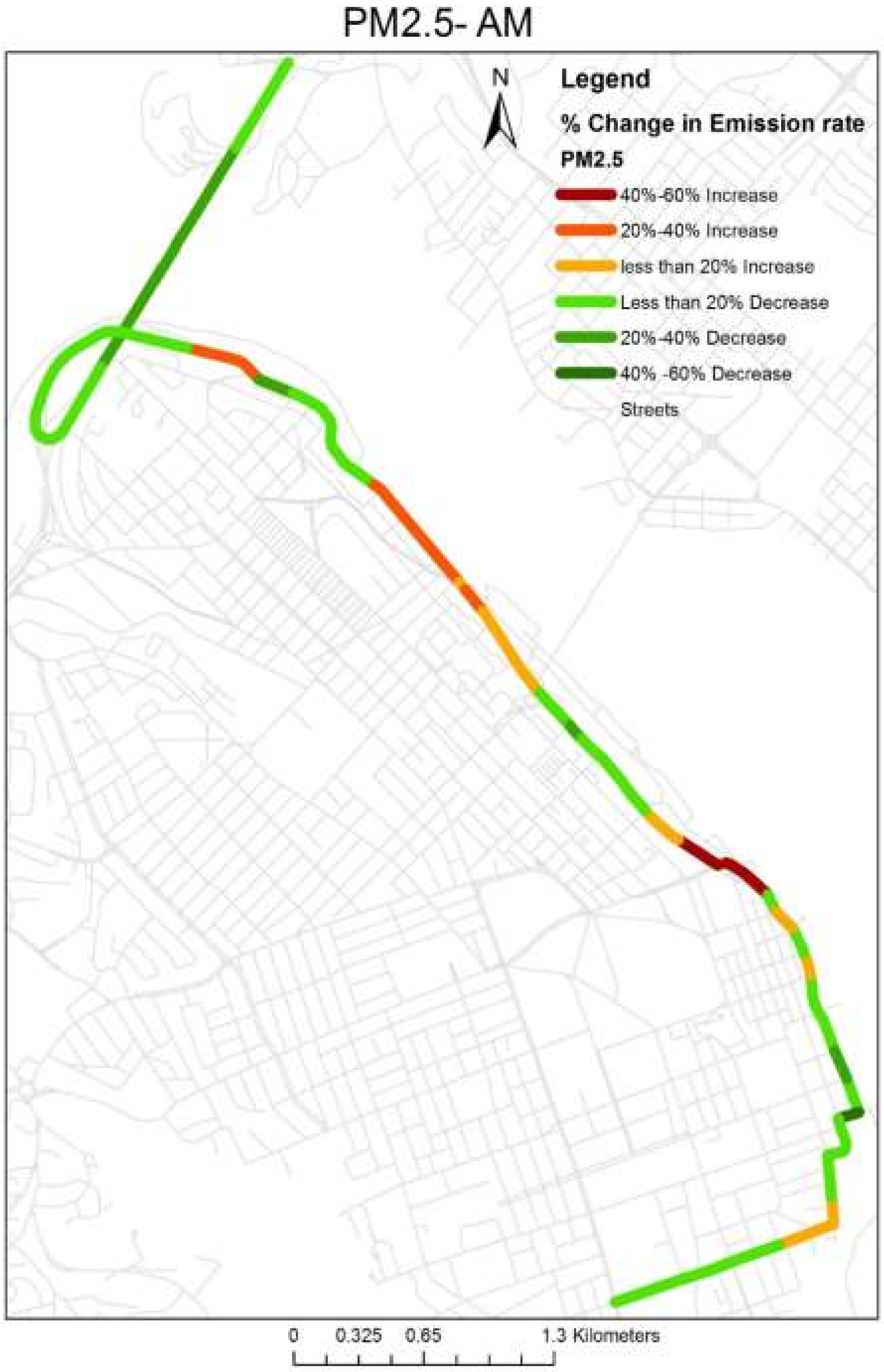

Figure 2-9 Relative Difference in PM2.5 Emission Rates from Link Average Emission Rate in AM Peak

2.6 Conclusion

This study evaluates the motor vehicle emissions of a major truck route on the Halifax peninsula of Nova Scotia, Canada. The research demonstrates a real-world application of emission modelling to estimate CO, NOx, PM_{10} and $PM_{2.5}$ emissions. The study also investigates the contribution of the trucks to total traffic emissions of CO, NOx, PM_{10} and $PM_{2.5}$ at the aggregate and link level. Air pollutant concentrations are highest during peak periods when the traffic volumes are high. It is found that existing truck traffic contributes significantly to the total emissions. Finally, the study presents a comparative assessment of two scenarios, including potential strategies to reduce emissions in the given route. A ban on all trucks along the route significantly reduces all types of emissions in comparison to the business-as-usual scenario. However limiting trucks at certain time periods also considerably reduces the amount of pollutants, ranging from 4.889 % (CO) to 27.207% (NOx).

The study has certain limitations including use of average speed as vehicle activity in emission modelling as detailed speed profile for many road segments were unavailable. Development of instantaneous speed information such as second by second acceleration, deceleration, idling, and cruising profile is required for finer scale, detailed analysis. Nevertheless, this study contributes to the existing literature by investigating vehicular emissions at both the aggregate and link level using real-word data, and applies these findings to different policy scenarios towards long term emission reductions. Particularly the application of emission modelling on a contentious truck route that runs through the downtown where considerable residential density exists is significant for public policy making. Future work should be taken to conduct an in-depth assessment of the major contributing factors of the hot spots in the Halifax peninsular truck route.

Chapter 3

Microsimulation–based Emission Model for a Major Infrastructure Renewal Plan in Downtown Halifax [2]

3.1 Chapter Overview

This study demonstrates a comprehensive microsimulation-based emission modelling framework for a 15.37 km (9.55 mile) long road network in the Halifax Downtown Core, Canada. The study develops a sequential microscopic traffic simulation and emission modelling tool to estimate vehicular emissions at a finer spatial resolution utilizing instantaneous speed profiles. The study evaluates the impacts of a major infrastructure renewal plan focusing on re-building a part of the expressway in the Downtown Core (i.e. the replacement of multi-grade signalized intersections at the Cogswell Interchange with roundabouts and associated network improvements). Emissions are estimated for six major criteria pollutants, including GHG, CO, NOx, SO_2, PM_{10} and $PM_{2.5.}$ The model results suggest significant changes in emission patterns as a result of implementing the infrastructure renewal plan. The study evaluates the sensitivity of different traffic attributes along with their isolated and combined effect on emission variation.

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[2] This Chapter is partially based on the **conditionally excepted Journal paper** Irin, S., and Habib, M.A. "Microsimulation-based Emission Modeling for a Major Infrastructure renewal Plan: An Assessment of Network attributes and Land Use Effects on Vehicular Emissions", *Transportation Research Records*, Journal of Transportation Research Board, and to be presented at 95th Annual Meeting of Transportation Research Board, Washington, D.C., USA, January 10-14, 2016.

Finally, a land use regression model is developed to examine the potential effect of land use and built environment attributes on emissions. Overall, the microscopic emission model results will assist transportation engineers and planners to consider strategies on mitigating air pollution in the final design process and implementation of the infrastructure renewal plan.

The organization of this chapter is as follows: it begins with a brief review of relevant literature, followed by a brief description of data and methodology. Next, the results of the study are presented and discussed. Finally, the chapter concludes with a summary of conclusion and the practical application of the research.

3.2 Introduction

Air quality deterioration resulting from an increasing trend of vehicular emissions in urban areas is becoming a critical health concern. Vehicular emissions are responsible for several health diseases, such as respiratory (*Suresh et al., 2000; Preutthipan et al., 2004*) and cardiovascular diseases (*Brunekreef et al., 2009*), asthma (*Preutthipan et al., 2004*), lung damage (*Suresh et al., 2000*) and premature death (*Künzli et al., 2000*). Residents and commuters in the urban core of cities are perhaps most venerable to near-roadway emissions. As a part of the sustainable transportation strategies, many cities are adopting policies and plans to reduce vehicular emissions. Also, cities are undertaking infrastructure renewal plans to replace aging infrastructure (*Sahely et al., 2005*). Prior to the implementation of an infrastructure renewal plan, it is imperative to examine vehicular emissions to better understand the effects of major transportation investments. This study presents findings of comprehensive emission modelling framework that combines a microscopic traffic simulation model to estimate and evaluate major pollutants of interest.

Nowadays, many North American cities are investigating the renewal of their aging infrastructure. For example, Toronto is evaluating the Gardiner Expressway for replacement, which is currently under consideration. Similarly, Downtown Halifax, the capital of Nova Scotia, is considering a renewal of the road network, which was a part of a planned but never-built expressway to increase the efficiency of the network and land uses in the urban core of the city. The Cogswell Interchange is a major multi-grade transportation gateway situated on the northern edge of Downtown Halifax connecting the approaching traffic from Dartmouth and Bedford to Halifax. The construction was begun in 1969 as a part of Halifax's plan to build Harbour Drive surrounding the Halifax peninsula, and opened the interchange in 1970 for public use (*Halifax Regional Municipality, and Ekistics Planning and Design, 2014*). The interchange consists of multi-lane roadway links, varying topographic elevations with ramps, underpasses, overpasses, and retaining constructions. It has the capacity to accommodate 90,000 trips daily in and out of the northern portion of Halifax downtown core (*Halifax Regional Municipality, and Ekistics Planning and Design, 2014*).However, the current traffic flow through the interchange indicates that it was overdesigned. Moreover, the interchange occupies 16 acres of valuable prime real estate which is underutilized (*Halifax Regional Municipality, and Ekistics Planning and Design, 2014*). Due to the increasing maintenance cost of this interchange, the Halifax Regional Municipality (HRM) is planning to replace it with at-grade roundabouts and other network improvements.

Therefore, this study develops a sequential microscopic traffic simulation and emission modelling tool to investigate the change in vehicular emissions due to this infrastructure renewal plan. The microscopic traffic simulation model provides finer grain spatial resolution, which includes instantaneous speed profile, including acceleration, deceleration, cruising, and idling.

Therefore, this microsimulation-based emission model enables us a finer grain estimation of vehicular emissions. This study evaluates all major vehicle related pollutants including Greenhouse Gas (GHG) as CO_2-equivalent, Carbon Monoxide (CO), Nitrogen Oxides (NOx), Sulfur Dioxide (SO_2), Particulate Matter PM_{10} and $PM_{2.5}$ based on emission model.

One of the unique contributions of this study is that it evaluates vehicular emissions resulting from a major infrastructure renewal, which is limited in the existing literature. In addition, the study evaluates the isolated and combined effect of network attributes, and develops a land use regression model to examine the effects of built environment characteristics on emissions.

3.3 Description of the Study area

This Study considers the Downtown Core of the city of Halifax in Nova Scotia, Canada as the study corridor. Several major roads such as Cogswell Street, North Park Street, Cornwallis Street, Rainnie Drive, Duke Street and Upper Water Street are connected with the downtown core at the Cogswell Interchange. The study area covers an area of approximately 0.56 km^2 (0.22 $mile^2$) having a total 15.37 km (9.55 mile) of road network with a diversity of road grades ranging from to -11.729% to +11.729%. Figure 3-1 illustrates the outline of the study area. The existing road network has total 98 links and 34 major intersections where 11 of them are signalized. Other intersections are either four way or two way stop sign controlled. A high frequency of transit buses run all day throughout the network as it goes through the downtown Halifax. There are also several major truck routes along the study corridor with operating hours from 7 AM to 9 PM. This study area represents heterogeneous land use with well mixture of residential, commercial and recreational areas. The focus area also has densely populated neighbourhoods which are responsible for generating significant pollutant exposure to humans.

Higher frequency of trip generation, multidirectional traffic flow distribution and having multiple major truck routes, make it an ideal study area for estimating vehicular emissions at link-level.

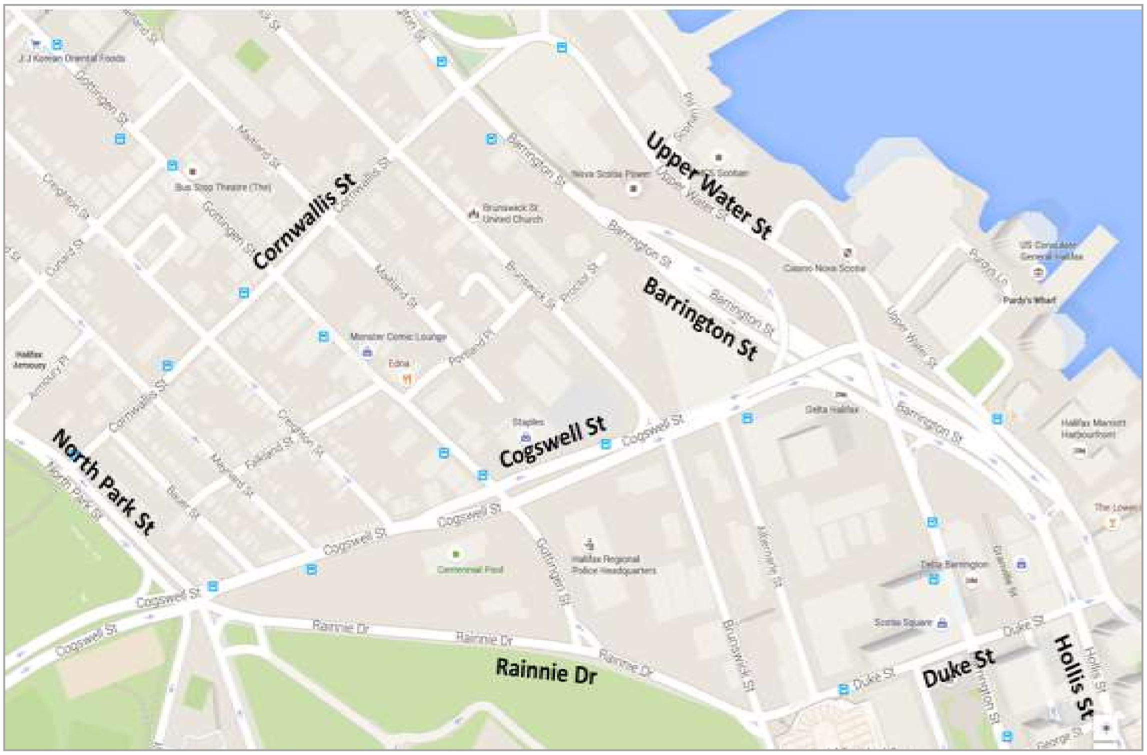


Figure 3-1 An illustration of the Study area

Figure 3-2 illustrates the proposed network of the study area developed by HRM.

Figure 3-2 An illustration of the proposed Scenario by HRM (*Halifax Regional Municipality, and Ekistics Planning and Design, 2014*)

3.4 Literature Review

Emission modelling has emerged as an important tool to assess environmental impacts of different transportation policies and network improvements. Emission models can be broadly categorized into regional level models, area or corridor level models, and traffic operation models as microscopic models. Regional models provide inventory of emissions at macro scale (*Houyoux et al., 2000*). These regional models are comparatively less sensitive to local changes in the network (*Sider et al., 2014*). However, area or corridor level models could reflect better spatial representation of emissions (*Xiong et al., 2015*). These area or corridor level models could be a macroscopic model or mesoscopic model depending on the scale and data availability for emission estimation. Area or corridor level models use simplified assumptions such as average speed as vehicle activity (*Chen et al., 2013; Chan et al., 2013; Irin and Habib, 2015; Xiong et al., 2015*). There are detailed literature reviews comparing different types of emission models (*Sharma and Khare, 2001; Rakha et al., 2003; Abo-Qudais and Qdais, 2005*). In a recent study for instance, Irin and Habib (*2015*) estimated CO, NOx, PM_{10} and $PM_{2.5}$ emissions for a 20.768 kilometer of truck corridor in the Downtown Halifax, Canada where average speed was used as vehicle activity. However, such models cannot capture many network attributes including congestion effects in driving cycles. Use of average speed or such simplifications could result in an overestimation of GHG, CO and NOx emissions (*Alam et al., 2014c*). In contrast, ignoring road grades results an underestimation of emissions at positive grade and overestimation of emissions at negative grade (*Boroujeni and Frey, 2014*). Therefore, microscopic emission models that generate driving cycles with instantaneous speed profiles and other congestion effects could be a better representation of emission studies for critical transportation investments (*Hirschmann et al., 2010; Lin et al., 2011; Abou-Senna and Radwan, 2014a; Yang et al., 2011*). The microscopic traffic simulation model provides vehicle trajectory including acceleration, deceleration, idling, and cruising profile which offers a better spatial and temporal resolution of an emission study (*Ghafghazi and Hatzopoulou, 2014; Sider et al., 2014; Burghout et al., 2005*).

There is a growing interest in microscopic emission models by combining microscopic traffic simulation models with emission models to quantify the effect of local level changes on air quality. For instance, Zhang et al. (*2009*) observed the impacts of signal timing and traffic flow management on emissions. They (*Zhang et al., 2009*) found that CO and HC emissions decrease by signal coordination, however, NOx emissions are reduced by traffic flow management. Lv and Zhang (*2012*) examined the effect of signal synchronization to analyse the influence of different cycle lengths on emissions. They (*Lv and Zhang, 2012*) concluded that long signal cycles increase delays per vehicle significantly, whereas the effect is minor on increasing emissions of CO, HC and NO. Ghafghazi and Hatzopoulou (*2014*) evaluated the effect of traffic calming in a small area of the Plateau, Montreal and observed that traffic calming measures at the corridor level increase CO emissions by 0.3 %, CO_2 by 1.5 %, and NOx by 1.5 %, whereas area wide implementation of traffic calming measures increase CO, CO_2, NOx emissions by 1.2%, 3.8 % and 2.2 %, although total VKT on the network decreases. Panis et al. (*2006*) demonstrated an Integrated Traffic Emission Model (ITEM) and concluded that higher frequency of acceleration and deceleration reduces the benefit of speed management policy on emission reductions. In another study by Abou-Senna and Radwan (*2014a*) found that speeds between 55 mph to 60 mph, with traffic volume level up to 90% of the road capacity emit the minimum recorded CO_2 per vehicle mile. Mahmod et al. (*2010*) investigated the impact of different traffic control measures on emissions for the Bentinckplein intersection of the Rotterdam City, Netherlands. They (*Mahmod et al., 2010*) revealed that a reduction in traffic demand decreases CO_2, PM_{10} and NOx emissions by 23%; banning of heavy duty vehicle decreases emissions by 25% to 50 %; and speed restriction decreases CO_2 emissions by 7%, and increases NOx and PM_{10} emissions by 1% and 31% respectively. Moreover, Adaptive Cruise Control (ACC) reduces CO_2 and NOx emissions by 3% and increase PM_{10} emissions by 3%. Huang et al. (*2009*) revealed that disrupted traffic flow due to the pavement redevelopment project of the road segment A-34 in UK increases pollutant emissions, which ranges from 0.1% to 5.5%. A study by Alam et al. (*2014c*) found that closing street in the Plateau borough area achieves the lowest CO_2 emission reduction (0.98%), followed by CO (2%) and NOx (3%). On the other hand, reduction in through traffic achieves the maximum CO_2 reduction (29%), followed by NOx (28%) and CO (27%). Abou-Senna and Radwan (*2014b*) examined a 10 mile long urban highway I-4 in Orlando, Florida and observed that the implementation of managed lanes (MLs) reduces CO, NOx, and CO_2 emissions. Alam and Hatzopoulou (*2014a*) simulated a 5.1 km long corridor in Montreal and revealed that the implementation of Transit Signal Priority (TSP) reduces GHG emissions by 14%. Moreover, they (*Alam and Hatzopoulou, 2014a*) observed that the benefit of TSP decreases in extremely congested networks. They (*Alam and Hatzopoulou, 2014a*) also found that Compressed Natural Gas (CNG) can reduce GHG emissions by 8% to 12% compared to diesel fuel, and the benefit of CNG increases in lower network speed.

Although microscopic emission modelling has emerged as a way to investigate the effects of emissions, the majority of these microscopic emission studies have focused on analyzing the impacts of traffic signal synchronization (*Zhang et al., 2009; Lv and Zhang, 2012*), changes in road network speed (*Panis et al., 2006; Abou-Senna and Radwan, 2014a; Ghafghazi and Hatzopoulou, 2014*), changes in traffic flow (*Mahmod et al., 2010; Abou-Senna and Radwan, 2014b; Alam et al., 2014c*), and changes in fuel types (*Alam and Hatzopoulou 2014a; Alam and Hatzopoulou 2014b*) on emissions. Limited studies have examined how major infrastructure renewal could affect emissions using microscopic traffic simulation techniques. Toronto's Gardener Expressway reconfiguration project, for instance, used an inventory-based regional air quality and GHG emission estimation to evaluate the removal of the 2.4 kilometer east elevated segment of the Gardiner expressway (*John Livey, 2014*). The study (*John Livey, 2014*) used mobile 6.2C model and concluded that the removal of the expressway has the least air quality burden contribution at 0.24%. However they (*John Livey, 2014*) analyzed emissions at the regional level instead of using a finer level microscopic emission modelling technique.

Therefore, this study aims to fill the gap in the literature by estimating the changes in emissions at the micro level for a $125 million major infrastructure renewal in the Halifax Downtown Core (*Halifax Regional Municipality, and Ekistics Planning and Design, 2014*). The study also evaluates the sensitivity of different traffic attributes along with their isolated and combined effects to better understand emission variations. Several recent studies examined these aspects utilizing microscopic traffic trajectory information. For instance, Khan and Clark (*2010*) concluded that the real effect of grades on fuel consumption and emissions can be fully captured only by considering vehicle speed and road grade simultaneously. Examination of combined effects of speed and grades are vital, particularly if grades vary significantly within short intervals, such as Halifax Downtown core. The analysis is also relevant since this study considers the replacement of multi-grade signalized intersections with at-grade roundabouts. The study extends this approach by developing a Digital Elevation Model (DEM) using Geographic Information Systems (GIS) platform (Figure 3-14) for the Halifax Downtown core and utilizes a simulated local drive cycle to better understand the effect of traffic attributes on emissions with respect to the Canadian context.

3.5 Methodology

This study proposes a comprehensive, sequential microsimulation-based traffic and emission modelling framework to assess a major renewal plan in Halifax downtown core. Figure 3-3 illustrates the conceptual framework for the sequential microscopic traffic simulation and emission model. The sequential emission model is developed in the following two stages: 1) Traffic simulation, and 2) Emission modelling. The first stage involves the development of microscopic traffic simulation models to replicate the existing network (business-as-usual scenario), and proposed at-grade network resulting from the implementation of infrastructure renewal plan. Traffic volume and speed trajectory data are extracted from the traffic simulation models developed in the first stage, which are then used as input data for the emission model developed in the second stage. In the second stage, emissions are calculated for both networks to investigate the effect of network attributes on vehicular emissions. Finally, a land use regression model is developed for each pollutant to capture the potential effect of land use and built environment attributes on emission rates. Details of these stages are discussed below.

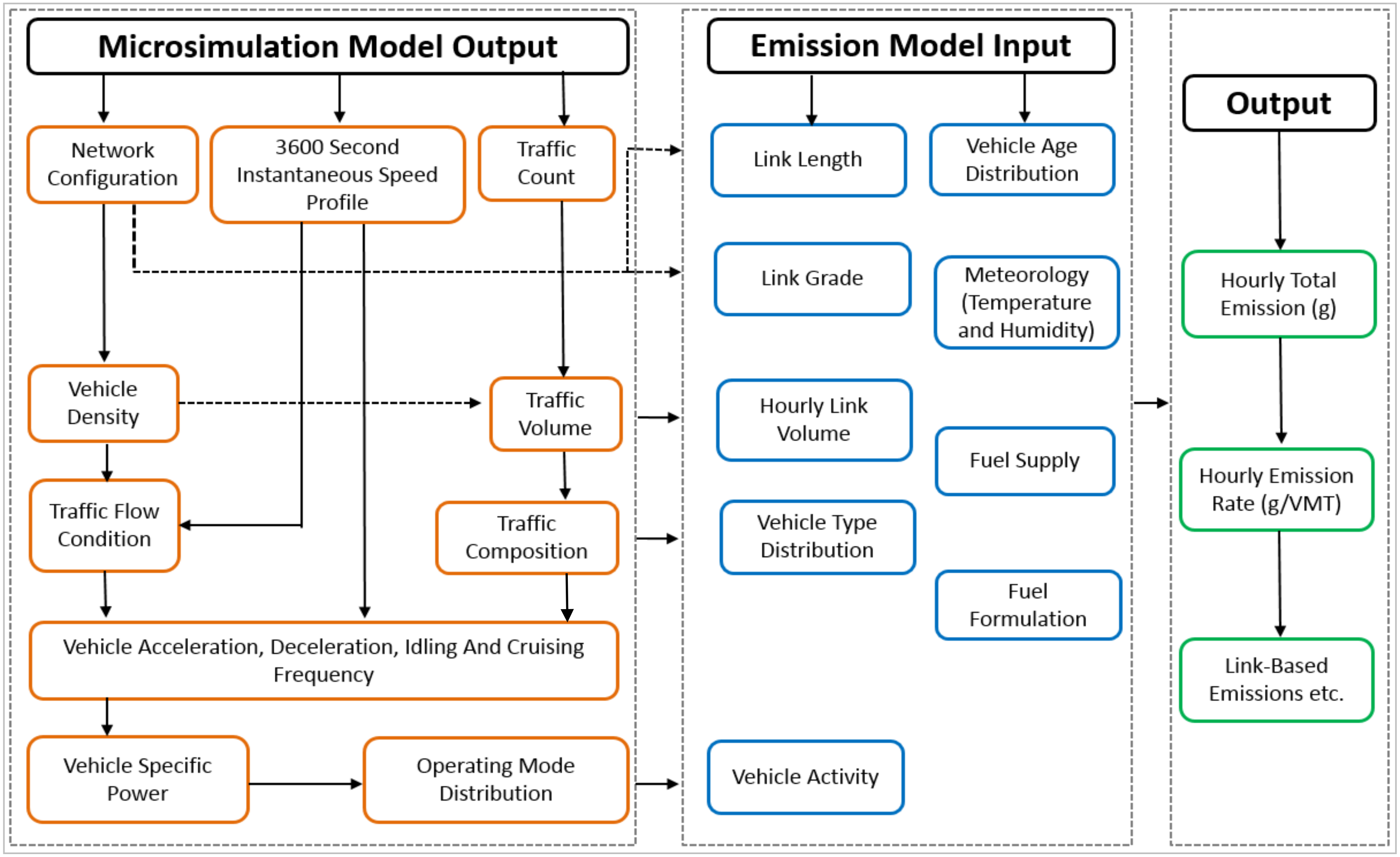


Figure 3-3 Conceptual Framework for the Sequential Microscopic Traffic Simulation and Emission Model

3.5.1 Traffic Simulation

A microscopic traffic simulation model is developed for the existing network of study area, which includes 15.37 km of road network. The following procedure includes network coding and simulation modelling, model validation, scenario building, simulation runs, and post processing.

3.5.1.1 Network Coding and Simulation Modelling

The network model of the existing (business-as-usual) scenario is developed based on Halifax Regional Municipality (HRM) Public Works traffic study in October 2014 using PTV VISSIM 6 platform (*PTV Group, 2015*). VISSIM is a traffic microsimulation tool which is used to simulate vehicles and their instantaneous speed profiles. Road geometry data is obtained from various sources including HRM's Spatial geo-database 2012, Goggle Earth, and field survey.

The network model consists of 98 links, 306 link connectors, and 129 origin-destination paths to assign the vehicles in the road network. The network model includes auto, transit, and truck routes according to HRM's Spatial geo-database 2012. Moreover, 31 Bus stops, 2 parking lots, and other network attributes are coded into the network with relevant dwelling time for boarding passengers and parking data collected from the field survey. The posted speed limit is used 50 km/hr since most of the roads are local. Based on this value, desired speed value is set as 40 km/hr and 30 km/hr for passenger cars and heavy duty vehicles respectively. A total 183 reduce speed areas (12 km/hr) are allocated in the network for turning movement. These values are incorporated based on multiple observations through field visits. Moreover, 21 stop signs and 11 signal controllers utilizing three timing schemes are placed in the network. Traffic signal data is collected from the HRM that represents signal timing scheme. Three types of signal timing schemes are identified as plan-1 (activated in off peak period), plan-2 (activated from 7:00 AM to 9:15 AM), and plan-3 (activated from 3:45PM to 6:00 PM), which are used to mimic realistic traffic signal timing for the modelling period. A total of 895 vehicular conflict areas at the intersections are resolved by applying the Right-of-way rules. Other traffic control measures such as, turning restrictions and priority rules are coded into the network to make the traffic simulation model more realistic and representative of the actual road configurations. After coding the network, simulation is conducted for AM peak (8AM - 9AM), off peak (12 PM - 1PM), and PM peak (4PM - 5PM) periods of a typical busy weekday in fall months. Multiple simulation runs are conducted to receive a visual confirmation of realistic driving behaviour and vehicular movement along with acceptable speed distribution and reasonable queue length in the links.

An example of coded intersection showing all network elements is illustrated in Figure 3-4. The coded network for the business-as-usual scenario is presented in Figure 3-5.

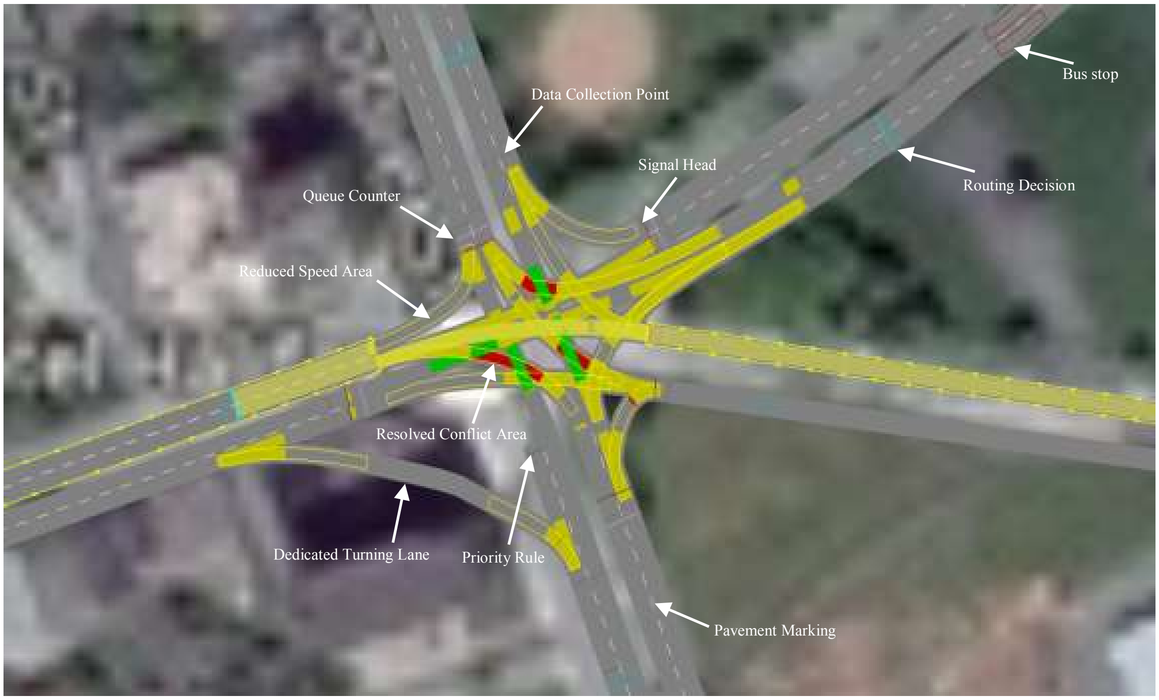


Figure 3-4 Network Coding

Figure 3-5 Coded Network for business-as-usual scenario (with Cogswell Interchange)

3.5.1.2 Model Validation

In developing a microscopic traffic simulation model, the basic principle is to make the model a better replica of the actual road network. Assuring proper driving behaviour by obeying all traffic rules in the roads make the model more efficient and effective. Therefore, it requires some adjustment of model parameters through calibration to achieve the best match between field data and simulated data (*Milam and Choa, 2002; Barceló 2010; Jobanputra and Vanderschuren, 2012*).Calibration needs to be multilayered iterative process to create the microsimulation model symbolic to local condition (*Dowling et al., 2004*) though there is no formal guideline for standard calibration process in transportation policy to follow (*Sacks et al., 2002; Jobanputra and Vanderschuren, 2012*).

Eight major peripheral intersections (shown in Figure 3-6) of the study area are selected to generate calibration parameters for the model.

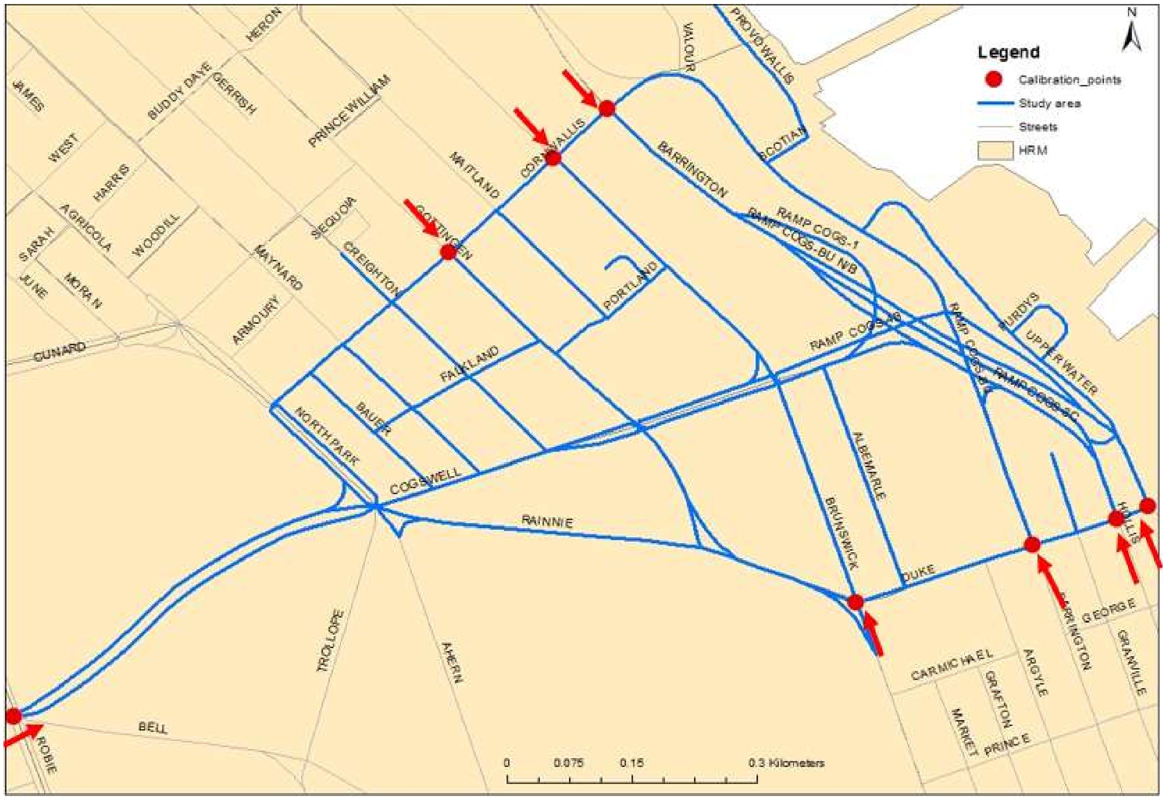


Figure 3-6 Intersections Used in the Calibration Process

The psychological driving behaviour is modeled based on Wiedemann 74 car following model which is used for urban motorized road networks. Vehicles are modelled to run along the right side of the road. Driver awareness and aggressiveness, vehicular headway and gap distance are modelled based on standard values to achieve realistic results. The following Table 3-1 shows other calibration parameters and their standard values used in the calibration process.

Table 3-1 Calibration parameters with standard values

Calibration Parameters	**Values**
Standstill distance	0.5 m
Lane change distance	200 m
Minimum headway (front/rear)	0.5 m
Waiting time before diffusion	60 s
No. of observed vehicles	4
Emergency stop distance	5m
Lane change deceleration rate	$-1m/s^2$ to $-3m/s^2$
Reaction time	0.4 s
Probability factors	$\alpha = 1.59$, $\beta 1 = -0.26$, $\beta 2 = 0.27$

According to the literature (*Milam and Choa, 2002; Barceló 2010; Jobanputra and Vanderschuren, 2012*), model validation means verify the model value with real world data to ensure the model accuracy. Simulated directional traffic volume data of 12 major intersections based on 99 data collection points in the study network are validated with field traffic volume. Directional field traffic volume data at intersections are obtained from video image processing using Miovision technology, based on the traffic study by HRM. Table 3-2 displays hourly field traffic volumes for the selected intersections in different time periods.

Table 3-2 Hourly Traffic Volume in AM peak, off peak and PM peak periods

Intersection Name	AM Peak	Off Peak	PM Peak
Brunswick@Cornwallis	1031	487	770
Barrington@Cornwallis	3157	2053	3341
Brunswick@Duke&Rannie	1828	1165	1879
Barrington @ Duke	1097	1029	2428
Duke @ Hollis	1145	794	1565
Gottingen @Cornwallis	1276	1041	1379
Robie @ Quinpool Cogswell & Bell	3185	2856	3158
Upper Water @ Duke	643	665	1245

Validation of the model is performed for the following two performance measure criteria adopted from US and international guidelines: the coefficient of determination (R^2) and GEH statistics. R^2 is used to measure the goodness of fit of the linear regression model. The scatter plots of simulated and field traffic volume reveal that the R^2 values for the AM peak, off peak, and PM peak periods are 0.866, 0.896, and 0.857 respectively (Figure 3-7 to Figure 3.9). These values signify a reasonable correlation between simulated and field traffic volume, which indicates that the microscopic traffic simulation model offers a good depiction of real road configuration and actual driving behaviour.

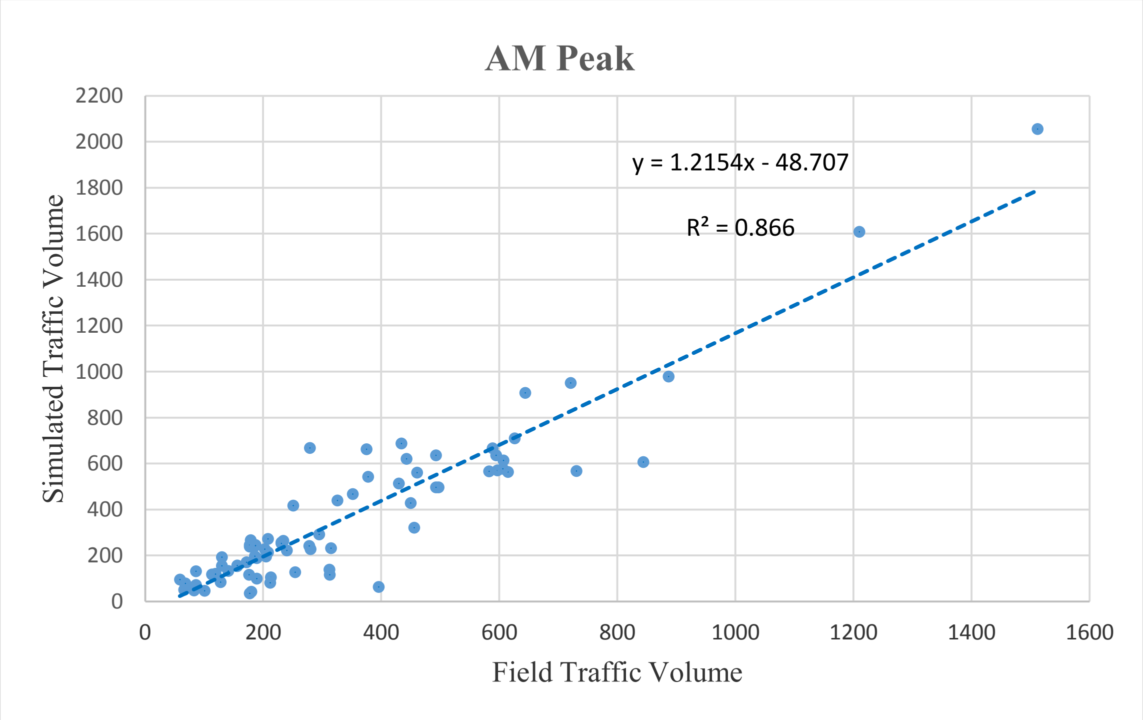


Figure 3-7 Comparison between Simulated and Field Traffic Volume in AM Peak Period

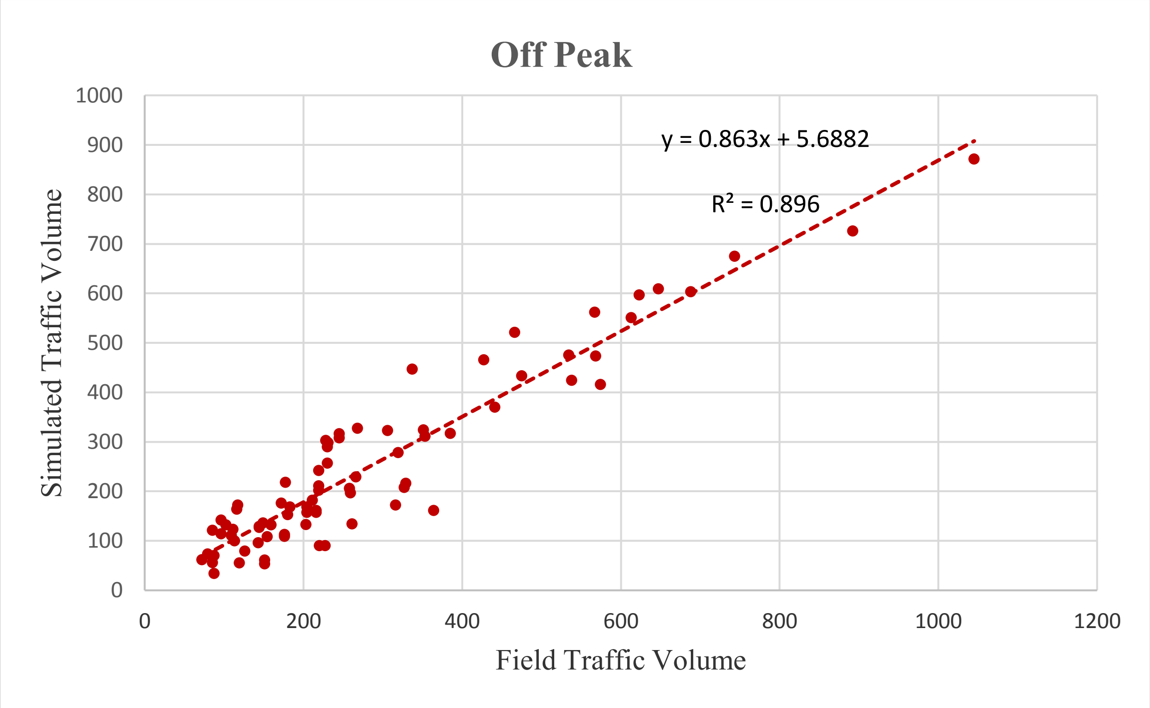


Figure 3-8 Comparison between Simulated and Field Traffic Volume in off Peak Period

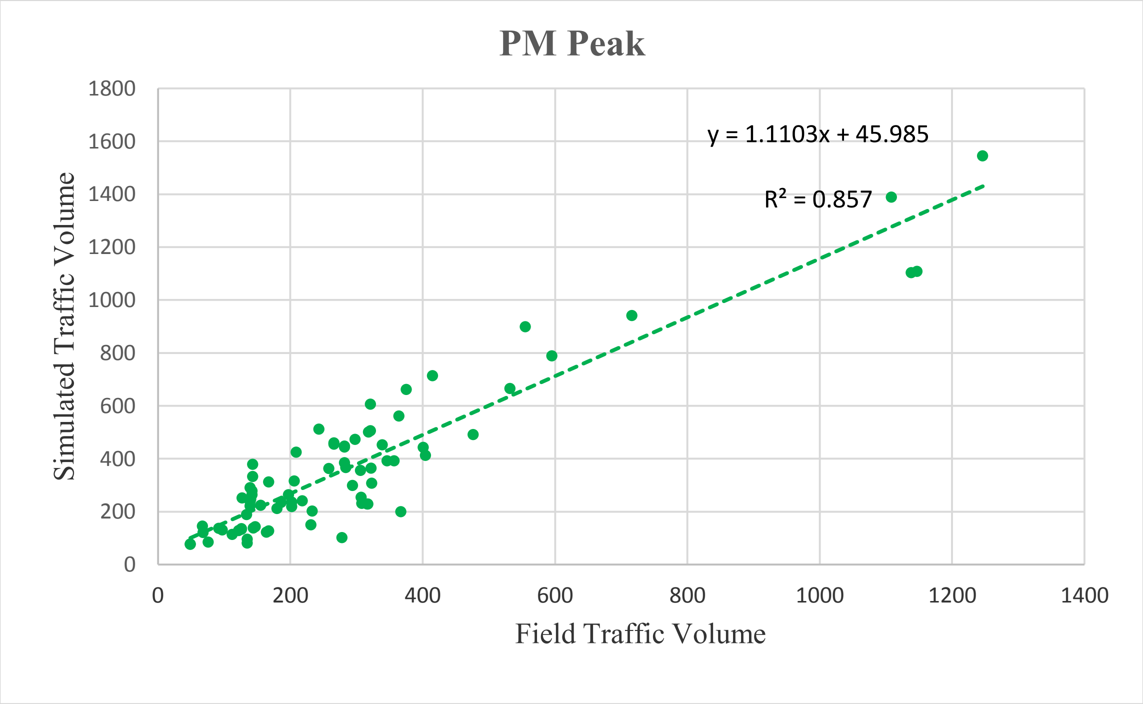


Figure 3-9 Comparison between Simulated and Field Traffic Volume in PM Peak Period

Additionally, GEH statistic is a modified form of chi squared statistic which is also used to detect the relative difference between the simulated and field traffic volume. It is expressed by the equation (1) as shown below:

$$GEH = \sqrt{\frac{2(S-F)^2}{S+F}} \qquad (1)$$

Where, S is the simulated traffic volume obtained from the model and F is the observed traffic volume through the field survey. Note that, hourly traffic volume is used to calculate the GEH value.

The GEH value also determines the goodness of fit of the traffic simulation model. A GEH value smaller than 5 represents a good match between simulated and field traffic volume. If the GEH value is between 5 and 10, investigation may be required to make the model more representative of the real world. On the other hand, if the GEH value is greater than 10, it represents a bad fit between the simulated volume and field volume. In that case more investigation and calibration techniques are strongly recommended to improve the accuracy of the model (*Oketch and Carrick, 2005*).

Overall GEH values of the network estimated for the AM peak, off peak and PM peak periods are 4.79, 3.76, and 5.7, respectively, which indicates a close match between simulated and field traffic volume.

Moreover, four routes are selected around the study area for travel time validation and the results for AM peak, off peak and PM periods are shown in Table 3-3. It is observed that in most cases, modelled travel time is higher than the field travel time. The difference can be demonstrated by the fact that only one observation has been made for each route to estimate field travel time. On the other hand, the microscopic traffic simulation model provides the hourly average value of travel time for each route. The variation between simulated and field traffic volume is also responsible for this travel time deviation. However, travel time validation shows only 5.17% error between simulated travel time and field travel time, which is consistent with other studies. Overall, the validation results based on the above mentioned measures of effectiveness allow us to accept the results of the traffic simulation model.

Table 3-3 Travel Time Validation

Route	Travel Time in AM Peak		Travel Time in off Peak		Travel Time in PM Peak	
	Field (mm:ss)	Modelled (mm:ss)	Field (mm:ss)	Modelled (mm:ss)	Field (mm:ss)	Modelled (mm:ss)
Upper Water@ Duke to North Park @ Cogswell	3:21	3: 30	2:48	3: 41	3:45	3:58
Barrington @Duke to Barrington @Upper Water	2:08	2:20	1:38	1:55	2:34	2:46
Barrington @Cornwallis to North Park@ Cornwallis	1:02	2: 14	2:08	3:50	1:06	2: 38
North Park@ Cogswell to Upper Water @Duke	3:34	3:42	3:09	2:03	2:21	2:23

3.5.1.3 Scenario Building

The traffic simulation model of the proposed at-grade network is developed using the design and the dimensions from a technical drawing in the consultancy report by HRM (*Halifax Regional Municipality, and Ekistics Planning and Design, 2014*). It is assumed that traffic demand will remain same in the proposed network. The proposed network is coded on the basis of similar assumptions and techniques applied for developing the model of the existing network. Additional priority rules are implemented in the roundabout area with minimum headway 5 meter and minimum gap time 3 second. Note that vehicles in roundabouts are modelled to flow counter clockwise around the central island. It is ensured that vehicles will wait at the entry of roundabouts for a safe gap by giving the right of way (ROW) to the vehicles in the roundabouts. The traffic simulation model of the proposed network consists of 111 links, 347 link connectors, 11 signal controllers, 22 stop signs, and 133 origin-destination paths. Figure 3-10 illustrates the coded network for the proposed at-grade Network.

Figure 3-10 Proposed at-grade Network (with Roundabouts)

Figure 3-11 and Figure 3-12 illustrate some animations from microscopic traffic simulation models of the existing network and the proposed network respectively.

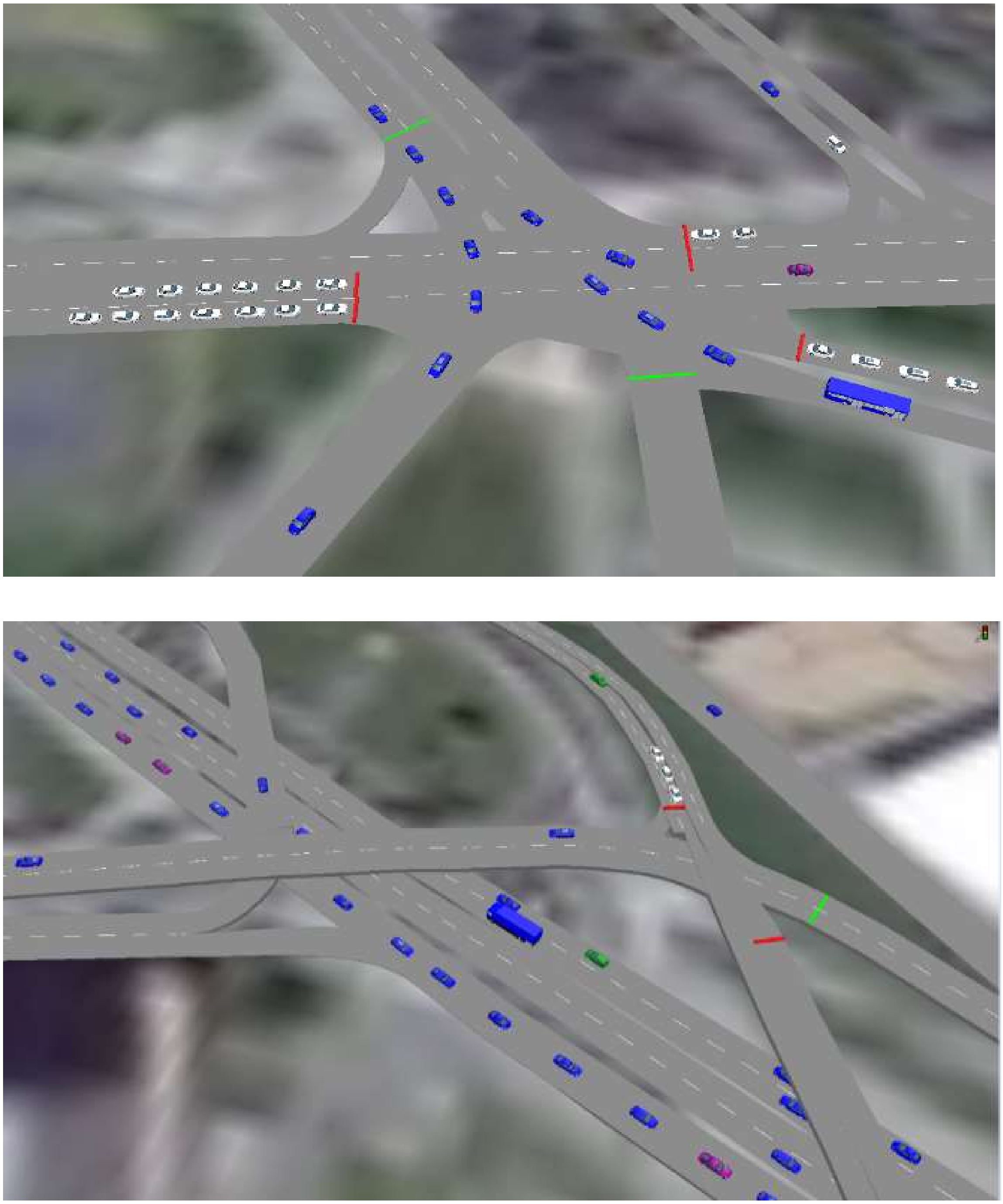


Figure 3-11 Animations from the microscopic traffic simulation models of the existing network

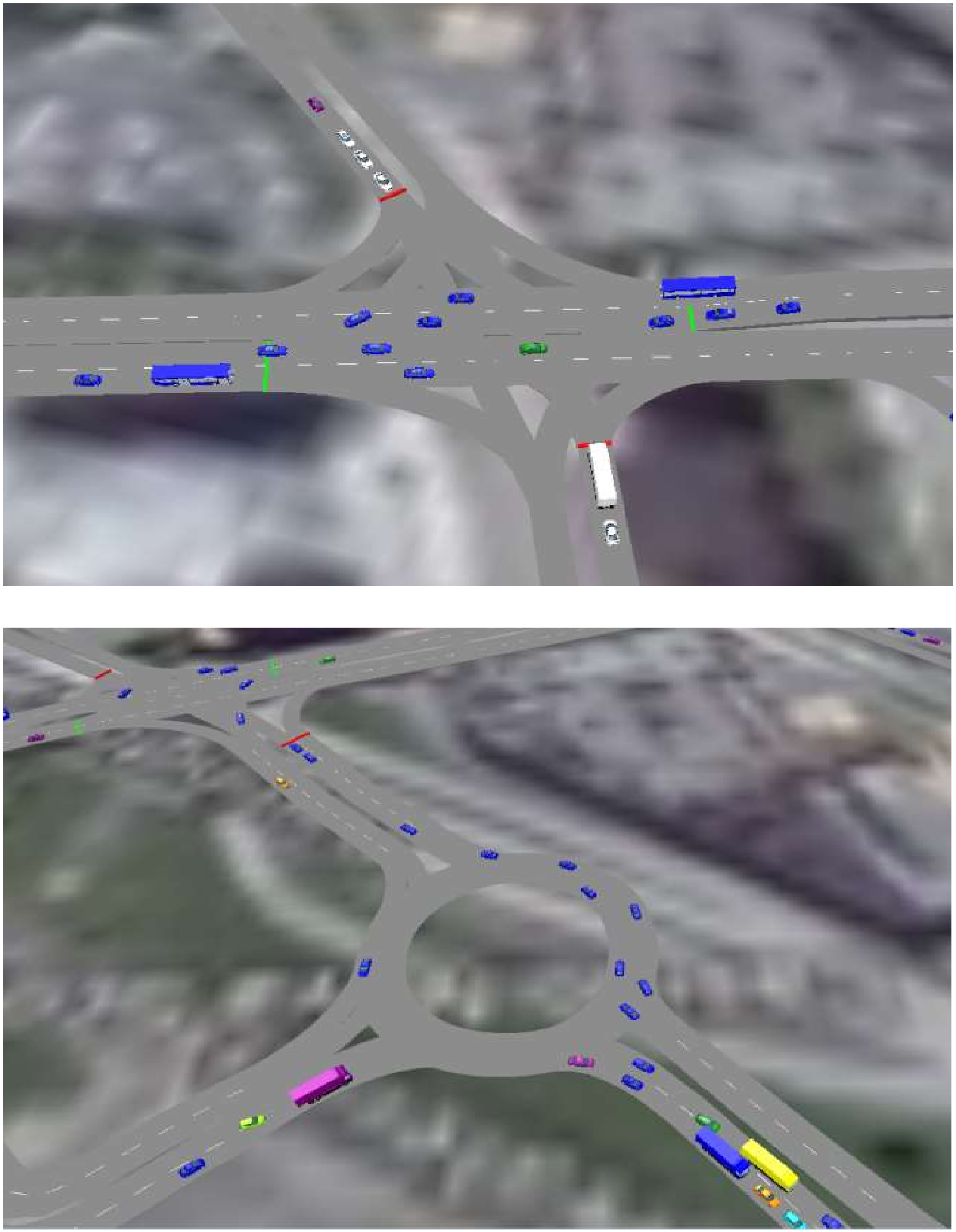


Figure 3-12 Animations from the microscopic traffic simulation models of the proposed network

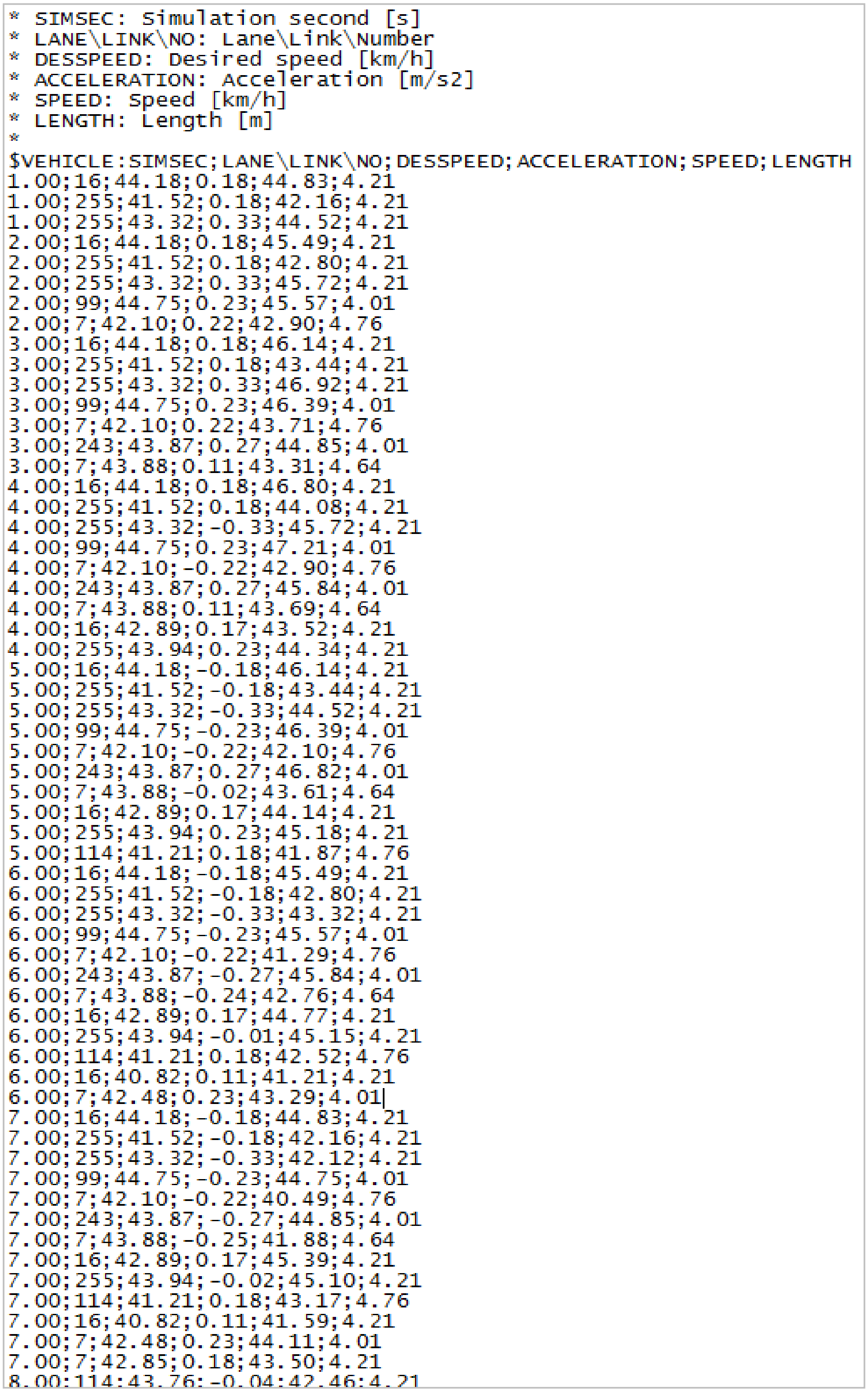
3.5.1.4 Simulation Runs

A total of fifteen simulation runs (Five runs for each simulation hour) are conducted for each scenario with the multiple random seed value gradually incremented by 1. Each model is set to run for 3600 seconds with a simulation resolution one time step per simulation second.

3.5.1.5 Post Processing

Following the simulation runs of the scenarios, traffic volume, traffic composition, and speed trajectory files are generated and are processed for emission model inputs. A total 3600 seconds of instantaneous speed profile for each link is estimated to develop local driving cycle of each modelling period (AM peak, off peak, and PM peak). Table 3-4 demonstrates an example of simulated speed trajectory of AM peak period. Hourly traffic volume in each link is estimated from the instantaneous traffic count profile in the link evaluation database of the traffic simulation model (shown in Table 3-5). A traffic composition profile of each link is estimated from the link evaluation database by disaggregating the traffic count profile by vehicle types.

Table 3-4 Simulated Speed Trajectory for Each Simulation second



```
* SIMSEC: Simulation second [s]
* LANE\LINK\NO: Lane\Link\Number
* DESSPEED: Desired speed [km/h]
* ACCELERATION: Acceleration [m/s2]
* SPEED: Speed [km/h]
* LENGTH: Length [m]
*
$VEHICLE:SIMSEC;LANE\LINK\NO;DESSPEED;ACCELERATION;SPEED;LENGTH
1.00;16;44.18;0.18;44.83;4.21
1.00;255;41.52;0.18;42.16;4.21
1.00;255;43.32;0.33;44.52;4.21
2.00;16;44.18;0.18;45.49;4.21
2.00;255;41.52;0.18;42.80;4.21
2.00;255;43.32;0.33;45.72;4.21
2.00;99;44.75;0.23;45.57;4.01
2.00;7;42.10;0.22;42.90;4.76
3.00;16;44.18;0.18;46.14;4.21
3.00;255;41.52;0.18;43.44;4.21
3.00;255;43.32;0.33;46.92;4.21
3.00;99;44.75;0.23;46.39;4.01
3.00;7;42.10;0.22;43.71;4.76
3.00;243;43.87;0.27;44.85;4.01
3.00;7;43.88;0.11;43.31;4.64
4.00;16;44.18;0.18;46.80;4.21
4.00;255;41.52;0.18;44.08;4.21
4.00;255;43.32;-0.33;45.72;4.21
4.00;99;44.75;0.23;47.21;4.01
4.00;7;42.10;-0.22;42.90;4.76
4.00;243;43.87;0.27;45.84;4.01
4.00;7;43.88;0.11;43.69;4.64
4.00;16;42.89;0.17;43.52;4.21
4.00;255;43.94;0.23;44.34;4.21
5.00;16;44.18;-0.18;46.14;4.21
5.00;255;41.52;-0.18;43.44;4.21
5.00;255;43.32;-0.33;44.52;4.21
5.00;99;44.75;-0.23;46.39;4.01
5.00;7;42.10;-0.22;42.10;4.76
5.00;243;43.87;0.27;46.82;4.01
5.00;7;43.88;-0.02;43.61;4.64
5.00;16;42.89;0.17;44.14;4.21
5.00;255;43.94;0.23;45.18;4.21
5.00;114;41.21;0.18;41.87;4.76
6.00;16;44.18;-0.18;45.49;4.21
6.00;255;41.52;-0.18;42.80;4.21
6.00;255;43.32;-0.33;43.32;4.21
6.00;99;44.75;-0.23;45.57;4.01
6.00;7;42.10;-0.22;41.29;4.76
6.00;243;43.87;-0.27;45.84;4.01
6.00;7;43.88;-0.24;42.76;4.64
6.00;16;42.89;0.17;44.77;4.21
6.00;255;43.94;-0.01;45.15;4.21
6.00;114;41.21;0.18;42.52;4.76
6.00;16;40.82;0.11;41.21;4.21
6.00;7;42.48;0.23;43.29;4.01
7.00;16;44.18;-0.18;44.83;4.21
7.00;255;41.52;-0.18;42.16;4.21
7.00;255;43.32;-0.33;42.12;4.21
7.00;99;44.75;-0.23;44.75;4.01
7.00;7;42.10;-0.22;40.49;4.76
7.00;243;43.87;-0.27;44.85;4.01
7.00;7;43.88;-0.25;41.88;4.64
7.00;16;42.89;0.17;45.39;4.21
7.00;255;43.94;-0.02;45.10;4.21
7.00;114;41.21;0.18;43.17;4.76
7.00;16;40.82;0.11;41.59;4.21
7.00;7;42.48;0.23;44.11;4.01
7.00;7;42.85;0.18;43.50;4.21
8.00;114;43.76;-0.04;42.46;4.21
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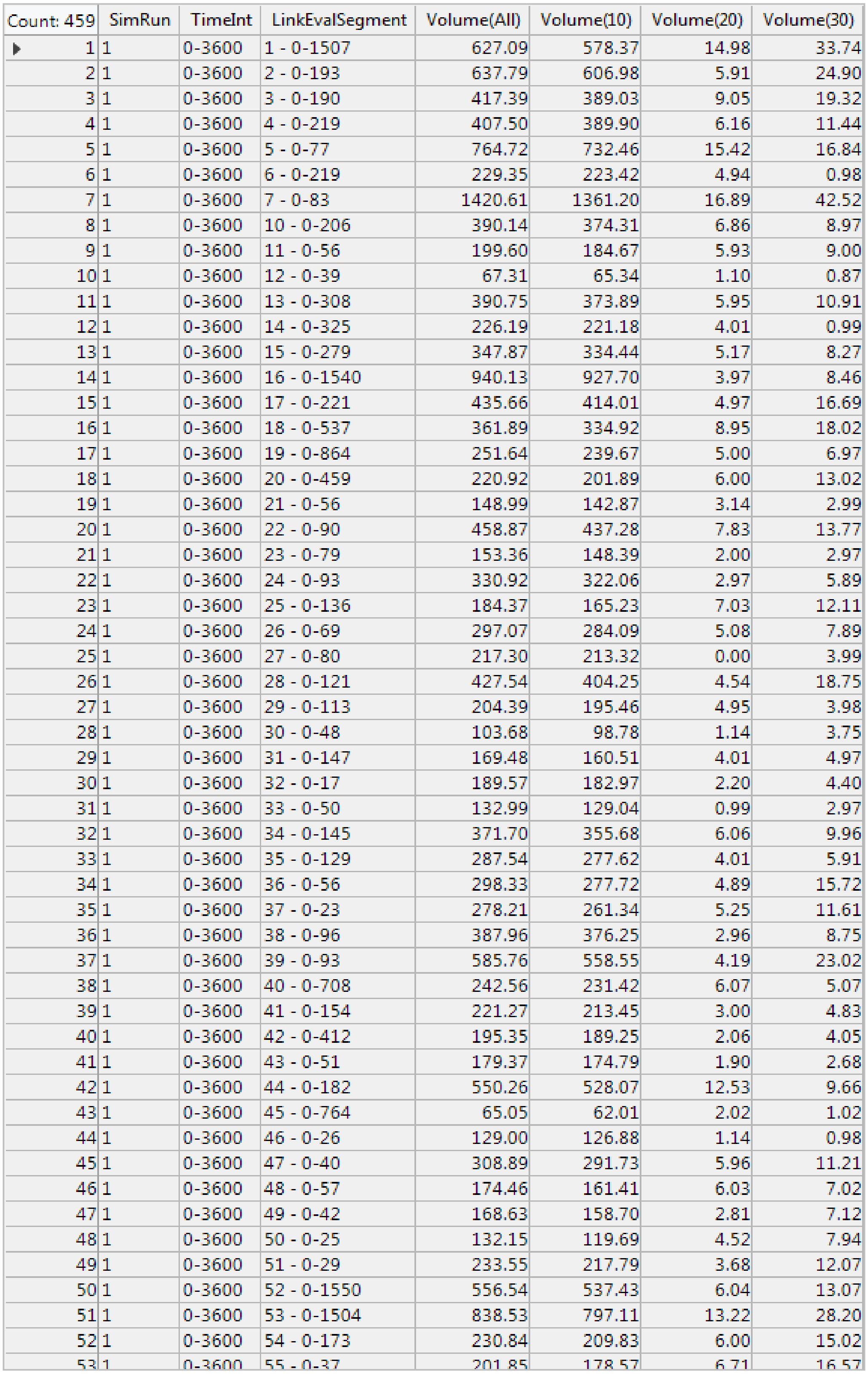
Table 3-5 Simulated Traffic Volume by Each Vehicle Type



Count: 459	SimRun	TimeInt	LinkEvalSegment	Volume(All)	Volume(10)	Volume(20)	Volume(30)
▶ 1	1	0-3600	1 - 0-1507	627.09	578.37	14.98	33.74
2	1	0-3600	2 - 0-193	637.79	606.98	5.91	24.90
3	1	0-3600	3 - 0-190	417.39	389.03	9.05	19.32
4	1	0-3600	4 - 0-219	407.50	389.90	6.16	11.44
5	1	0-3600	5 - 0-77	764.72	732.46	15.42	16.84
6	1	0-3600	6 - 0-219	229.35	223.42	4.94	0.98
7	1	0-3600	7 - 0-83	1420.61	1361.20	16.89	42.52
8	1	0-3600	10 - 0-206	390.14	374.31	6.86	8.97
9	1	0-3600	11 - 0-56	199.60	184.67	5.93	9.00
10	1	0-3600	12 - 0-39	67.31	65.34	1.10	0.87
11	1	0-3600	13 - 0-308	390.75	373.89	5.95	10.91
12	1	0-3600	14 - 0-325	226.19	221.18	4.01	0.99
13	1	0-3600	15 - 0-279	347.87	334.44	5.17	8.27
14	1	0-3600	16 - 0-1540	940.13	927.70	3.97	8.46
15	1	0-3600	17 - 0-221	435.66	414.01	4.97	16.69
16	1	0-3600	18 - 0-537	361.89	334.92	8.95	18.02
17	1	0-3600	19 - 0-864	251.64	239.67	5.00	6.97
18	1	0-3600	20 - 0-459	220.92	201.89	6.00	13.02
19	1	0-3600	21 - 0-56	148.99	142.87	3.14	2.99
20	1	0-3600	22 - 0-90	458.87	437.28	7.83	13.77
21	1	0-3600	23 - 0-79	153.36	148.39	2.00	2.97
22	1	0-3600	24 - 0-93	330.92	322.06	2.97	5.89
23	1	0-3600	25 - 0-136	184.37	165.23	7.03	12.11
24	1	0-3600	26 - 0-69	297.07	284.09	5.08	7.89
25	1	0-3600	27 - 0-80	217.30	213.32	0.00	3.99
26	1	0-3600	28 - 0-121	427.54	404.25	4.54	18.75
27	1	0-3600	29 - 0-113	204.39	195.46	4.95	3.98
28	1	0-3600	30 - 0-48	103.68	98.78	1.14	3.75
29	1	0-3600	31 - 0-147	169.48	160.51	4.01	4.97
30	1	0-3600	32 - 0-17	189.57	182.97	2.20	4.40
31	1	0-3600	33 - 0-50	132.99	129.04	0.99	2.97
32	1	0-3600	34 - 0-145	371.70	355.68	6.06	9.96
33	1	0-3600	35 - 0-129	287.54	277.62	4.01	5.91
34	1	0-3600	36 - 0-56	298.33	277.72	4.89	15.72
35	1	0-3600	37 - 0-23	278.21	261.34	5.25	11.61
36	1	0-3600	38 - 0-96	387.96	376.25	2.96	8.75
37	1	0-3600	39 - 0-93	585.76	558.55	4.19	23.02
38	1	0-3600	40 - 0-708	242.56	231.42	6.07	5.07
39	1	0-3600	41 - 0-154	221.27	213.45	3.00	4.83
40	1	0-3600	42 - 0-412	195.35	189.25	2.06	4.05
41	1	0-3600	43 - 0-51	179.37	174.79	1.90	2.68
42	1	0-3600	44 - 0-182	550.26	528.07	12.53	9.66
43	1	0-3600	45 - 0-764	65.05	62.01	2.02	1.02
44	1	0-3600	46 - 0-26	129.00	126.88	1.14	0.98
45	1	0-3600	47 - 0-40	308.89	291.73	5.96	11.21
46	1	0-3600	48 - 0-57	174.46	161.41	6.03	7.02
47	1	0-3600	49 - 0-42	168.63	158.70	2.81	7.12
48	1	0-3600	50 - 0-25	132.15	119.69	4.52	7.94
49	1	0-3600	51 - 0-29	233.55	217.79	3.68	12.07
50	1	0-3600	52 - 0-1550	556.54	537.43	6.04	13.07
51	1	0-3600	53 - 0-1504	838.53	797.11	13.22	28.20
52	1	0-3600	54 - 0-173	230.84	209.83	6.00	15.02
53	1	0-3600	55 - 0-37	201.85	178.57	6.71	16.57

3.5.2 Emission Modelling

In this study, instantaneous emissions for both scenarios are estimated using the US Environmental Protection Agency (EPA)'s Motor Vehicle Emission Simulator (MOVES) 2014 tool (*US Environmental Protection Agency, 2014*). Figure 3-13 shows the conceptual framework of MOVES model in estimating vehicular emissions (*koupal et al. 2002*). MOVES is capable of estimating emissions at multi scales such as the macro, meso and micro scales. Macro and meso scales are used to estimate emissions for nations and counties respectively by using link average speed as vehicle activity. On the other hand, micro scale analysis evaluates vehicular emissions at link level by using instantaneous speed profile as vehicle activity. In addition, it enables users to input modelling parameters on a link by link basis. Therefore, the current study emphases on assessing vehicular emissions at micro scale by simulating instantaneous speed profile at link level to fully capture the effect of network attributes on emissions. All default distributions in 'MOVES' are replaced by Halifax-specific data to develop an emission model representing the local context. Multiple sources of data are used as emission model input, including link length (mile), link grade (%), vehicle type, vehicle age, fuel supply and formulation, hourly temperature (^{0}F), relative humidity (%), link volume, and instantaneous speed.

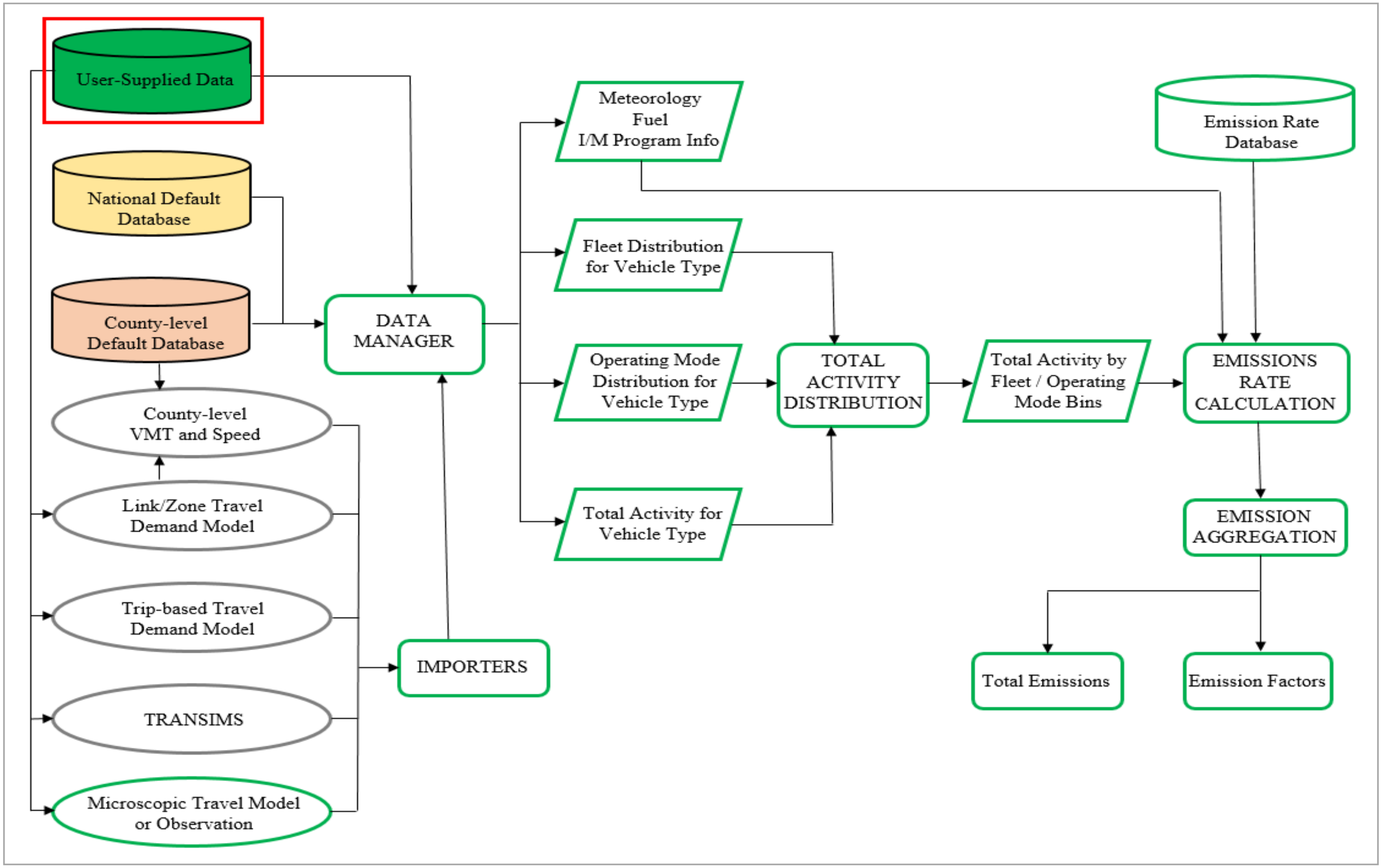


Figure 3-13 Conceptual Framework of MOVES Model

The length of the each link is estimated from the HRM's Spatial geo-database 2012. Instantaneous grade of each link is estimated utilizing the Digital Elevation Model (DEM) developed for the study area in GIS (Shown in Figure 3-14). Moreover, Figure 3-15 displays the frequency distribution of link grade in the study area where the negative sign indicates downward grade and positive sign indicates upward grade. The link grade of the study area ranges from -12% to +12 % and the maximum frequency is found for the grade -3% to +2%. Note that all links are defined as 'unrestricted urban road' in the emission model since the study area goes through the downtown core of Halifax.

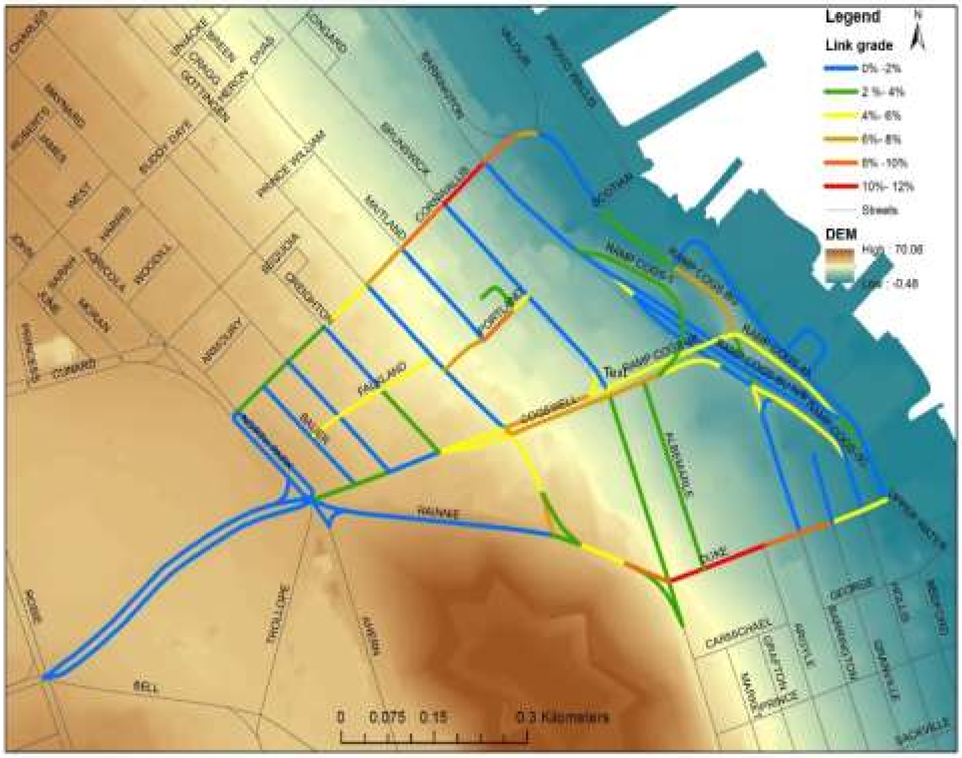


Figure 3-14 Digital Elevation Model (DEM) of the Study Area

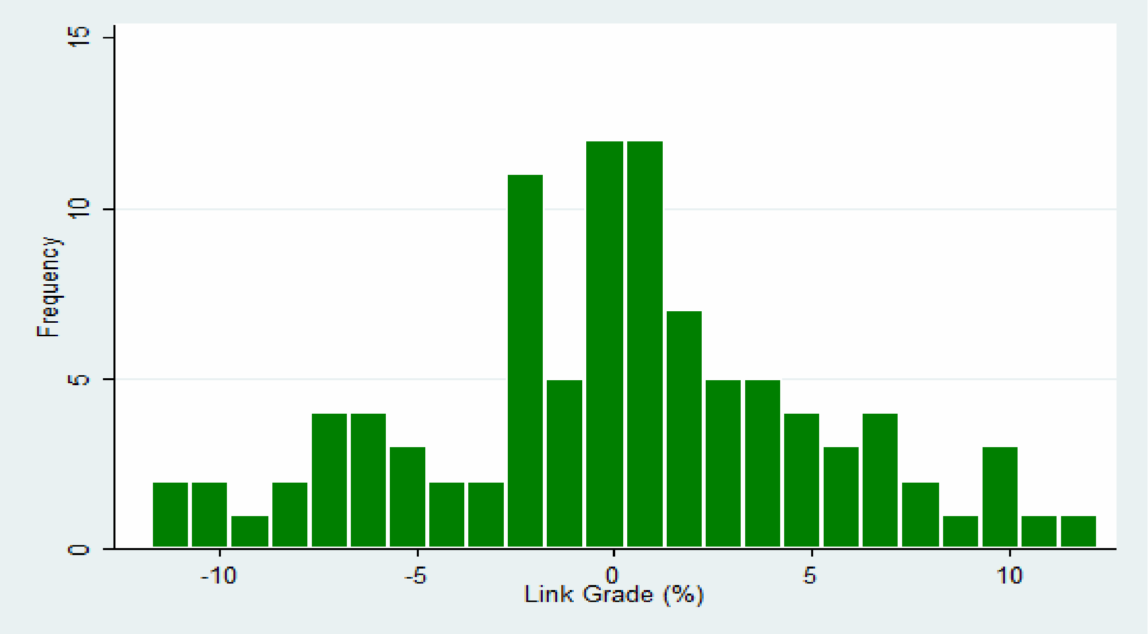


Figure 3-15 Frequency Distribution of Link Grade in the Study Area

Distribution of vehicle types in each link is estimated from the traffic composition profile generated in the traffic simulation model. The vehicle age distribution fraction is estimated from the vehicle registry database based on Canadian Vehicle Survey. The study estimates the age distribution of vehicles for 30 year periods ranging from 1984 to 2014. For example, 72.11% of passenger cars, 61.27 % of transit buses, and 52.33% of short haul trucks running through the network are less than 10 years old (shown in Figure 3-16). All passenger cars run on gasoline fuel, whereas, transit buses, and single unit short haul trucks run on diesel fuel. Hourly meteorological data, such as temperature and relative humidity, are obtained from the Halifax Naval Dockyard weather station (around 0.4 km away from the study area) by Environment Canada. Hourly meteorological data is collected for October, 2014 which matches with the date of traffic study (shown in Table 3-6). For instance, 54.465 ^{0}F is recorded as the hourly temperature and 67.875% is recorded as the hourly humidity for AM peak period. With the increase of temperature, the relative humidity value goes down and vice versa.

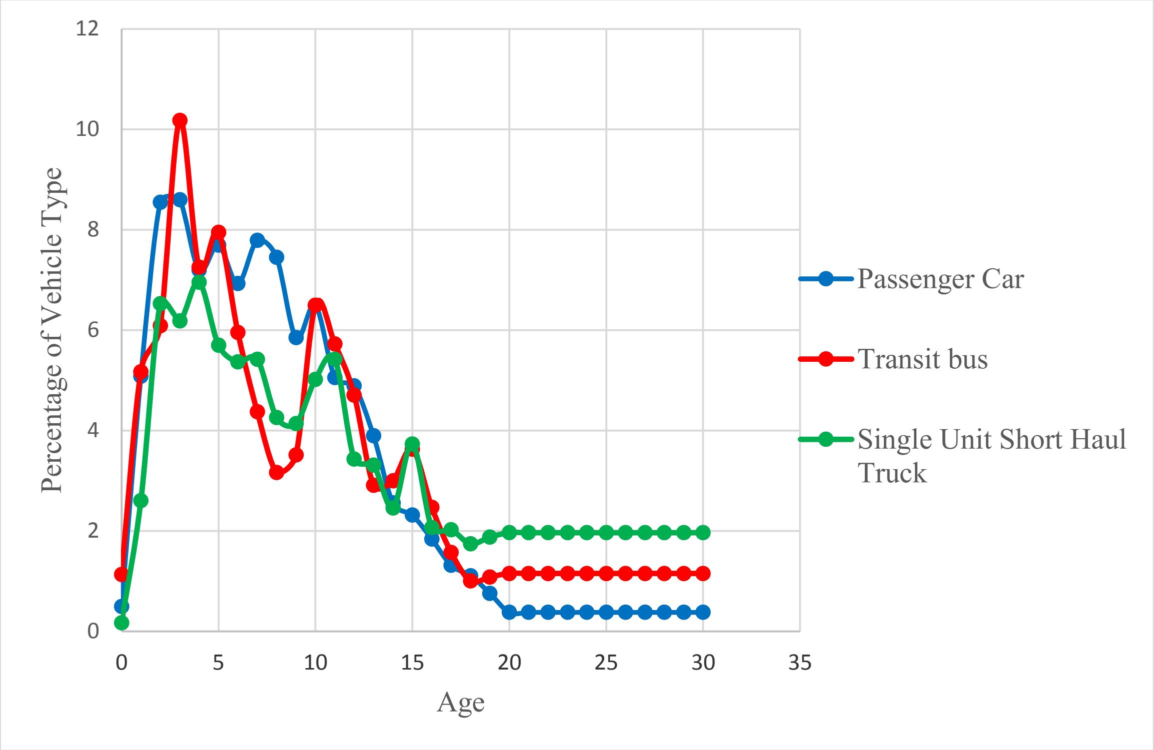


Figure 3-16 Vehicle Age Distribution by Vehicle Type

Table 3-6 Temperature and Relative Humidity in AM peak, Off Peak, and PM Peak Periods

Time	**Temperature (° F)**	**Relative Humidity (%)**
AM Peak	54.465	67.875
Off Peak	58.269	52.50
PM Peak	53.112	73.529

Hourly traffic volume and 3600 seconds of instantaneous speed profiles generated for each link in the traffic simulation model are then utilized as inputs in the emission model. This instantaneous speed profile characterizes the second by second vehicular speed and link grade as a function of time of the corresponding link. It allows to capture the acceleration, deceleration, cruising, and idling effect on emission estimation. A second by second Vehicle Specific Power (VSP) is estimated within the MOVES (using Equation 2) for the corresponding instantaneous speed profile of each link (*US Environmental*

Protection Agency, 2004). VSP is described as the engine power of each vehicle unit mass representing the tractive power of the engine required to drag the vehicle (*Christopher Frey et al., 2006*).

It is a function of vehicle instantaneous speed, vehicle weight, acceleration and road grade (*US Environmental Protection Agency, 2004*).

$$VSP = \left(\frac{A}{M}\right) * v + \left(\frac{B}{M}\right) * v^2 + \left(\frac{C}{M}\right) * v^3 + (a + g\ Sin\Theta) * v \qquad (2)$$

Where, v is the vehicle speed in meter/second, a is the vehicle acceleration in meter/second^2, $Sin\Theta$ is the (fractional) road grade, M is the fixed mass factor in metric tons, g is the acceleration due to gravity (9.8 meter/second^2), and A, B, C are the road load coefficients where, A is the rolling term in kilowatt-second/meter, B is the rotating term in kiloWatt-second^2/meter^2, C is the drag term in kiloWatt-second^3/meter^3. Following Table 3-7 shows the value of A, B, C and M for different vehicle types evaluated in this study.

Table 3-7 Road Load Coefficients and Fixed Mass Factor Values

Vehicle Type	A	B	C	M
Passenger Car	0.156461	0.002002	0.000493	1.4788
Transit Bus	1.0944	0	0.003587	17.1
Single Unit Short Haul Truck	0.561933	0	0.001603	17.1

An operating mode ID is determined for each combination of VSP and instantaneous speed according to MOVES's Operating Mode ID classifications (*US Environmental Protection Agency, 2011b*) shown in Table 3-8. Operating Mode ID 0 and 1 represent braking and idling conditions respectively whereas the remaining operating mode IDs (e.g. 11, 12, 13, 14,15,16,21, 22, 23, 24, 25, 27, 28, 29, 30, 33, 35, 37, 38, 39, and 40) represent running conditions including low speed coasting, cruising and acceleration as well. These running Operating Mode IDs are also classified into three groups, where Operating Mode IDs 11 to 16 are for speed between 1 mph to 25 mph, Operating Mode IDs 21 to 30 are for speed between 25 mph to 50 mph and Operating Mode IDs 33 to 40 are for speed greater than 50 mph.

After that, Operating Mode Distribution is developed for each link to identify the percentage of time spent by vehicles in each Operating Mode ID. Each Operating Mode ID has a VSP modal emission rate (g/hr) embedded into MOVES which varies with fuel type, vehicle age distribution, and meteorological conditions. The VSP modal emission rate is lowest in braking and idling conditions. On the other hand, VSP modal emission rate increases with the increment of Operating Mode IDs (*US Environmental Protection Agency, 2011b*). Finally, hourly total emission (g/hr) of each link is estimated using the link-specific Operating Mode Distribution and corresponding VSP modal emission rate (shown in equation 3) (*Zhai et al., 2008*).

$$E_j = \sum_{i=1} \left(\frac{t_{i,j}}{T_j} * ER_i \right) \tag{3}$$

Where, E_j is the hourly total emission (g/hr) for link j; T_j is the total travel time (sec) in link j; $t_{i,j}$ is the time spent (sec) in the operating mode ID i in the drive cycle of link j; and ER_i is the VSP modal emission rate (g/hr) for operating mode ID i.

Link emission rates (g/VMT) are calculated by dividing the corresponding link total emissions (g) with the link length (mile) and volume. Finally, a total number of 7524 emission rates are generated (209 links *3 times of a day *2 emission types * 6 pollutants) which lead to a large multi-dimensional output table. These outputs are then converted into six matrix forms, where each matrix represents the hourly emission rates of GHG, CO, NO_X, SO_2, PM_{10} and $PM_{2.5}$ for each link. These emission rates are disaggregated by vehicle type, and vehicle model year for more detailed analysis.

Table 3-8 Operating Mode ID Classifications

Operating Mode ID	**Operating Mode Name**	**VSP**	**Speed**
0	Braking		
1	Idling		
11	Low Speed Coasting	VSP<0	1<= Speed<25
12	Cruise/ Acceleration	0<=VSP<3	1<= Speed<25
13	Cruise/ Acceleration	3<=VSP<6	1<= Speed<25
14	Cruise/ Acceleration	6<=VSP<9	1<= Speed<25
15	Cruise/ Acceleration	9<=VSP<12	1<= Speed<25
16	Cruise/ Acceleration	12<=VSP	1<= Speed<25
21	Moderate Speed Coasting	VSP<0	25<= Speed<50
22	Cruise/ Acceleration	0<=VSP<3	25<= Speed<50
23	Cruise/ Acceleration	3<=VSP<6	25<= Speed<50
24	Cruise/ Acceleration	6<=VSP<9	25<= Speed<50
25	Cruise/ Acceleration	9<=VSP<12	25<= Speed<50
26	Cruise/ Acceleration	12<=VSP	25<= Speed<50
27	Cruise/ Acceleration	12<=VSP<=18	25<= Speed<50
28	Cruise/ Acceleration	18<=VSP<=24	25<= Speed<50
29	Cruise/ Acceleration	24<=VSP<=30	25<= Speed<50
30	Cruise/ Acceleration	30<=VSP	25<= Speed<50
33	Cruise/ Acceleration	VSP<6	50<= Speed
35	Cruise/ Acceleration	6<=VSP<=12	50<= Speed
36	Cruise/ Acceleration	12<=VSP	50<= Speed
37	Cruise/ Acceleration	12<=VSP<=18	50<= Speed
38	Cruise/ Acceleration	18<=VSP<=24	50<= Speed
39	Cruise/ Acceleration	24<=VSP<=30	50<= Speed
40	Cruise/ Acceleration	30<=VSP	50<= Speed

3.5.3 Land Use Regression Model

A land use regression model is developed to explore the effects of different predictors on emission rate of each pollutant. A land use regression model can be explained by the following equation (4):

$$y = \beta_o + \beta_1 x_{1+} \beta_2 x_2 + \ldots\ldots\ldots + \beta_k x_k + \mathcal{E} \quad (4)$$

Where, y is the dependent variable representing the emission rate of each pollutant. The independent variables, x_1, x_2 and x_k represent the potential predictors on emission rates. β_o is the constant, and β_1, β_2, β_k denote the parameters to be estimated , which demonstrates the magnitude and nature of the potential predictors. Lastly, $\mathcal{E}$ is the random error term representing the unexplained portion of the regression model.

The goodness of fit of the models is evaluated by the coefficient of determination which is denoted by R squared. R squared value ranges from 0 to 1, where the value closer to 1 represents better model fit.

In this study, the potential predictors are categorised into two broad classes: 1) street and traffic attributes, and 2) land use and built environment attributes. Street and traffic attributes include traffic volume, roadway grade, average speed, percentage of time spent in acceleration, percentage of time spent in idling, and percentage of heavy duty vehicles on the roads. One of the key features of this model is to capture the combined effects of street attributes, traffic attributes, land use and built environment attributes on the emission rates. Land use and built environment attributes include number of commercial establishments, number of educational institutions, number of bus stops, percentage of residential area, percentage of green park area for recreational purposes, and land use mix index at the Dissemination Area (DA) level. Note that all land use and built environment attributes are obtained from HRM Geo-database 2012 and Enhanced Point of Interest (EPOI) data from the DMTI Spatial Inc. by generating a 200 meter buffer around each link in the network using GIS functions. Figure 3-17 shows the land use map developed for the study area. Land use mix index represents the diversity of land use of an area (*Bhat and Gossem, 2004*). A well-mixed land use refers to active transportation supportive neighbourhood and proximity to different activity points, which in turn promotes walking, the use of bicycles and transit, and reduces car use. In this study, land use mix index is computed at the Dissemination Area (DA) level and can be expressed by the following equation (*Bhat and Gossem, 2004*):

$$\text{Land Use Mix Index} = 1 - \left\{ \frac{\left| \frac{R}{T} - \frac{1}{3} \right| + \left| \frac{C}{T} - \frac{1}{3} \right| + \left| \frac{O}{T} - \frac{1}{3} \right|}{\frac{4}{3}} \right\} \tag{5}$$

Where, R = residential land use (acres), C = commercial or industrial land use (acres), O = other land use (acres) and T = total land use (acres). The value of land use mix index ranges from 0 to 1, where, the values closer to zero indicates land use homogeneity. On the other hand, the values closer to one indicates land use heterogeneity.

These regression models can be applied to predict vehicular emissions of other areas with limited instantaneous drive cycle information due to unavailability of Global Positioning Systems (GPS) devices and traffic simulation models.

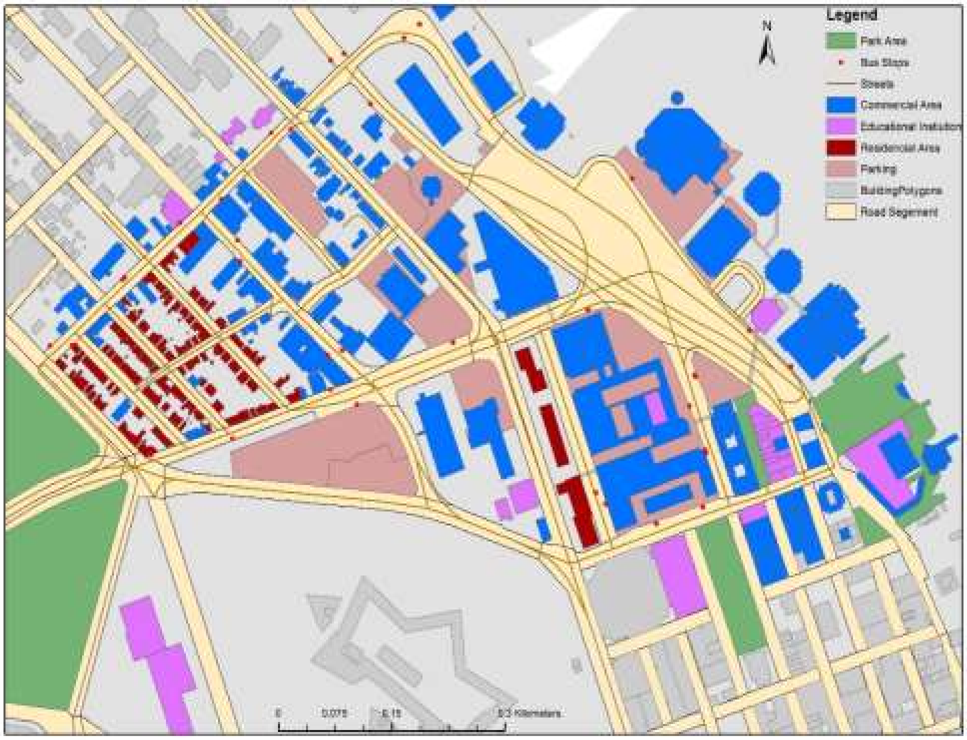


Figure 3-17 Land Use Map of the Study Area

3.6 Results and Discussion

3.6.1 Factors Affecting Emission Rates of Various Pollutants

There are numerous studies in the literature that investigate the factors affecting vehicular emissions. Among them, the majority of the researchers (*Pierson et al., 1996; Huai et al., 2005; Frey et al., 2006; Zhang and Frey, 2006; Frey et al., 2008*) are in general agreement that, variation of vehicular emissions are strongly correlated with road grade, speed, acceleration which is associated with operating mode distribution. Therefore, this section discusses the effects that speed and grade have on emission rates in the study area. For detailed analysis, both isolated and combined effects of these factors on emission rates are described at link level.

3.6.1.1 Isolated Effects of Speed and Grade on Emission Rates

This sub section explores the influence of link average speed and link grade on emission rates of various pollutants. Figure 3-18 to Figure 3-23, and Figure 3-24 to Figure 3-29 illustrate the relationship of emission rates with speed (ranging from 2.556 mph to 25.673 mph) and grade (ranging from -11.729% to +11.729%) respectively, for all pollutants. Overall, emission rates of all pollutants generally tend to decrease with the increase of speed, conversely, emission rates tend to escalate when grade increases. Model results reveal that GHG and SO_2 emission rates show better correlation with change in speed and grade compared to other pollutants.

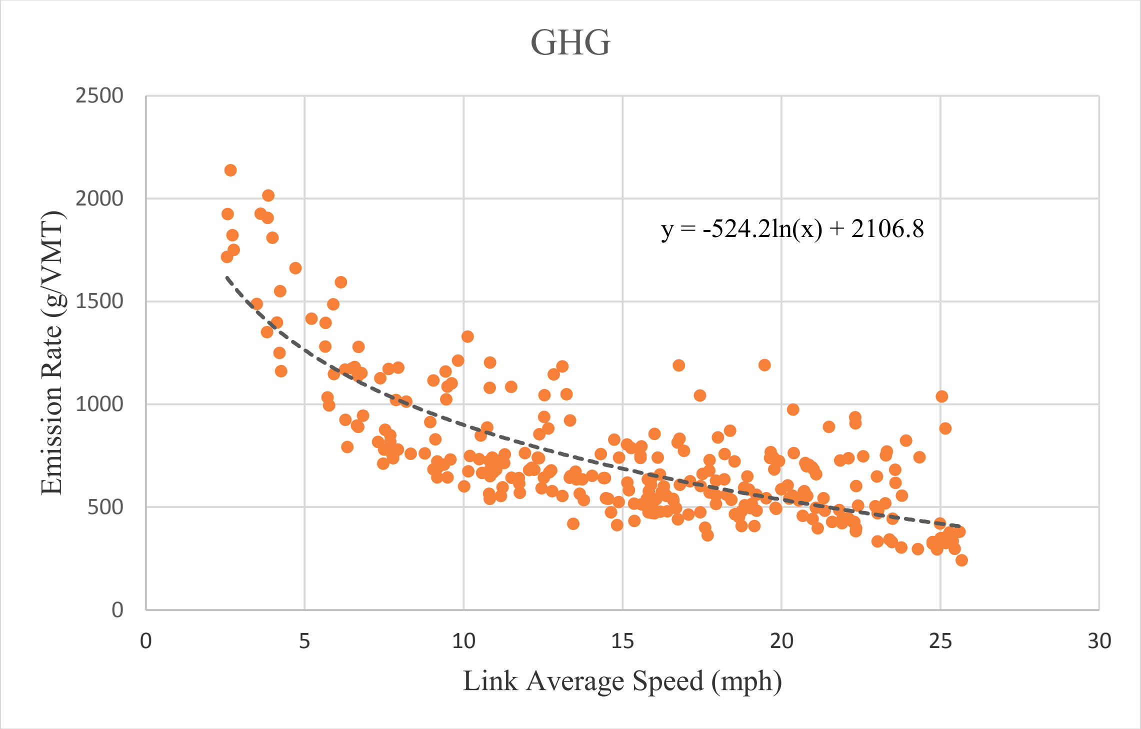


Figure 3-18 Effects of Link Average Speeds on GHG Emission Rate

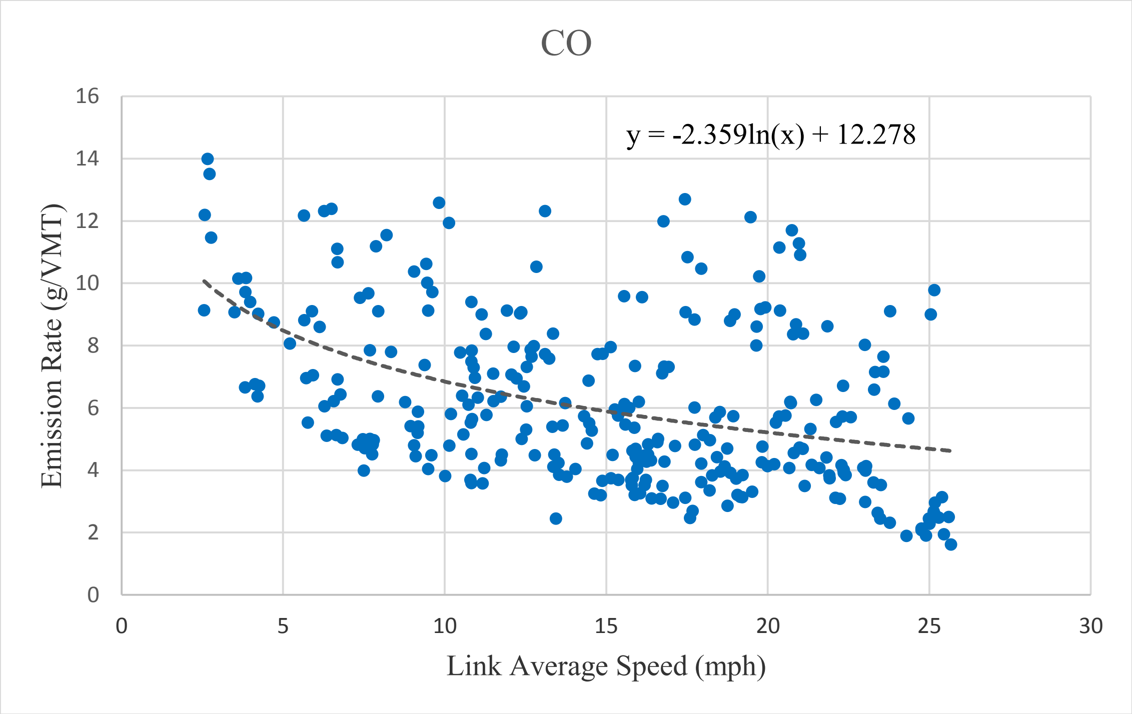


Figure 3-19 Effects of Link Average Speeds on CO Emission Rate

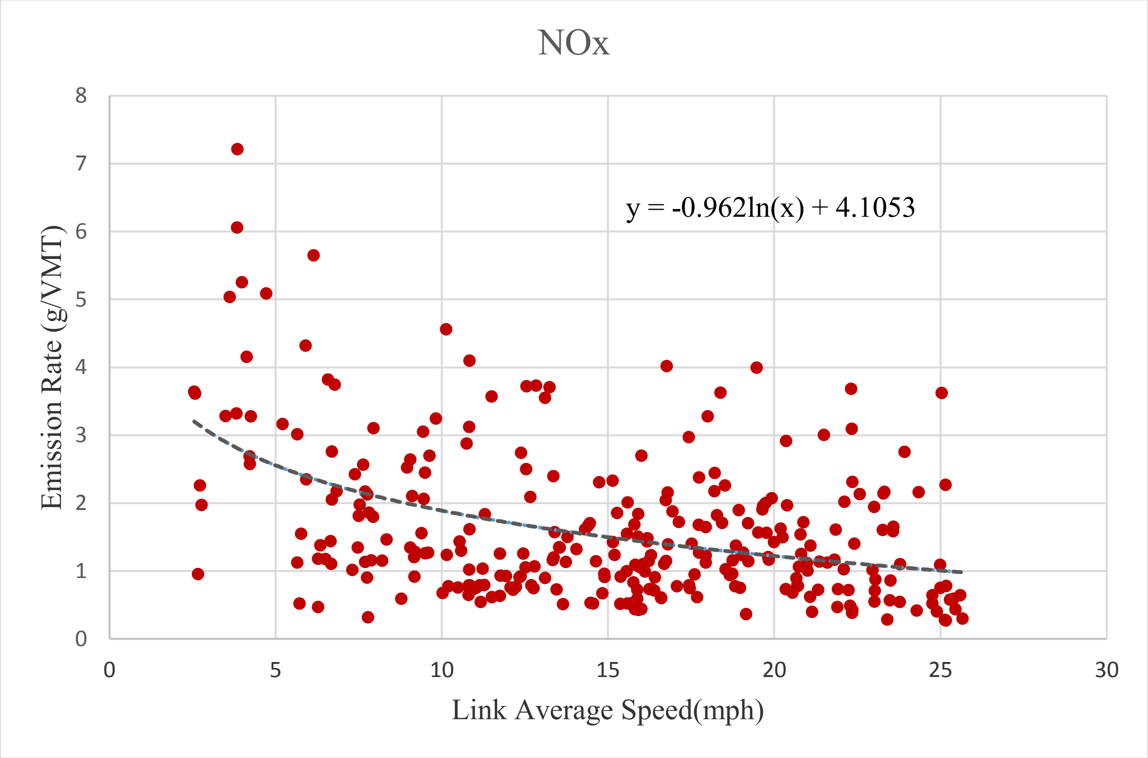


Figure 3-20 Effects of Link Average Speeds on NOx Emission Rate

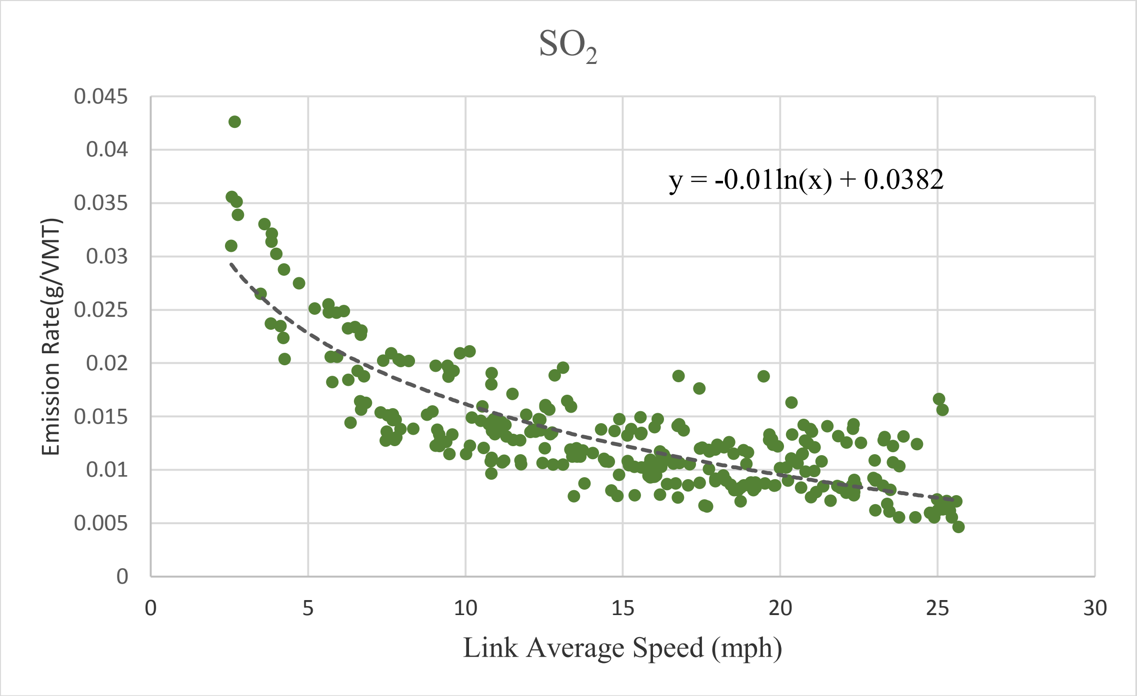


Figure 3-21 Effects of Link Average Speeds on SO_2 Emission Rate

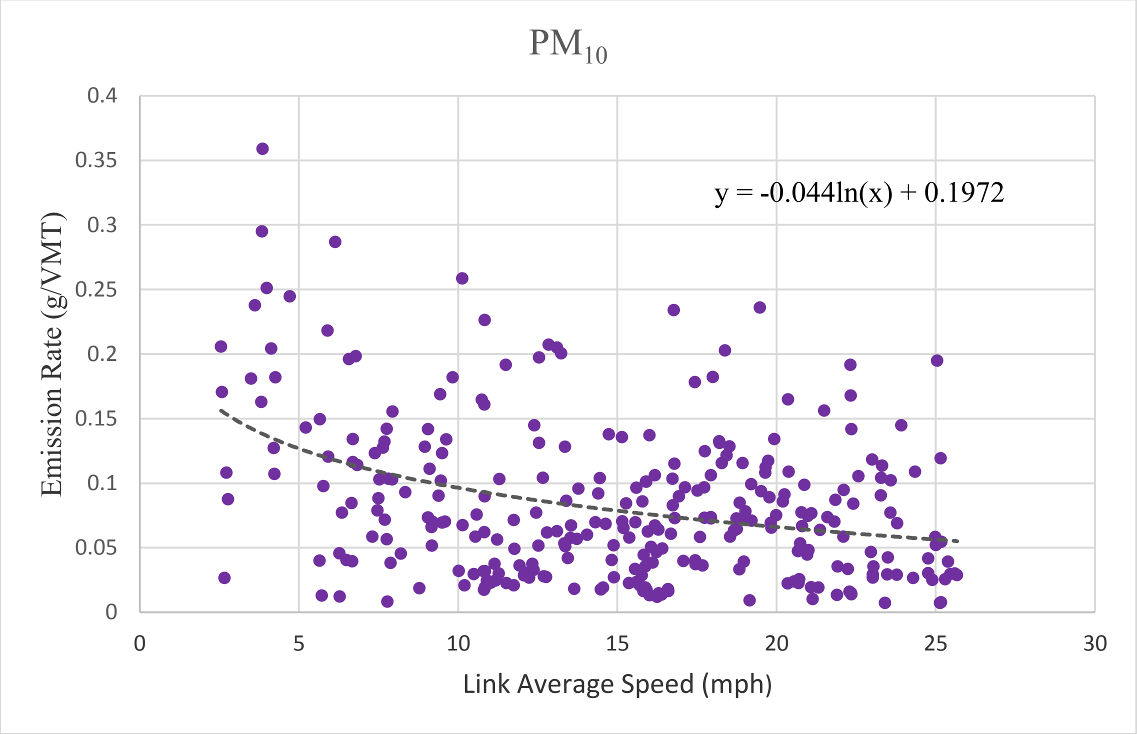


Figure 3-22 Effects of Link Average Speeds on PM$_{10}$ Emission Rate

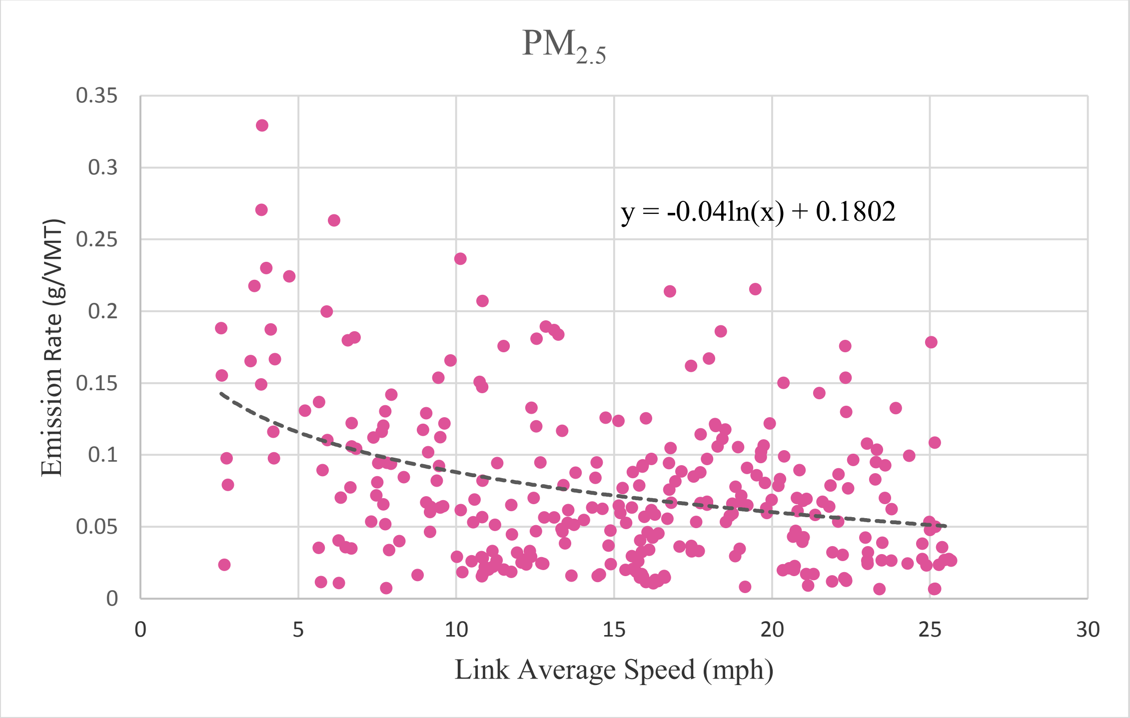


Figure 3-23 Effects of Link Average Speeds on PM$_{2.5}$ Emission Rate

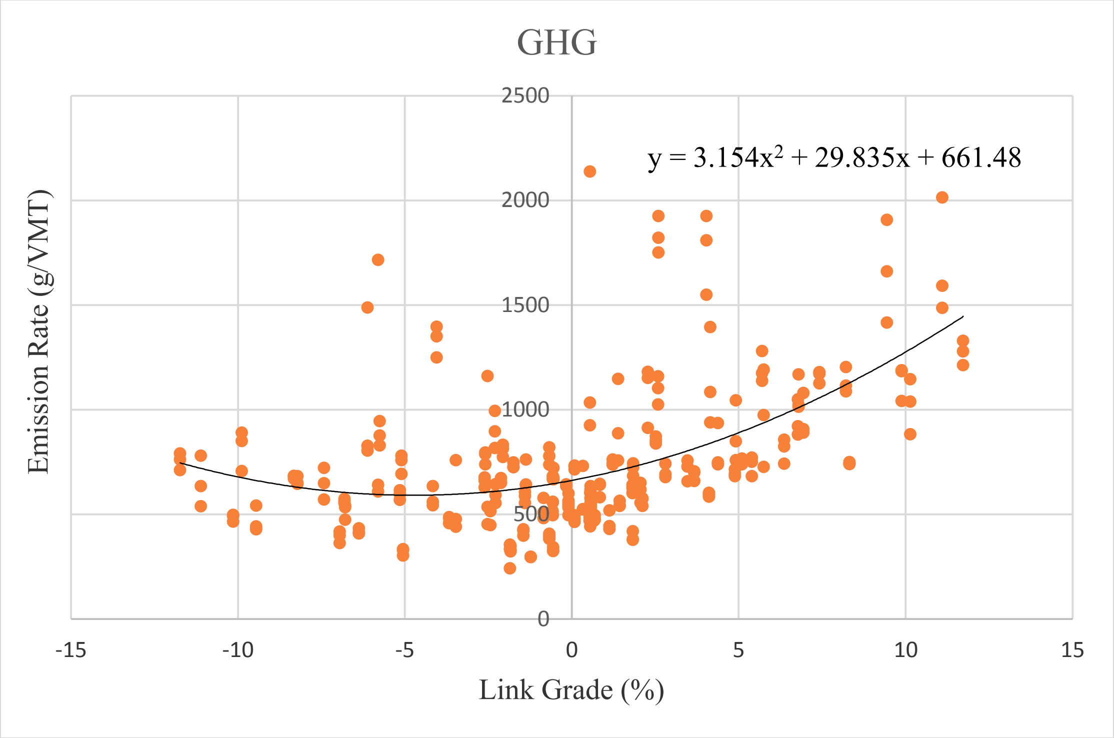


Figure 3-24 Effects of Link Grade on GHG Emission Rate

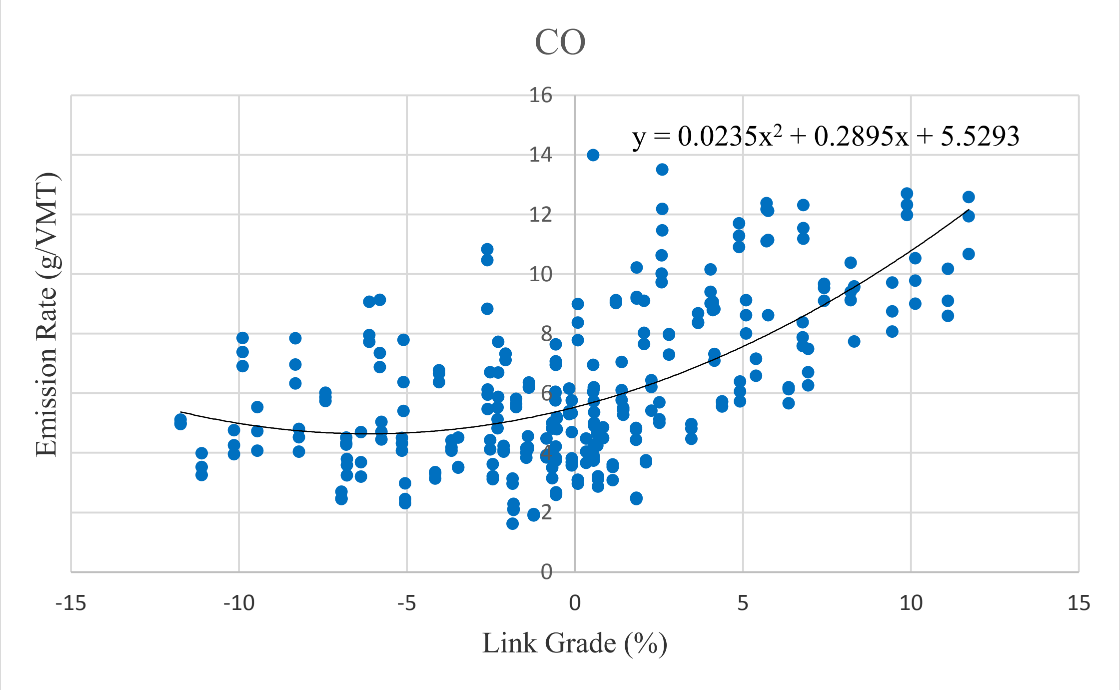


Figure 3-25 Effects of Link Grade on CO Emission Rate

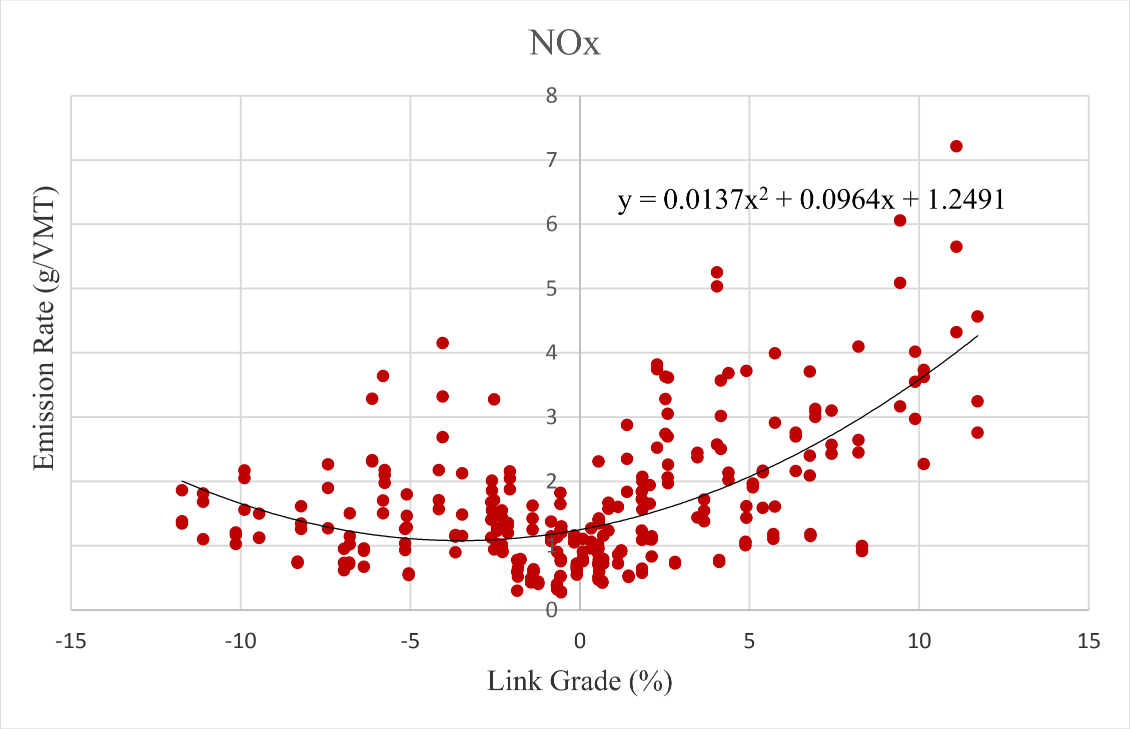


Figure 3-26 Effects of Link Grade on NOx Emission Rate

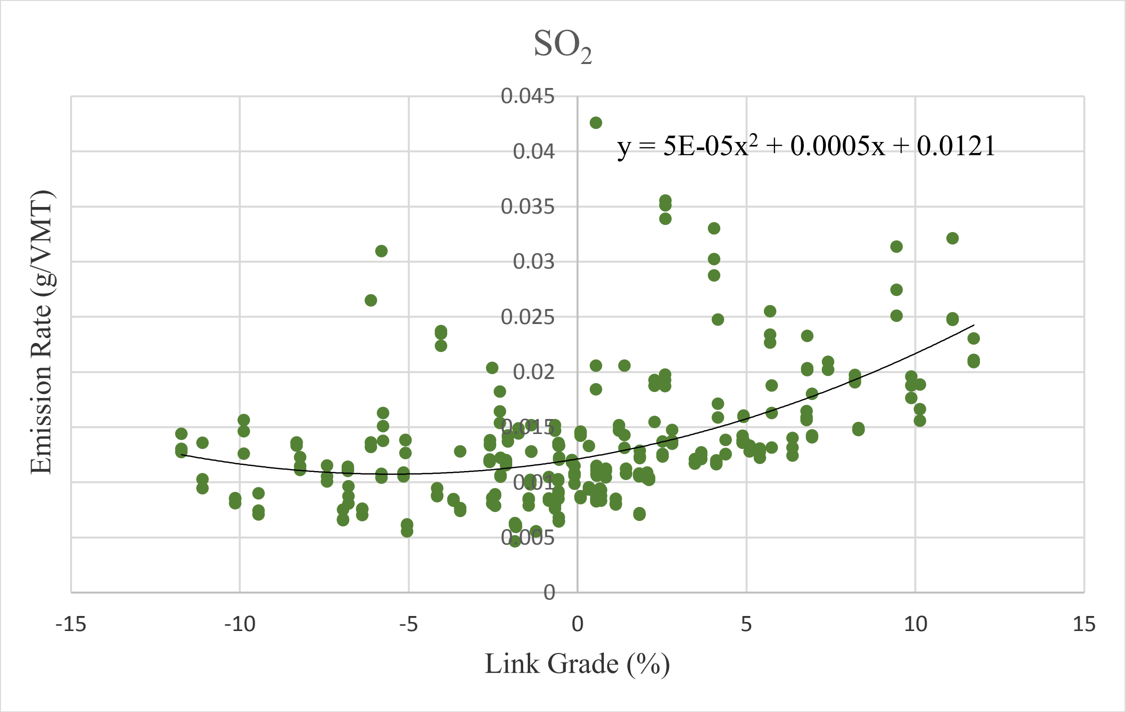


Figure 3-27 Effects of Link Grade on SO2 Emission Rate

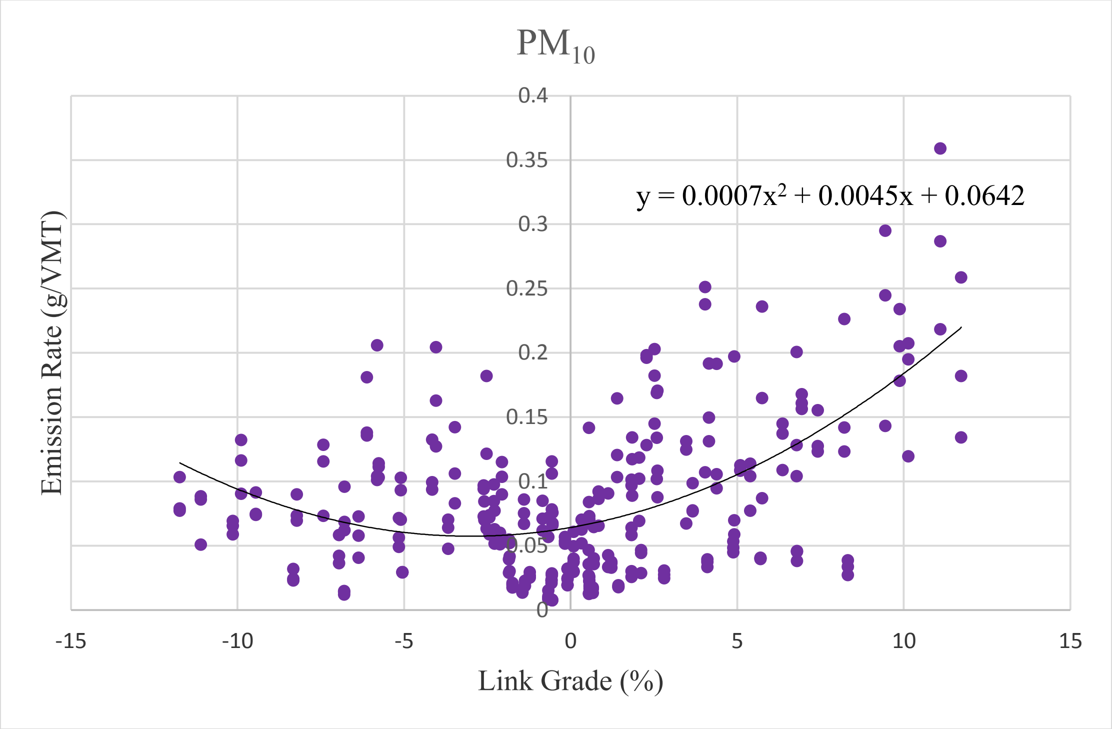


Figure 3-28 Effects of Link Grade on PM_{10} Emission Rate

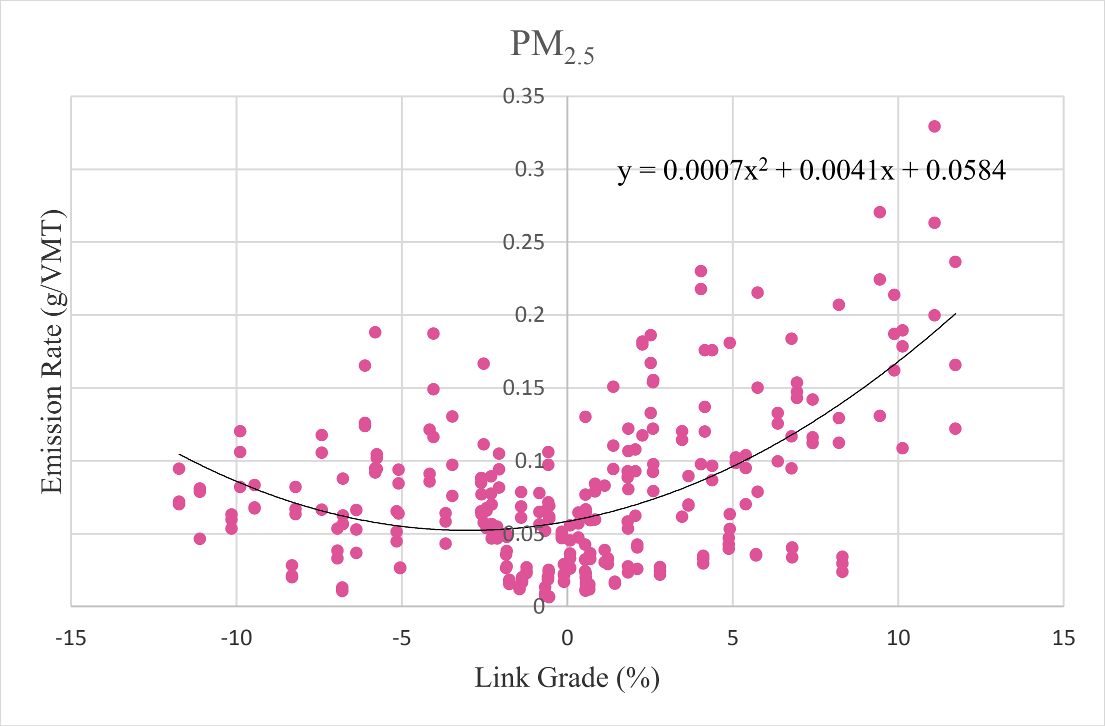


Figure 3-29 Effects of Link Grade on $PM_{2.5}$ Emission Rate

The Figure 3-18 to Figure 3-23, and Figure 3-24 to Figure 3-29 also exhibit that emission rates fluctuate widely for the same speed as well as for the same grade. This phenomenon reveals that lower speed and higher grade do not always necessarily increase emission rates. This reflects the fact that emission rates are not only depend on speed and grade; driving behaviour and vehicle types are also influential factors. This finding indicates the importance of developing local link drive schedule for emission analysis rather than using link average speed.

It is also interesting to observe that the emission rate fluctuation increases for lower speed and higher grade. For example, at a lower speed of 3.85 mph, the emission rate of NOx ranges from 2.57 g/VMT to 7.213 g/VMT with a fluctuation of 4.64 g/VMT. On the other hand, at a higher speed of 25.04 mph, the emission rate varies from 0.403 g/VMT to 3.623 g/VMT with a fluctuation of 3.22 g/VMT, which is 30.60% lower than the fluctuation for lower speed. In addition, at lower grade of -11.729 %, the NOx emission rate varies from 1.34 g/VMT to 1.86 g/VMT, having a fluctuation of 0.52 g/VMT. In the case of higher grade of 11.104%, the emission rate ranges from 4.32g/VMT to 7.213g/VMT showing a difference of 2.893 g/VMT, which is 456.346% higher than the fluctuation for lower grade.

3.6.1.2 Variation in Emission Rates by Grade and Vehicle Type during Cruising and Acceleration

In this sub section, variation in emission rates by grade and vehicle type during cruising and acceleration is presented. The model results suggest that the acceleration of vehicles increases emission rates of all pollutants (shown in Table 3-9). For example, it is found that emission rates are increased by 22.066% for PM_{10} and $PM_{2.5}$ due to the shifting of gear from cruising to acceleration mode, which is the maximum increase among all pollutants.

Moreover, it is imperative to examine the variation of emission rates by grades during cruising and acceleration. Figure 3-30 to Figure 3-35 illustrate the change in emission rates of all pollutants with grades during cruising, and Figure 3-36 to Figure 3-41 illustrate the changes during acceleration. The results show that positive grades have higher effect in emission rates in both cruising and acceleration mode than negative grades. Emission rates increase gradually with the increase of positive grade during cruising and acceleration. On the other hand, the variation in emission rates is not significant while vehicles are running through the downgrades (ranging from -6% to -12 %) during cruising and acceleration.

Table 3-9 Percentage increase in emission rates from cruising to acceleration mode

Pollutant Name	% Increase in emission rates from cruising to acceleration
GHG	2.560%
CO	15.981%
NOx	5.413%
SO_2	2.559%
PM_{10}	22.066%
$PM_{2.5}$	22.066%

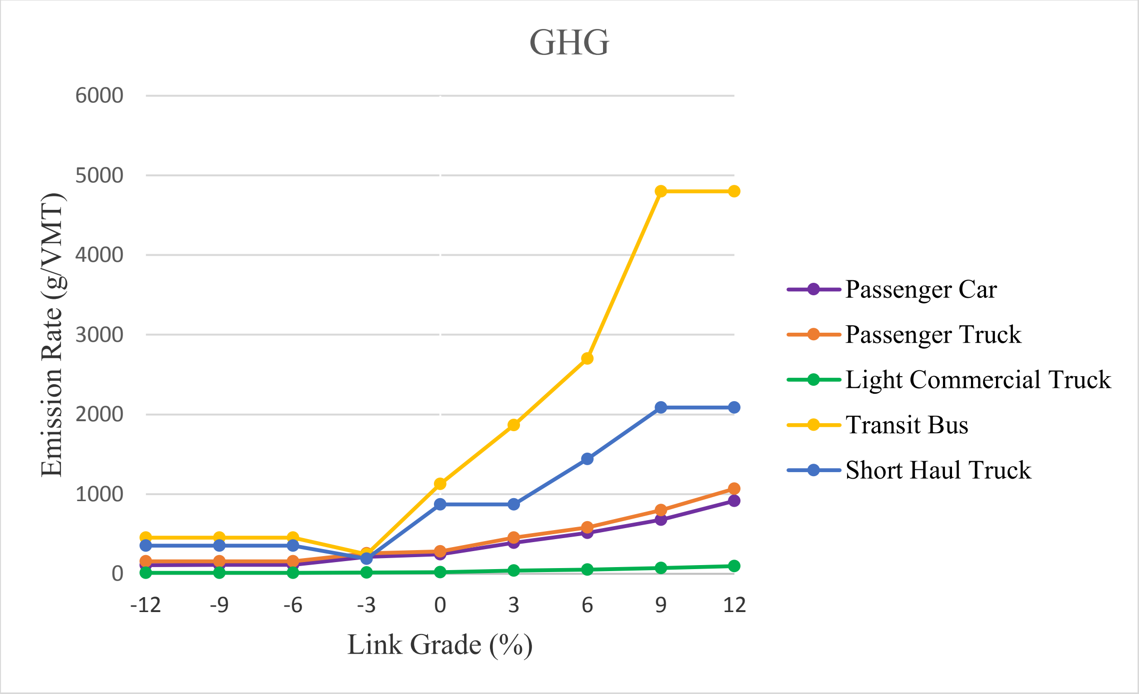


Figure 3-30 Variation in GHG Emission Rates by Grade and Vehicle Type during Cruising

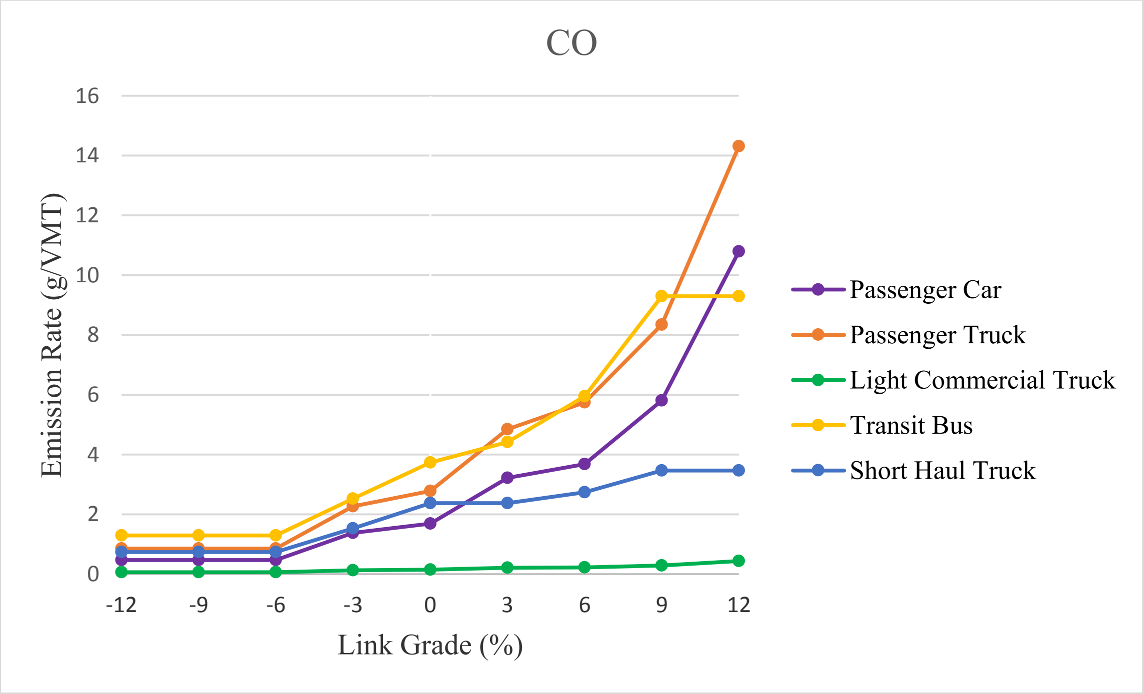


Figure 3-31 Variation in CO Emission Rates by Grade and Vehicle Type during Cruising

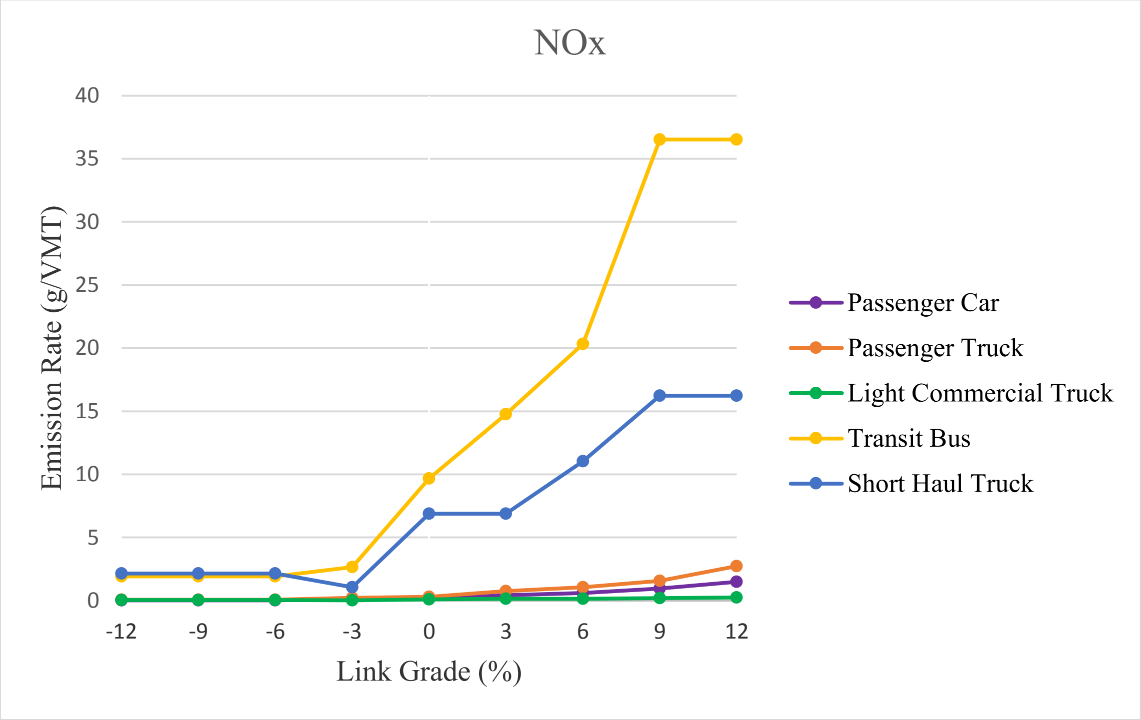


Figure 3-32 Variation in NOx Emission Rates by Grade and Vehicle Type during Cruising

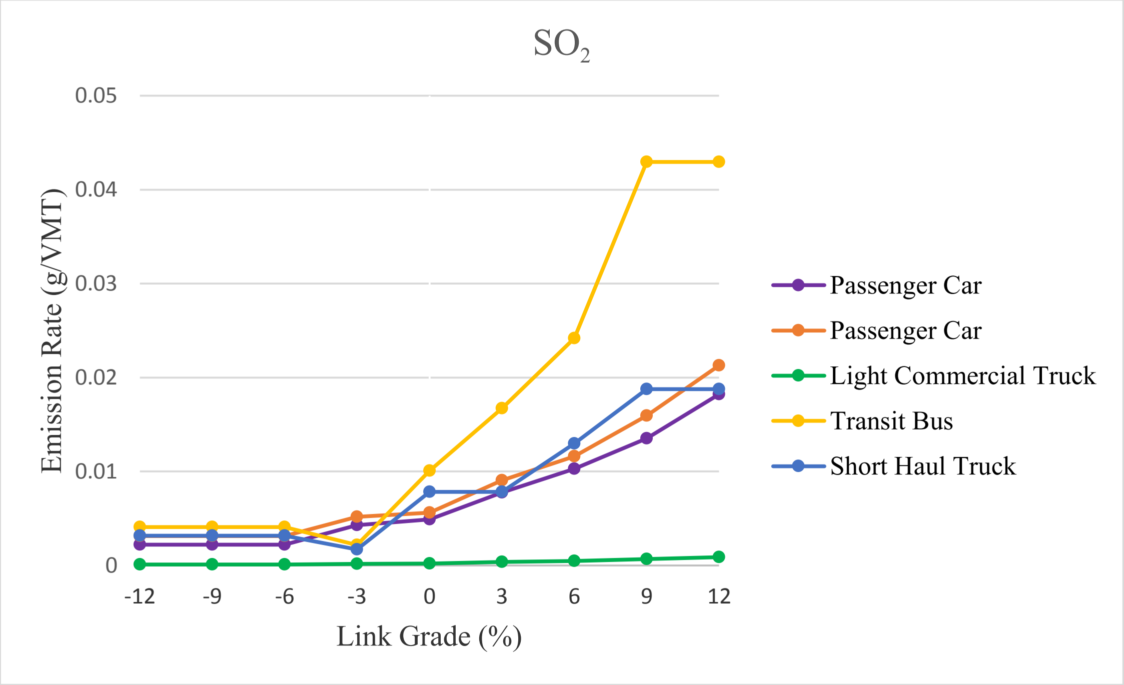


Figure 3-33 Variation in SO_2 Emission Rates by Grade and Vehicle Type during Cruising

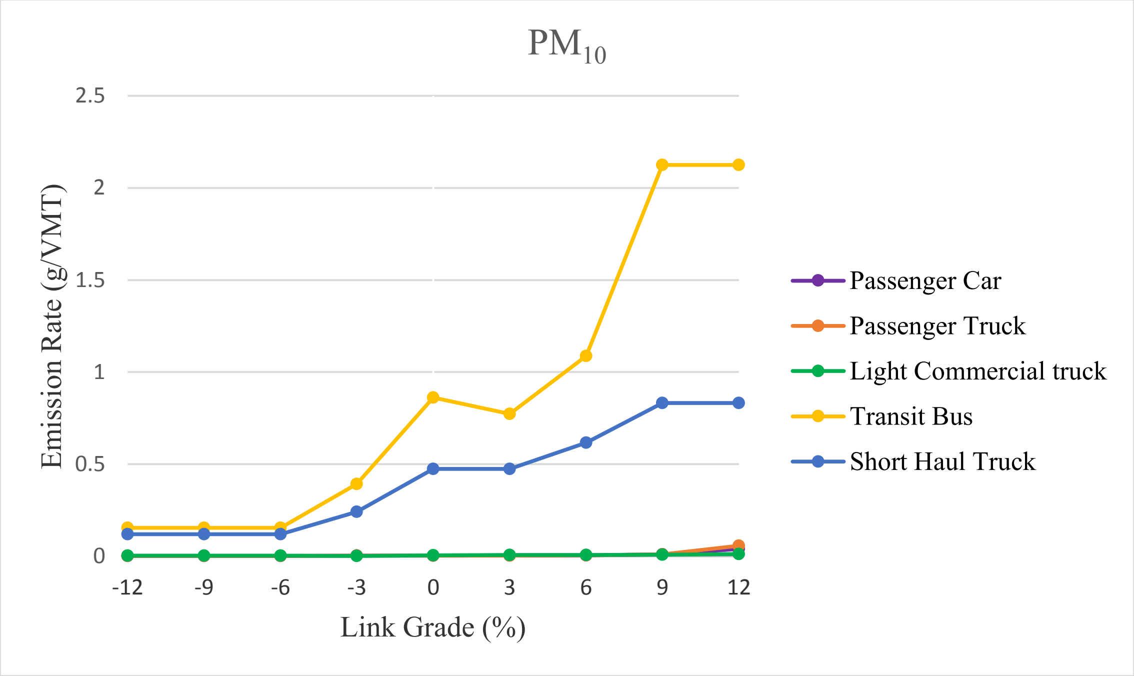


Figure 3-34 Variation in PM_{10} Emission Rates by Grade and Vehicle Type during Cruising

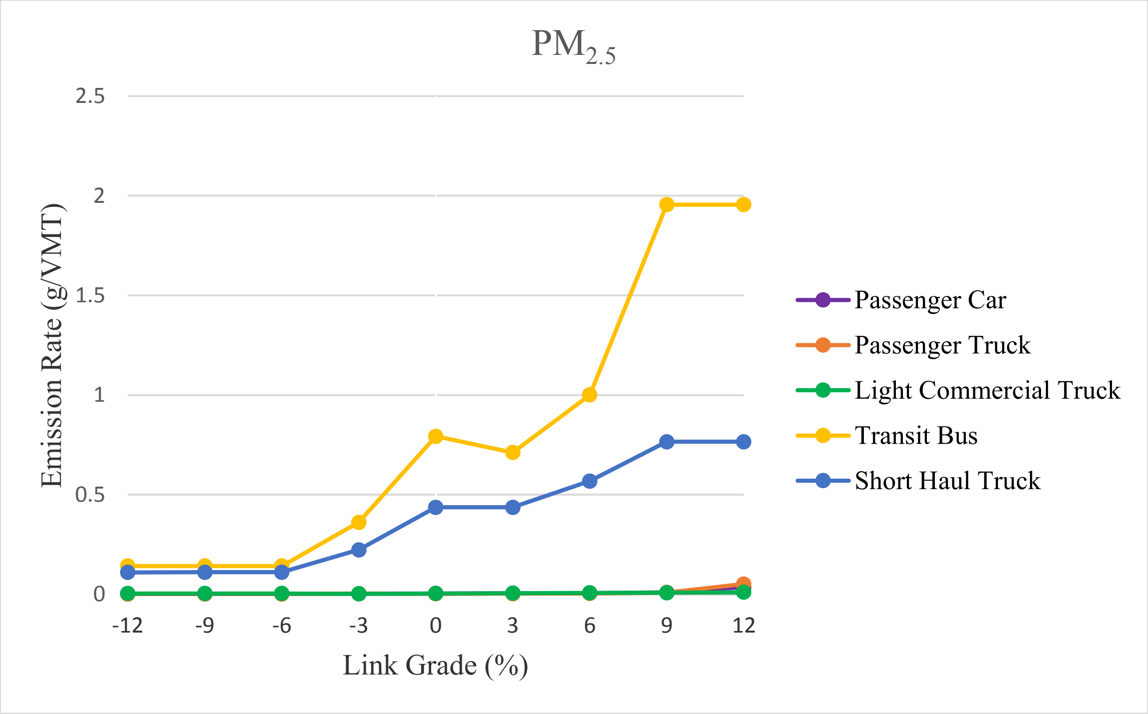


Figure 3-35 Variation in $PM_{2.5}$Emission Rates by Grade and Vehicle Type during Cruising

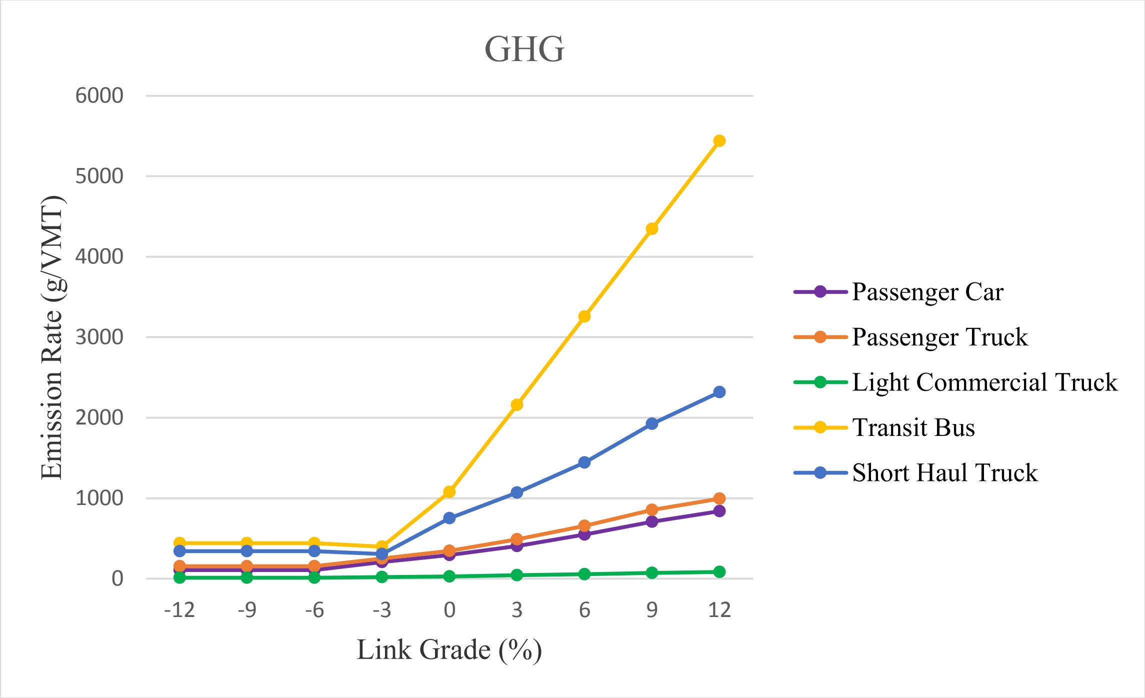


Figure 3-36 Variation in GHG Emission Rates by Grade and Vehicle Type during Acceleration

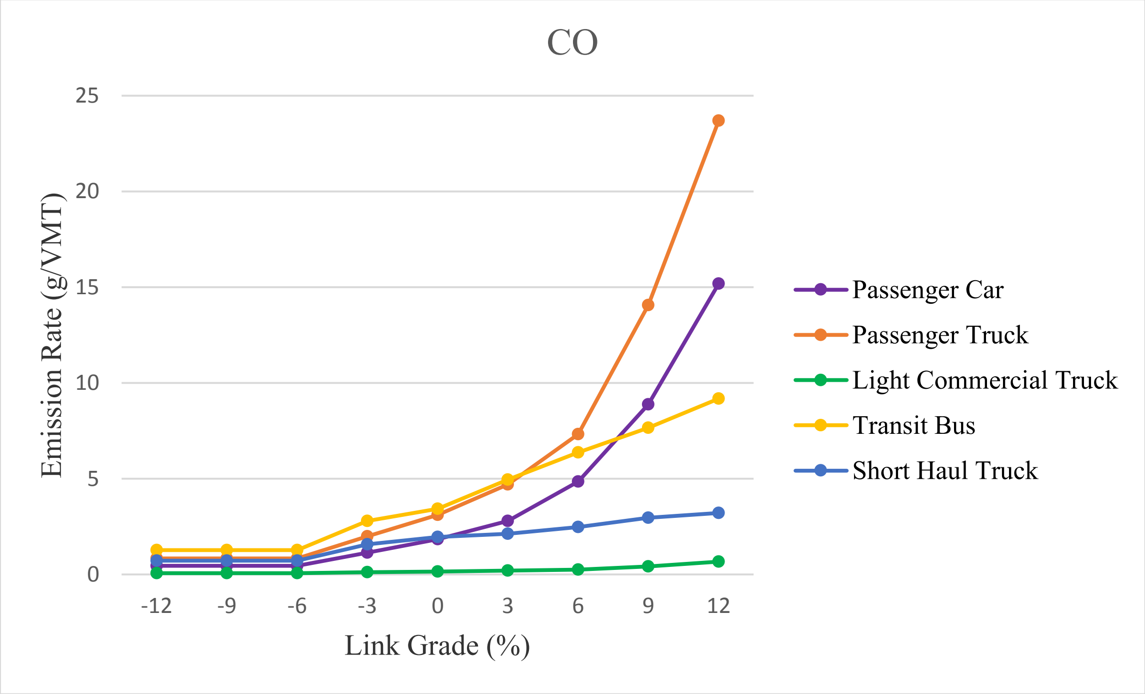


Figure 3-37 Variation in CO Emission Rates by Grade and Vehicle Type during Acceleration

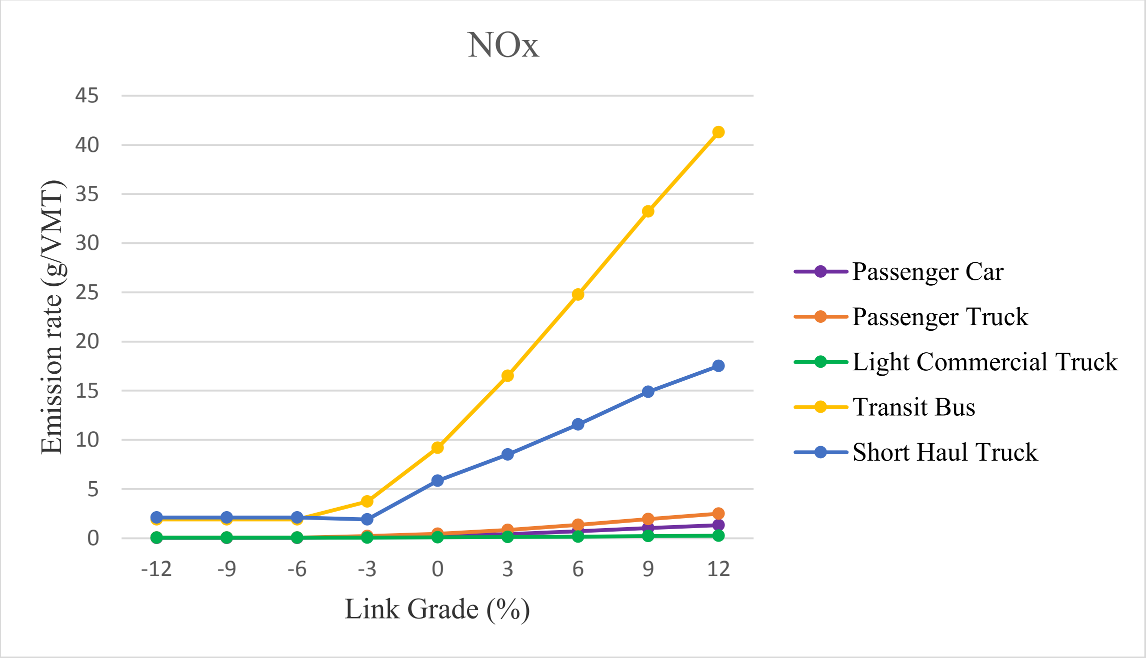


Figure 3-38 Variation in NOx Emission Rates by Grade and Vehicle Type during Acceleration

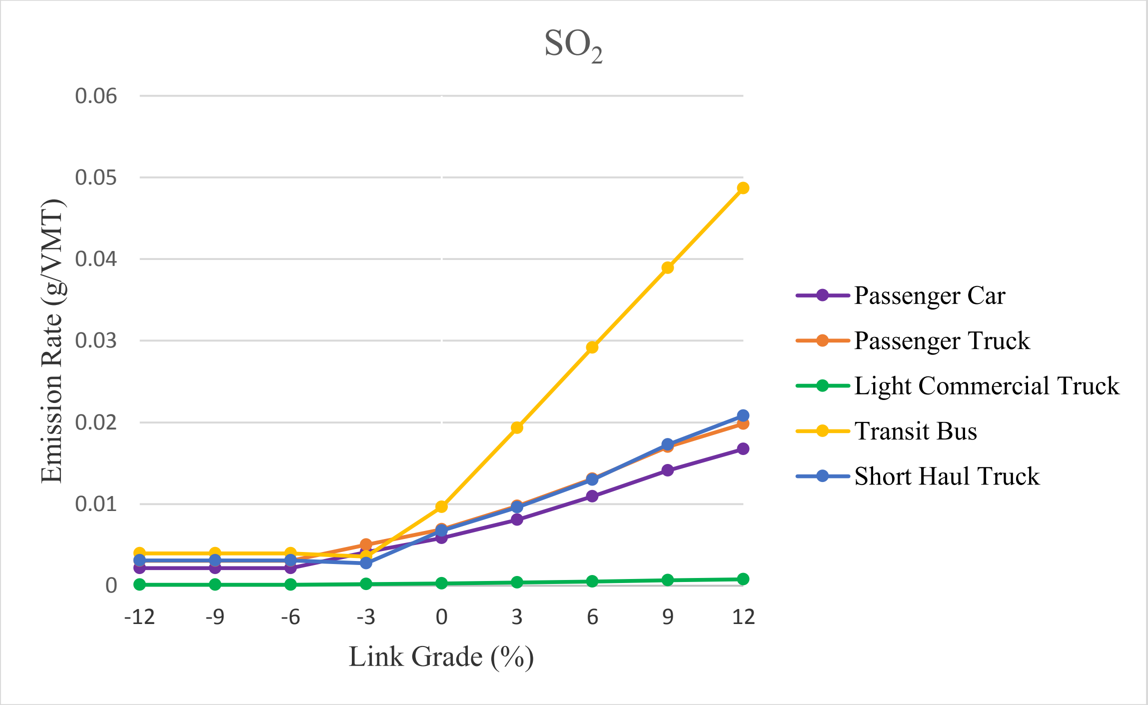


Figure 3-39 Variation in SO_2Emission Rates by Grade and Vehicle Type during Acceleration

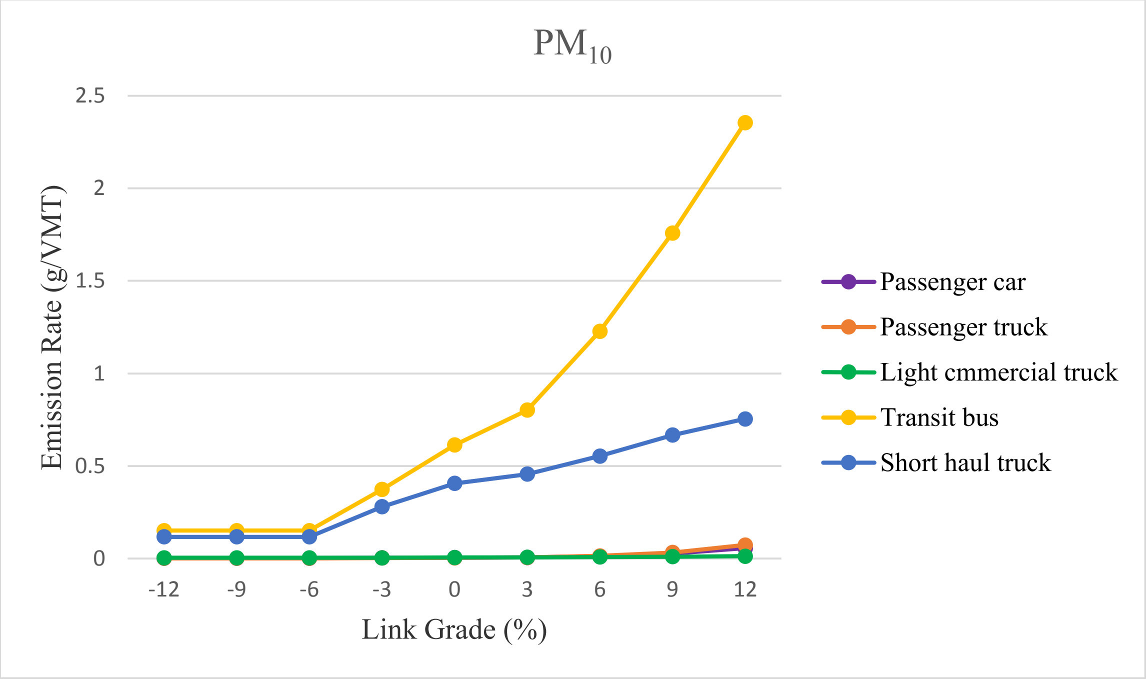


Figure 3-40 Variation in PM_{10}Emission Rates by Grade and Vehicle Type during Acceleration

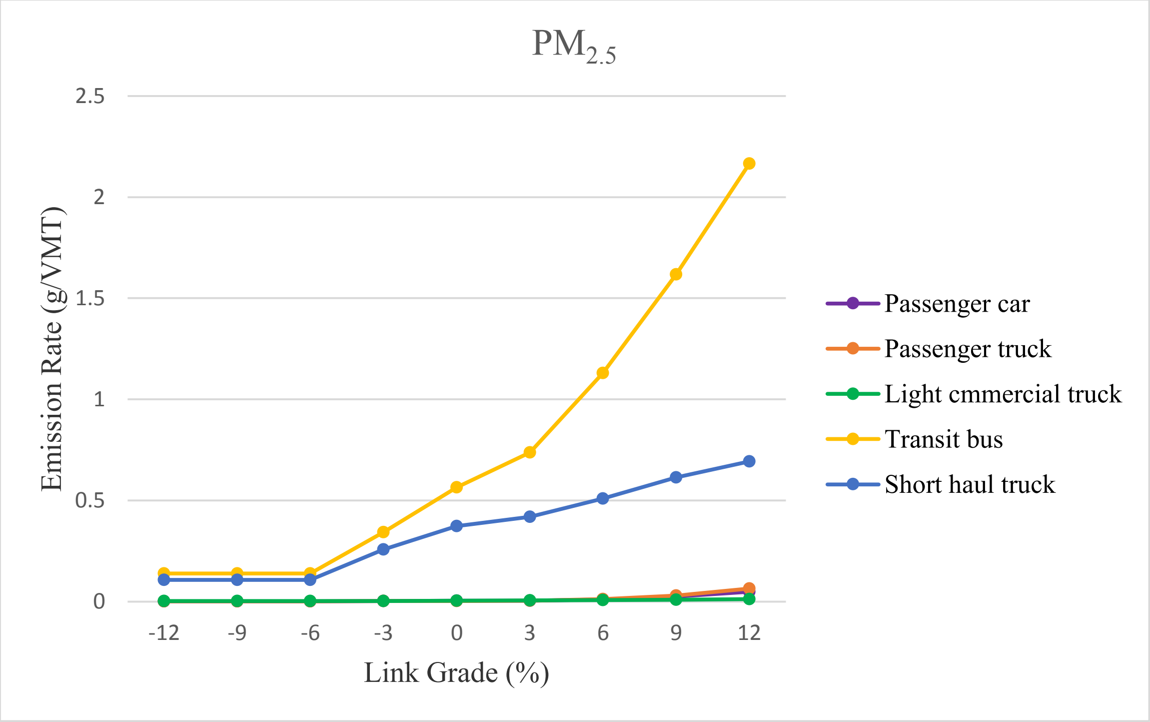


Figure 3-41 Variation in $PM_{2.5}$ Emission Rates by Grade and Vehicle Type during Acceleration

Additionally, Figure 3-30 to Figure 3-41 indicate that changes in emission rates with grades vary by vehicle type. Short haul trucks and transit buses exhibit the most significant effect in emission rates due to the change in grade compared to other types of vehicles. As the positive grade increases, emission rates of all pollutants produced by transit buses and short haul trucks reveal noteworthy increase. Conversely, the effect of grade is not very significant for passenger cars, passenger trucks, and light commercial trucks compared to transit bus and short haul trucks. Interestingly, only in the case of GHG, CO and SO_2 emission rates, passenger car and passenger truck response notably with grade change.

Note that, it is assumed that all types of vehicles are running at same speed during cruising, and at same acceleration rate during acceleration to capture the emission rate variation by vehicle types.

3.6.1.3 Evaluation of Combined Effects of Speed and Grade on Emission Rates

This sub section reveals the combined effect of speed and grade on emission rates of different pollutants. The straightforward interpretation of the effects of speed and grade could not be confirmed unless combined effects are evaluated. Therefore, link by link emission inventories generated from the sequential microscopic simulation and emission model are utilized to develop an emission rate matrix for the combination of twenty-six speeds (ranging from 0 mph to 25 mph) and twenty-five grades (ranging from -12 % to +12 %). Figure 3-42 to Figure 3-47 demonstrate emission rate patterns of GHG, CO, NOx, SO_2, PM_{10}, and $PM_{2.5}$ due to the combined effect of speed and grade, which exhibits a complex nonlinear relationship among speed, grade, and emission rates.

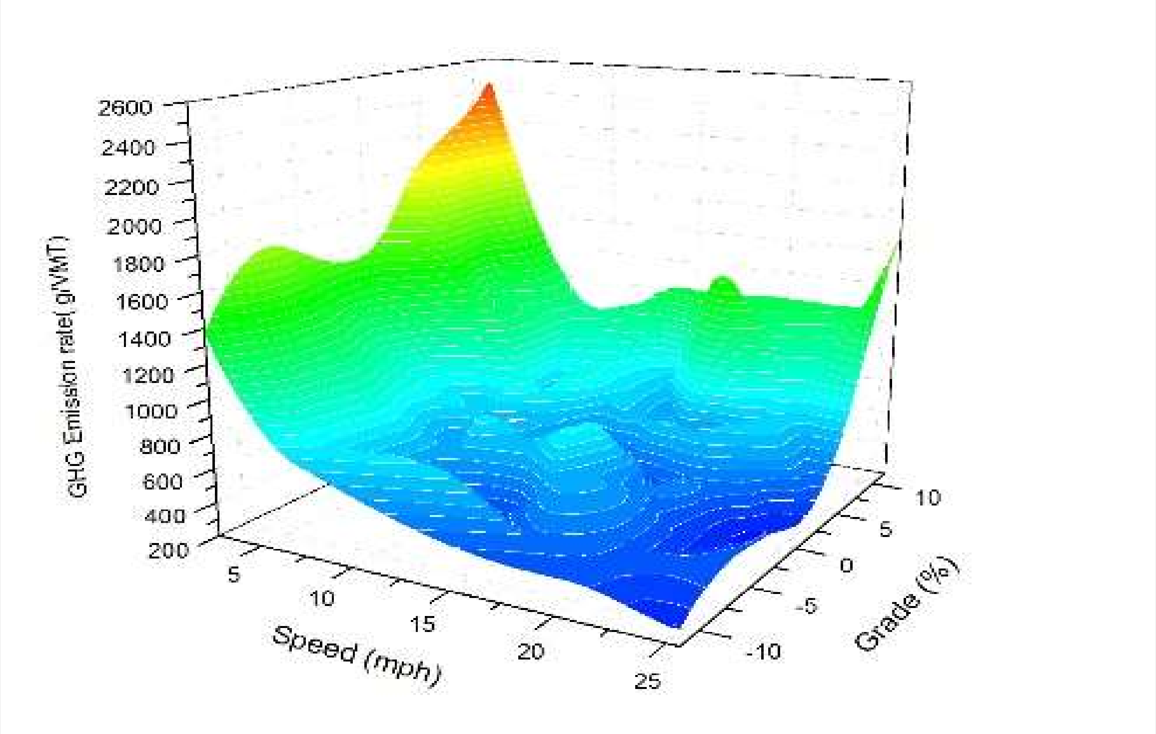


Figure 3-42 Combined Effect of Speed and Grade on GHG Emission Rate

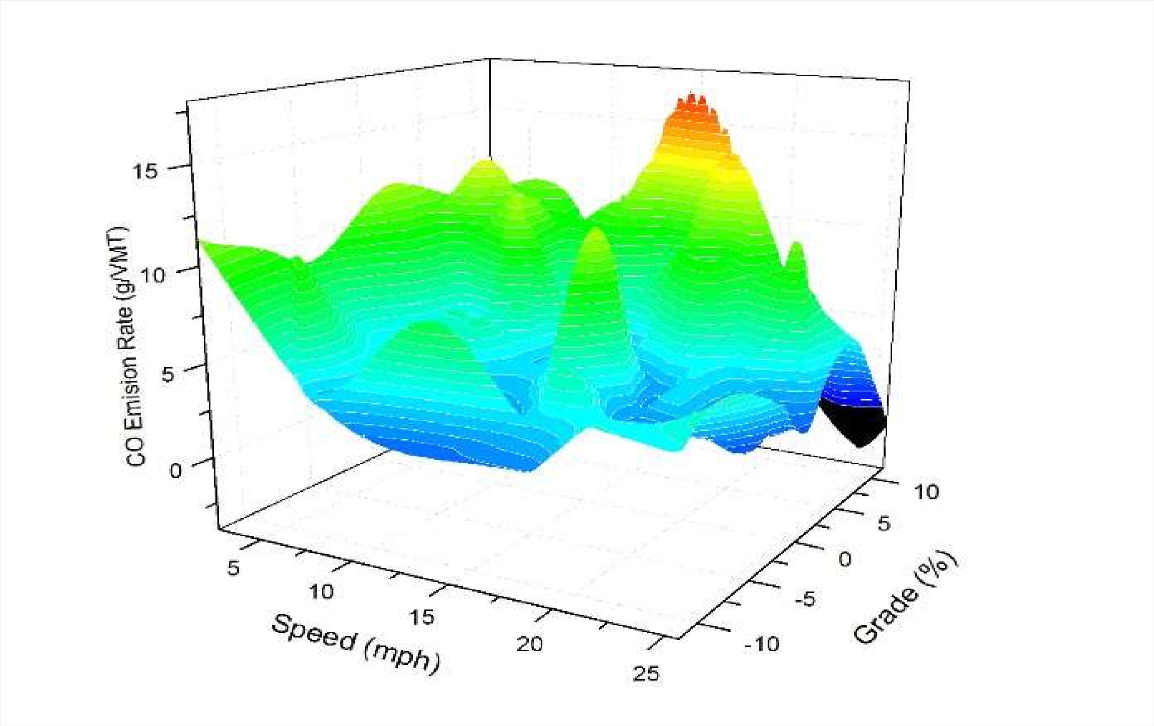


Figure 3-43 Combined Effect of Speed and Grade on CO Emission Rate

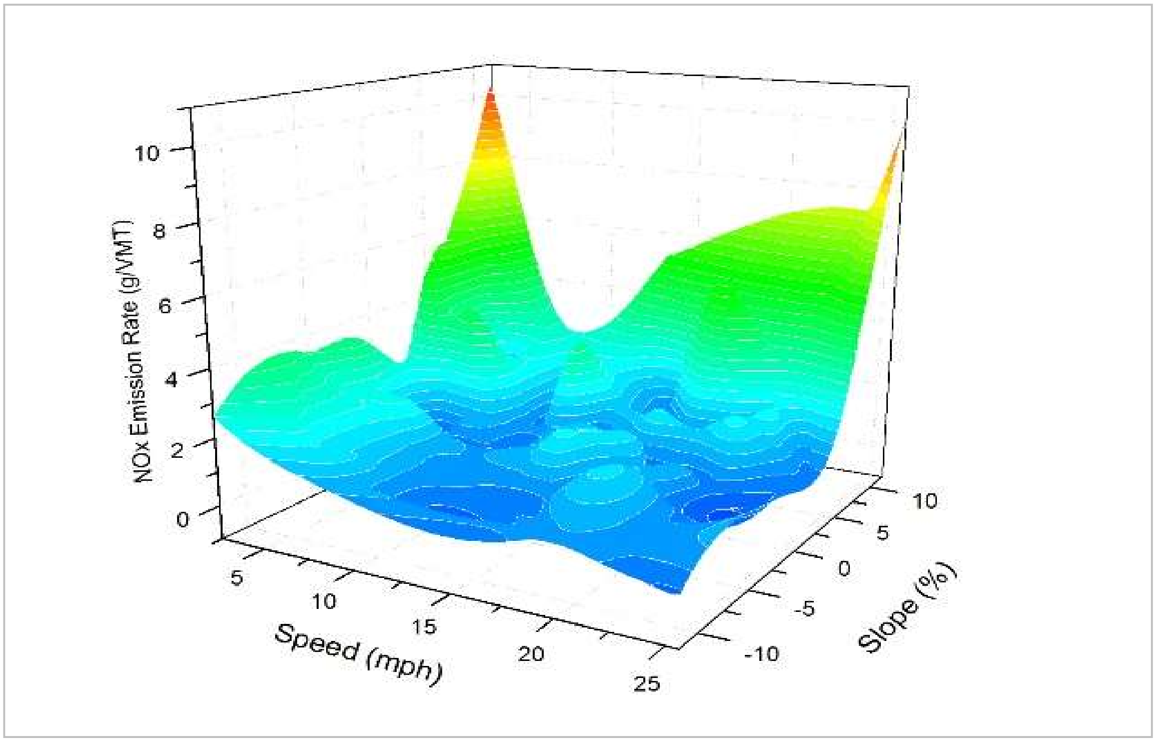


Figure 3-44 Combined Effect of Speed and Grade on NOx Emission Rate

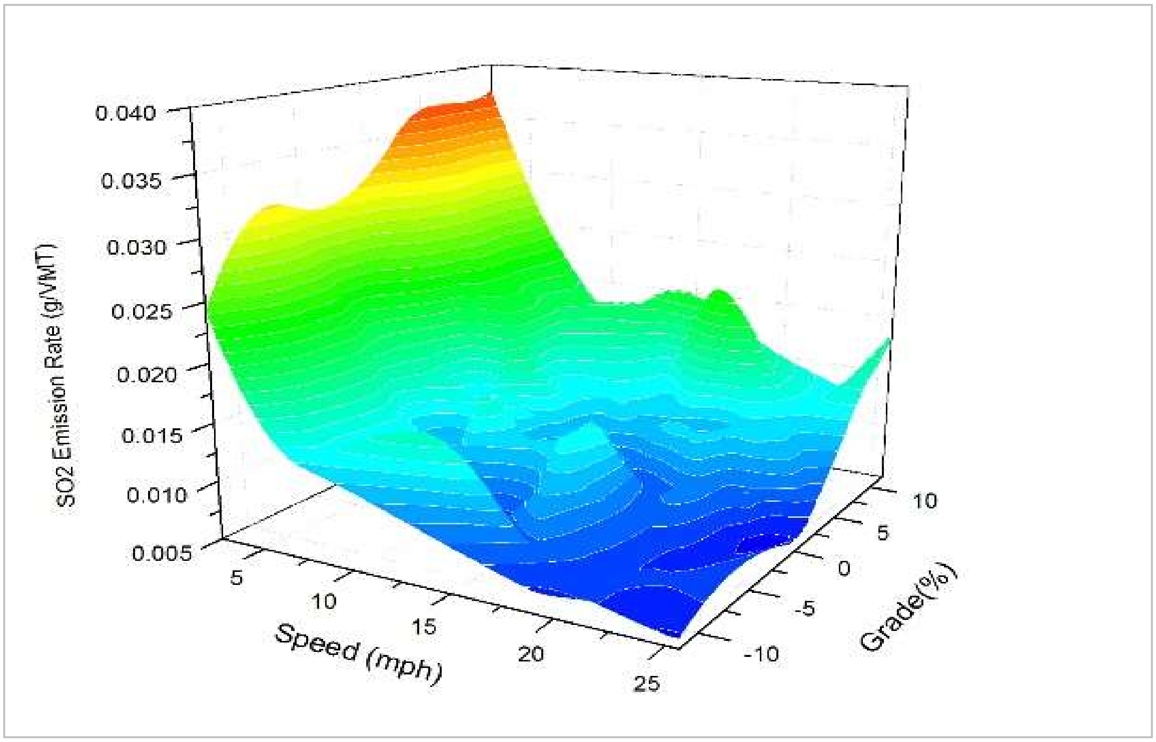


Figure 3-45 Combined Effect of Speed and Grade on SO_2 Emission Rate

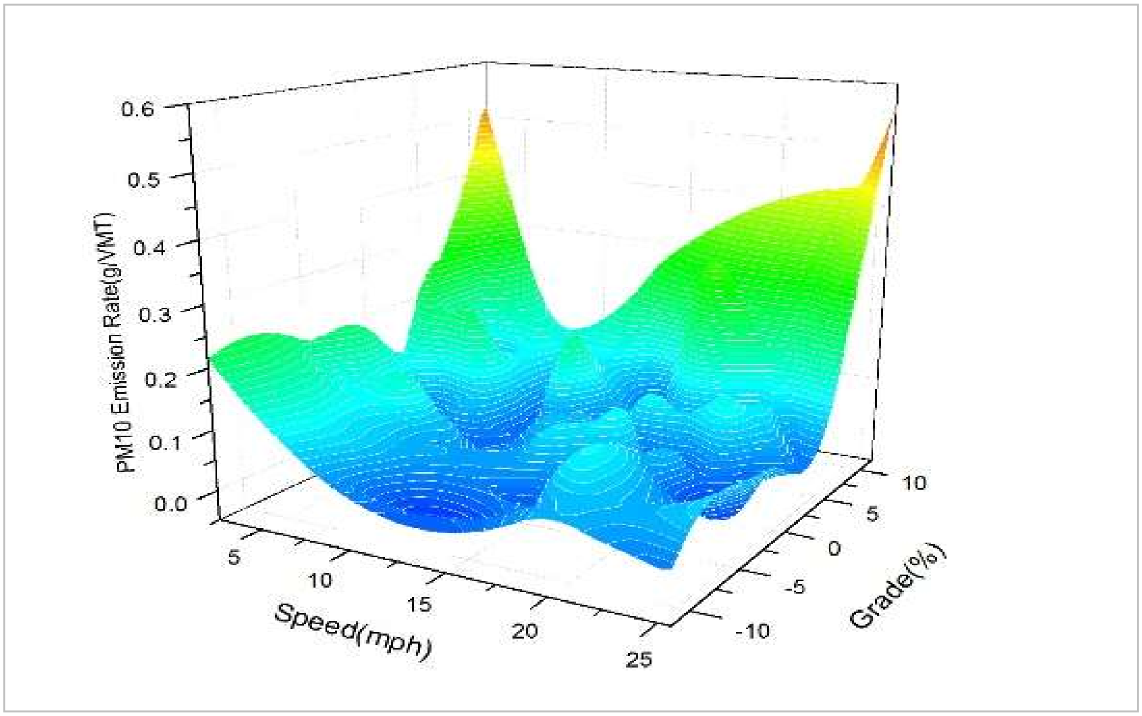


Figure 3-46 Combined Effect of Speed and Grade on PM_{10} Emission Rate

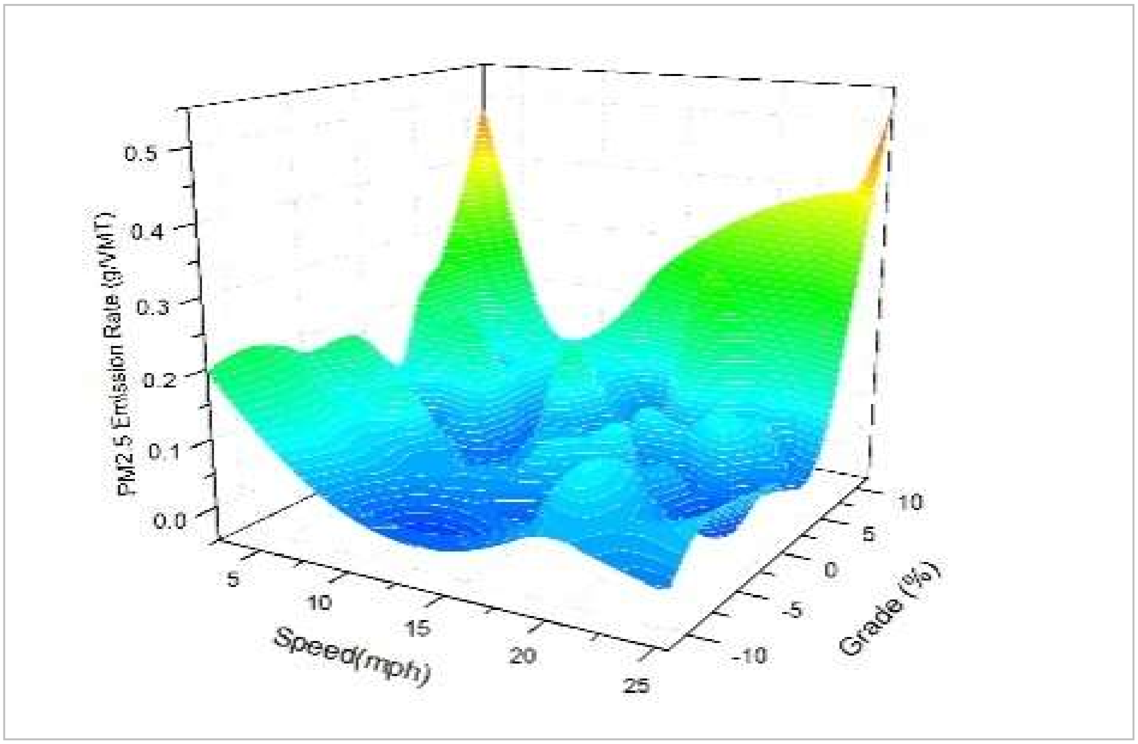


Figure 3-47 Combined Effect of Speed and Grade on $PM_{2.5}$ Emission Rate

As seen in Figure 3-42 to Figure 3-47, the fluctuation of emission rates is small in negative grades, whereas the fluctuation is comparatively high in positive grades. This implies that the effect of speed on emission rates is more dominant in positive grades. Note that emission rates which are in negative grades are particularly influenced by lower speed. Emission rates increase significantly in negative grades when the speed is less than 5 mph. These patterns of emission rate are found similar for all pollutants in negative grades.

On the other hand, in the case of positive grades, emission rates are increased significantly in both lower speed and higher speed. While comparing among all pollutants at higher grade, emission rates for GHG and SO_2 are found to be dominated by lower speed. Emission rates of these pollutants increase significantly at lower speed (less than 10 mph). Conversely, for PM_{10}, $PM_{2.5,}$ and NO_X pollutants; emission rates are increased significantly in higher speed ranging from 10 mph to 25 mph. However, the emission rates of CO do not follow a particular pattern, which indicates that CO emission is highly sensitive to other factors, including the driving behaviour.

3.6.1.4 Variation in Emission Rates by Vehicle Age and Vehicle Type

In this study, emission rates for vehicle model years 1984 to 2014 are generated for passenger car, transit bus and short haul truck. Figure 3-48 to Figure 3-53 demonstrate that emission rate increases with the vehicle age. A significant increase in emission rate of NOx, PM_{10}, and PM $_{2.5}$ by older aged transit bus is observed compared to other types of vehicles. On the other hand, GHG and SO_2 emission rates do not fluctuate significantly with the increase of vehicle age. Note that, although passenger cars are primarily responsible for the CO emissions (*Irin and Habib, 2015*), transit buses aged between 10 to 20 years (manufactured between 1994 and 2004) produce more CO compared to passenger car.

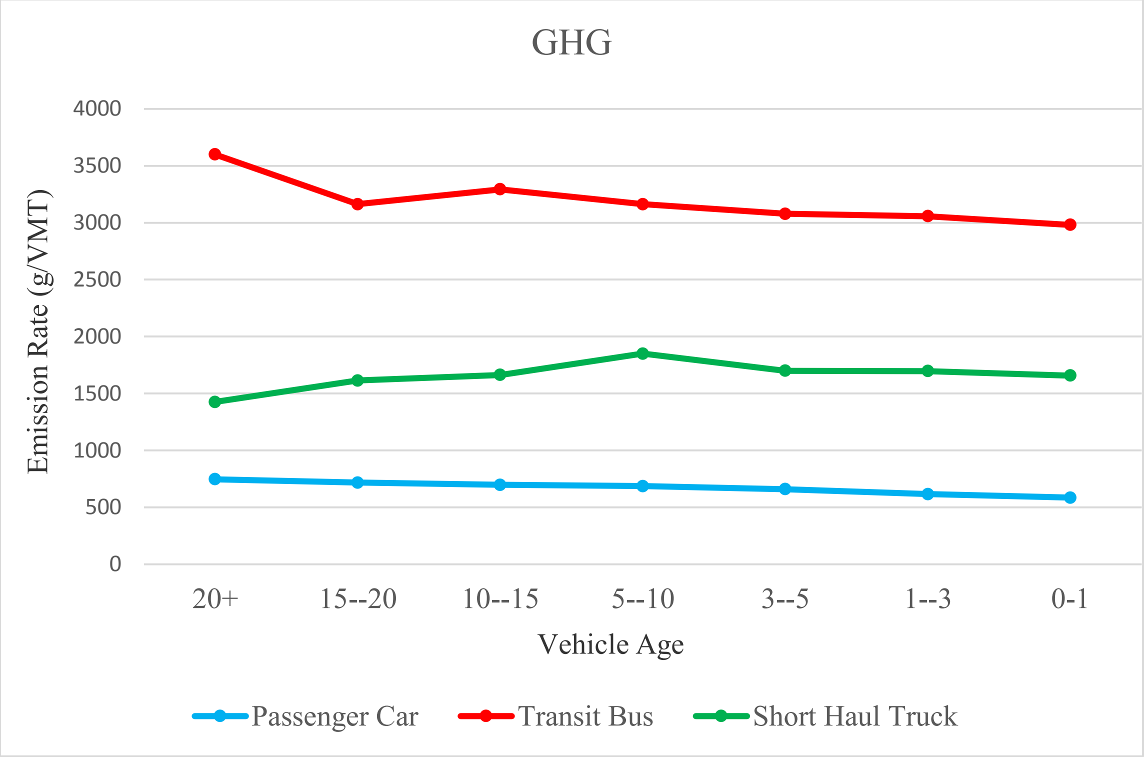


Figure 3-48 GHG Emission Rate by Vehicle Age and Vehicle Type

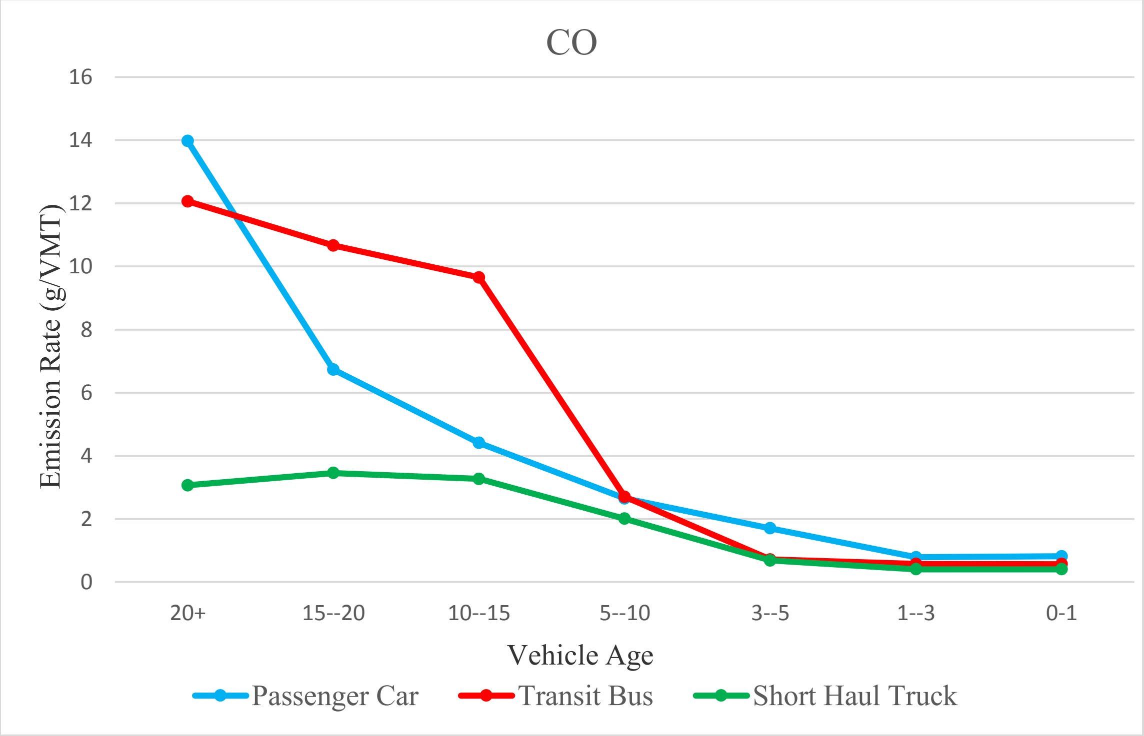


Figure 3-49 CO Emission Rate by Vehicle Age and Vehicle Type

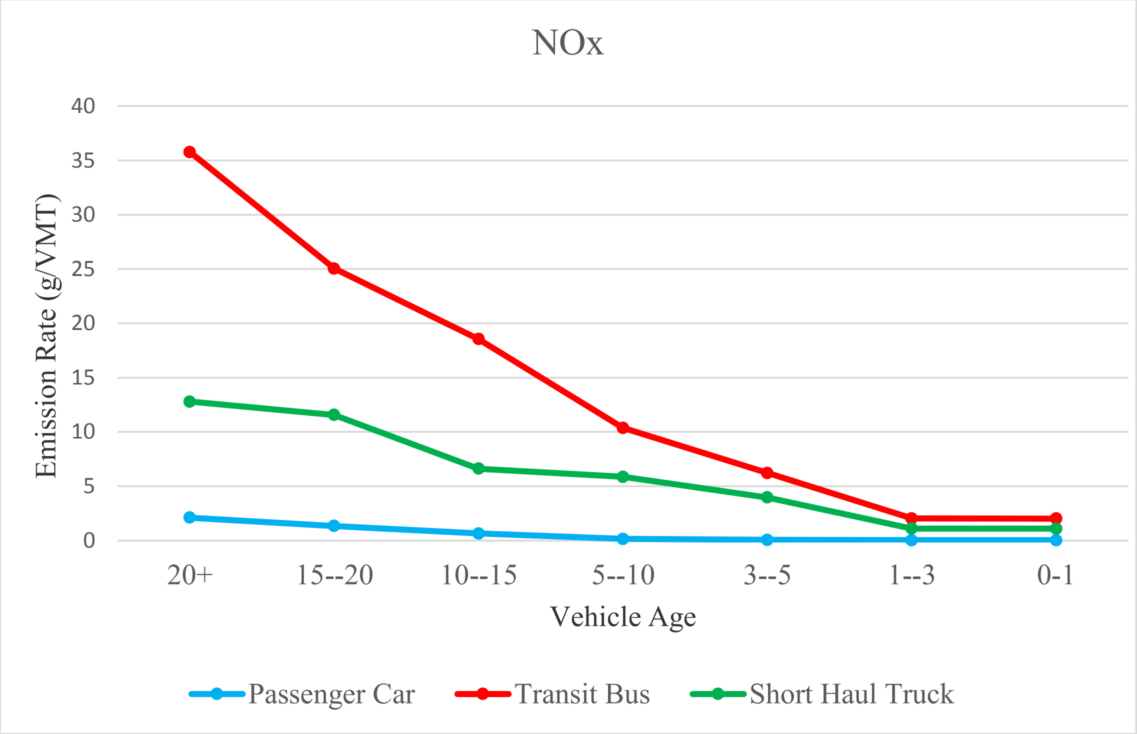


Figure 3-50 NOx Emission Rate by Vehicle Age and Vehicle Type

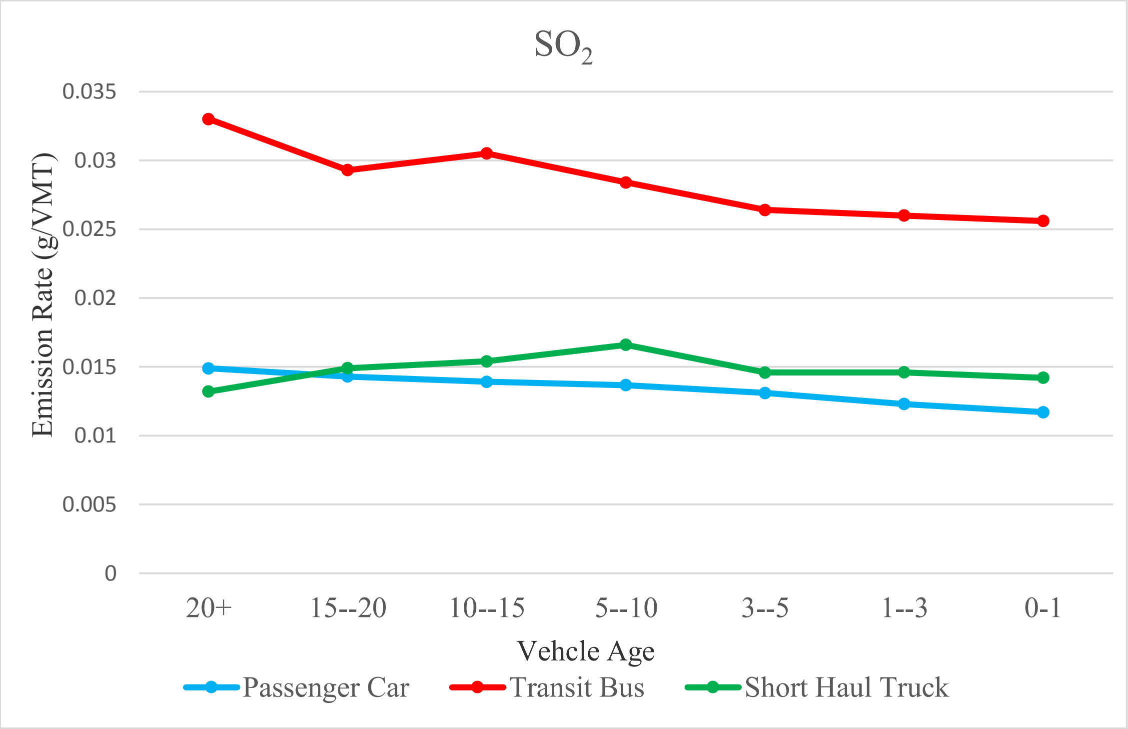


Figure 3-51 SO_2 Emission Rate by Vehicle Age and Vehicle Type

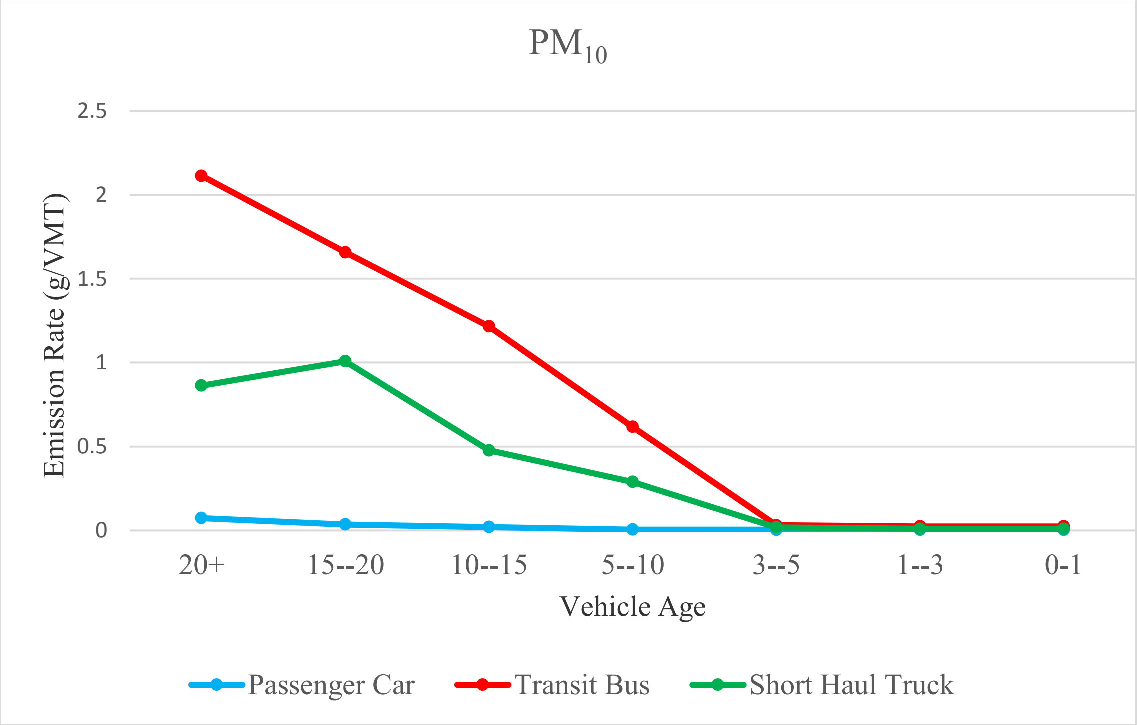


Figure 3-52 PM_{10} Emission Rate by Vehicle Age and Vehicle Type

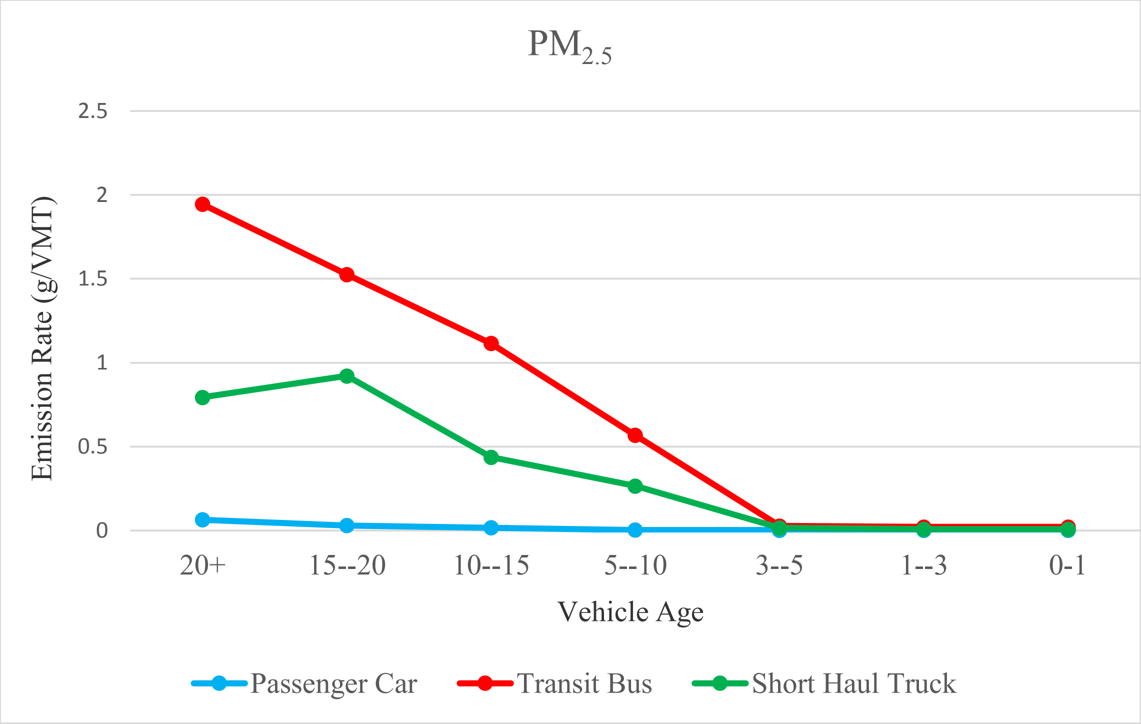


Figure 3-53 $PM_{2.5}$ Emission Rate by Vehicle Age and Vehicle Type

3.6.2 Effect of Congestion Level Variation on Emissions in Existing Network

In order to understand the pattern of the emissions (g) with congestion level variation at different times of the day, the hourly total emission is divided into hourly running emission and hourly idling emission. Hourly running, and idling emission are estimated by calculating hourly total running time and idling time of vehicles in each link based on microscopic traffic simulation model. Note that it is assumed that vehicles having running speed less than 1.96 mph are in idling mode. Hourly running, and idling emissions of all pollutants for AM peak, off peak and PM peaks are illustrated in Figure 3-54 to Figure 3-57. For instance, hourly running emissions of NOx are 2476.34 g, 2959.86 g, and 2533.57 g in AM peak, off peak and PM peak periods respectively. Moreover, hourly idling emissions of NOx are 742.67 g, 201.76 g, and 241.36 g in AM peak, off peak and PM peak periods respectively. It is observed that, idling emissions of all pollutants are maximum in AM and PM peak periods and minimum in off peak period, which is expected since there is relatively less traffic congestion in off peak period than AM and PM peak periods. The average network delay is also found minimum in off peak period (2.5 minutes) whereas in AM and PM peak periods, the average network delay goes relatively higher at 5.5 minutes and 4.5 minutes respectively. This reflects the fact that most of the commuters travel through downtown core in AM and PM peak periods. One of the interesting findings is that the variation of running emissions with time follows similar patterns to idling emissions of all pollutants, except PM_{10}, $PM_{2.5}$ and NOx. Presumably, truck is the primary contributors of PM_{10}, $PM_{2.5}$ and NOx emissions (*Irin and Habib, 2015*) and a large percentage of trucks run along the study corridor in off peak period (4.13%) compared to AM (2.47%) and PM (1.73%) peak periods, resulting a higher running emissions in off peak period.

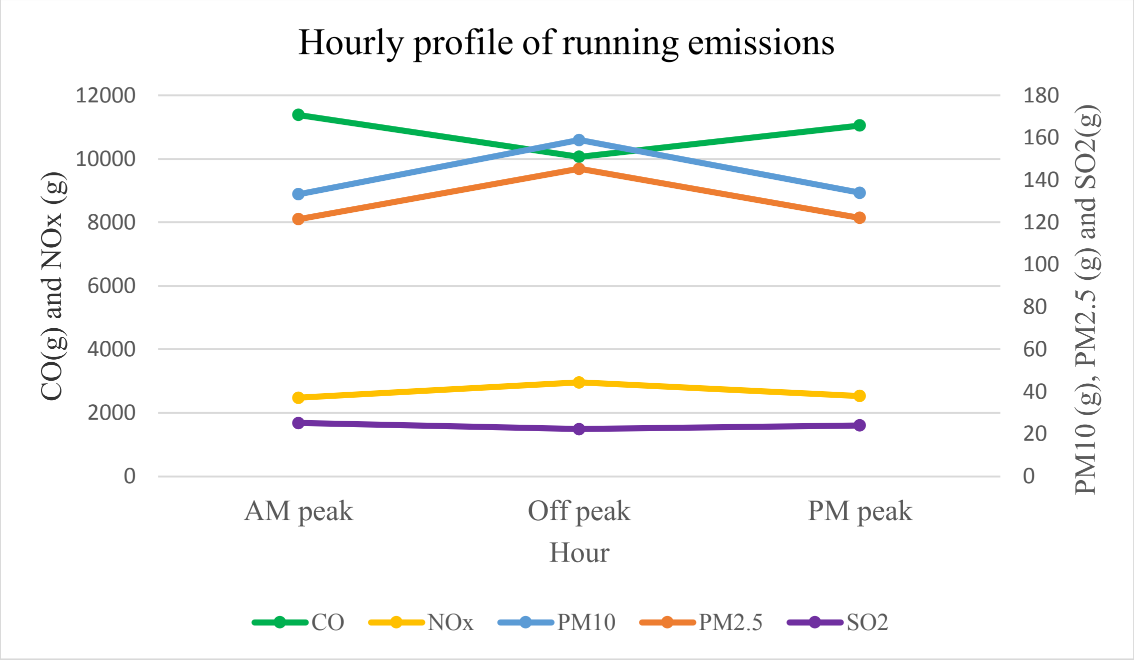


Figure 3-54 Hourly Profile of Running Emissions (g) of CO, NOx, SO_2, PM_{10} and $PM_{2.5}$

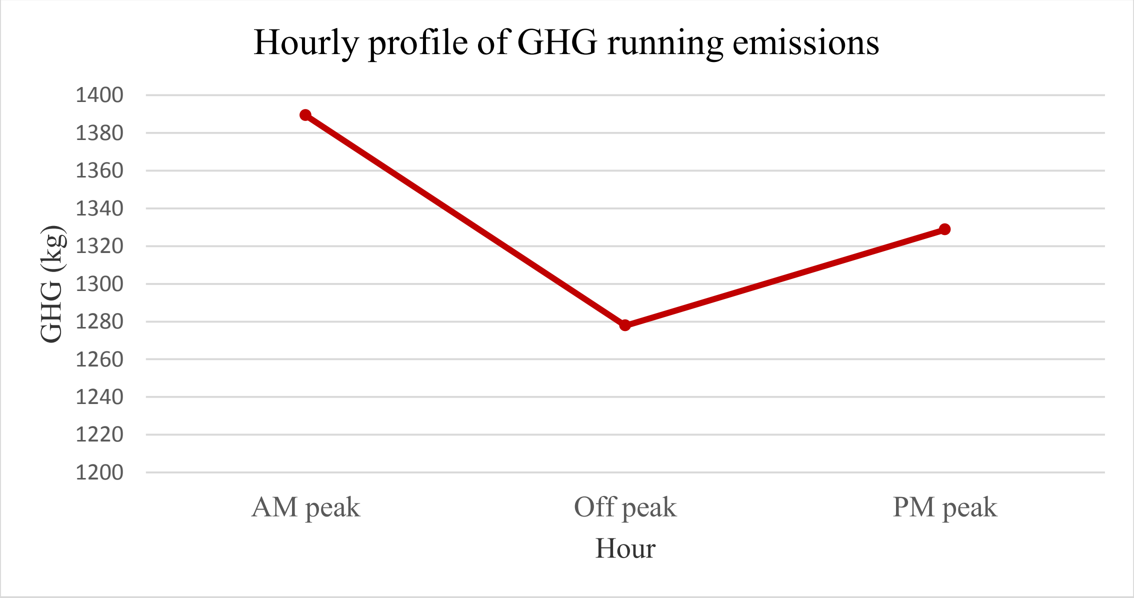


Figure 3-55 Hourly Profile of Running Emissions (kg) of GHG

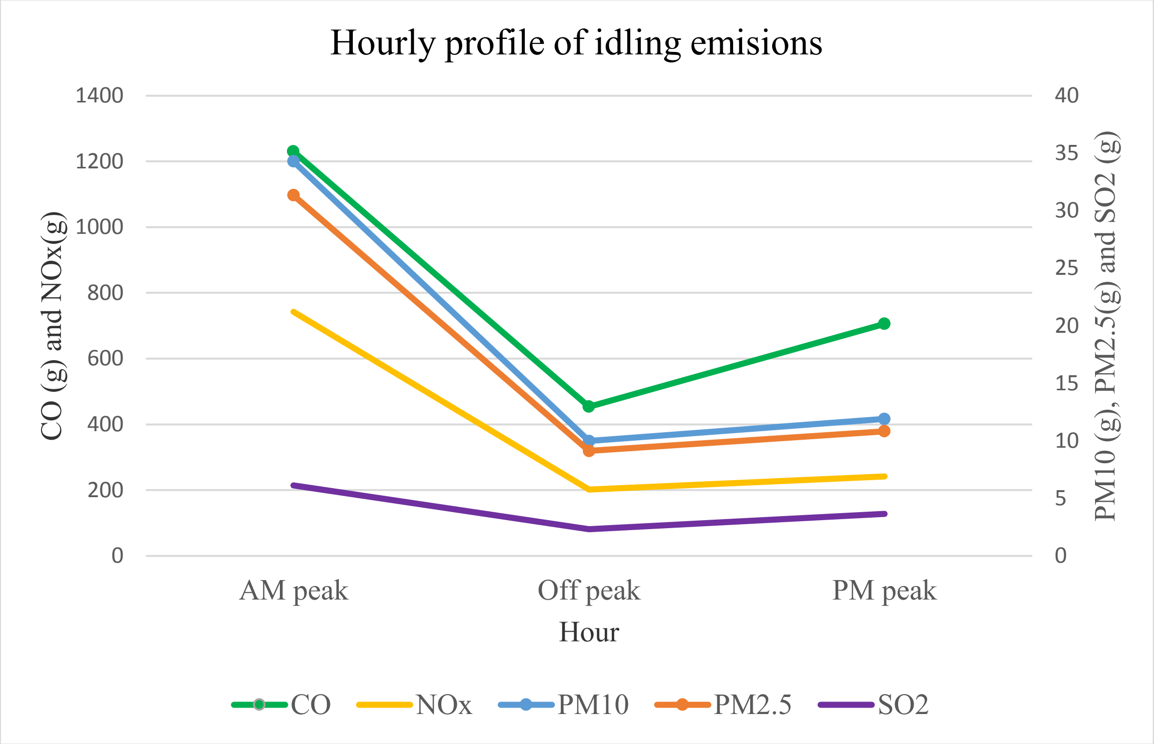


Figure 3-56 Hourly Profile of Idling Emissions (g) of CO, NOx, SO_2, PM_{10} and $PM_{2.5}$

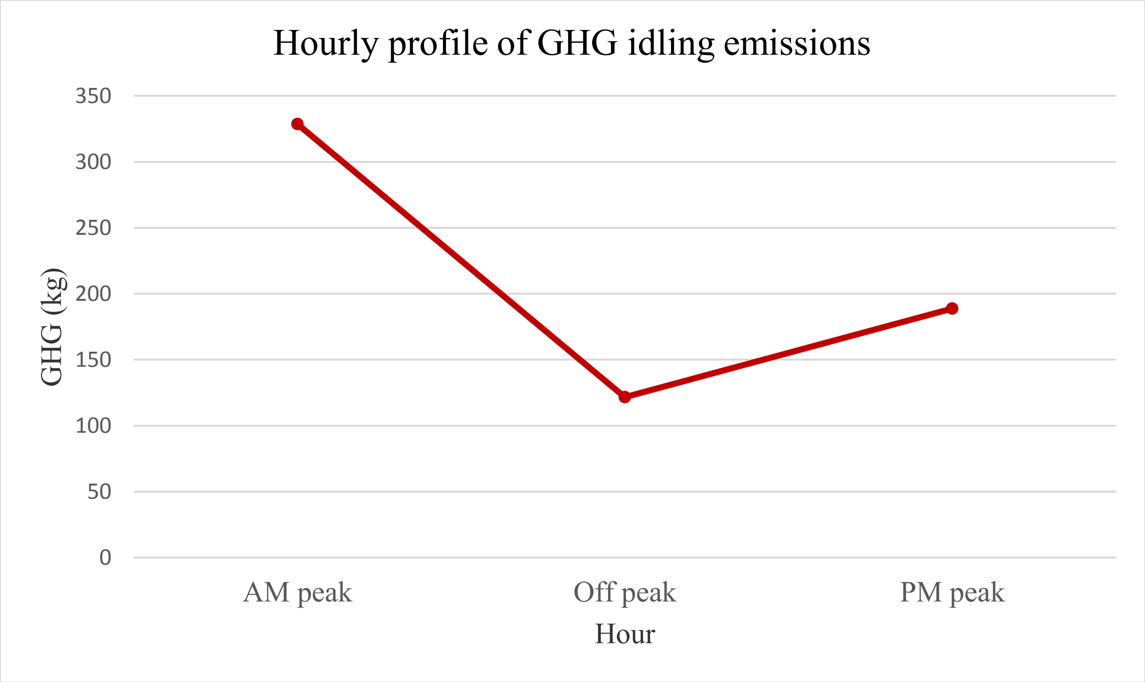


Figure 3-57 Hourly Profile of Idling Emissions (kg) of GHG

A total thirty-six maps (Appendix B and Appendix C) are generated using Arc GIS to represent the spatial distribution of hourly total emissions (g), and idling emissions (g) of GHG, CO, NOx, SO_2, PM_{10} and $PM_{2.5}$ in the study area. These maps assist to identify the most vulnerable links in the study area with respect to emissions based on link location and trip frequency. The result indicates that, the highest emissions are associated with those links which connect the northern part and southern part with the Downtown Core. Residential areas in the western part are experiencing relatively less pollution. The reason behind this behaviour is that large number of commuters enters into the Downtown Core via MacDonald Bridge in AM peak and returns in PM peak period.

3.6.3 Assessment of Emissions

In order to assess the effect of infrastructure renewal on vehicular emissions, two levels of measures (shown in Figure 3-58) are evaluated: (1) network level evaluation (2) Area level evaluation. These two levels of measures are briefly discussed below.

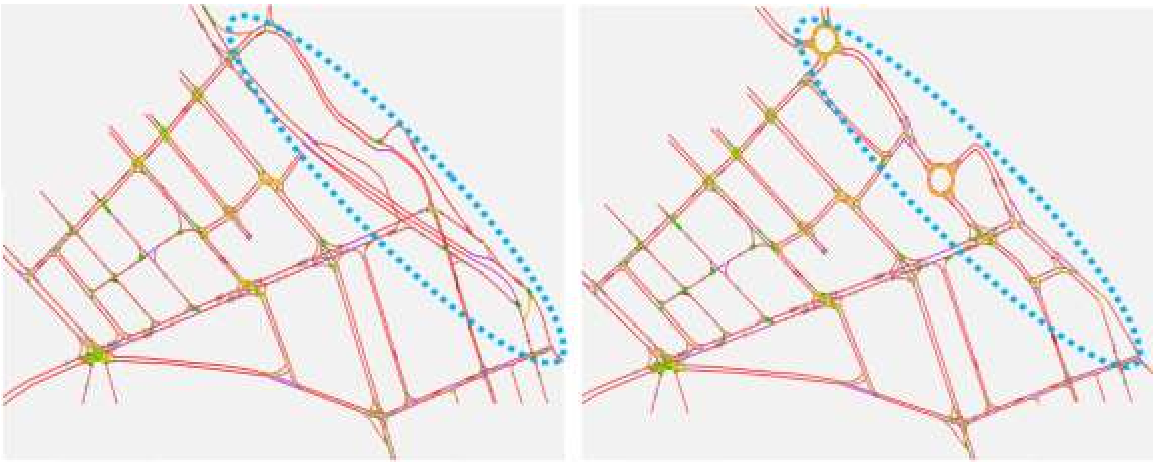


Figure 3-58 Existing and Proposed network

Note that the network level evaluation is conducted for the whole network shown in Figure 3-58. ⬭ depicts multi-grade Cogswell Interchange area in the existing network, which will be replaced by the at-grade roundabouts in the proposed network. This portion of the network is used for the area level evaluation.

3.6.3.1 Network Level Emission Evaluation

Table 3-10, 3-11 and 3-12 report network wide total emissions and emission rates estimated for both scenarios as well as the percentage change in emissions due to the infrastructure renewal. For instance, in the PM peak period of the existing network, the total amount of GHG and SO_2 emission are 1517410.73 g and 27.72 g respectively. In the proposed network, the amount of GHG and SO_2 emission are 1924826.9 g and 35.64 g respectively. It is found that GHG has the maximum amount of emission (g) and SO_2 has the minimum amount of emission (g) among all pollutants in both network.

Table 3-10 Total Emissions (g) and Emission Rates (g/VMT) of All Pollutants in Existing Network and Proposed Network for AM Peak Period

Pollutant Name	**Existing Network**		**Proposed Network**		**% Increase in Total Emission**	**% Increase in Emission Rate**
	Total Emission (g)	**Emission Rate (g/VMT)**	**Total Emission (g)**	**Emission Rate (g/VMT)**		
AM Peak (8 AM – 9 AM)						
GHG	1717941.79	604.271	1910244.63	780.329	11.194	29.136
CO	12616.55	4.438	14140.62	5.776	12.079	30.165
NOx	3219.01	1.132	3431.76	1.402	6.609	23.811
SO_2	31.36	0.011	35.00	0.014	11.607	29.607
PM_{10}	167.55	0.059	174.81	0.071	4.333	21.168
$PM_{2.5}$	152.86	0.054	159.35	0.065	4.246	21.067

Table 3-11 Total Emissions (g) and Emission Rates (g/VMT) of All Pollutants in Existing Network and Proposed Network for Off Peak Period

Pollutant Name	Existing Network		Proposed Network		% Increase in Total Emission	% Increase in Emission Rate
	Total Emission (g)	Emission Rate (g/VMT)	Total Emission (g)	Emission Rate (g/VMT)		
Off Peak (12 PM – 1 PM)						
GHG	1399375.55	590.703	1545053.49	748.935	10.410	26.787
CO	10519.19	4.440	11510.16	5.579	9.421	25.651
NOx	3161.62	1.335	3386.59	1.642	7.116	23.004
SO_2	24.67	0.010	27.44	0.013	11.228	27.722
PM_{10}	168.92	0.071	176.21	0.085	4.316	19.789
$PM_{2.5}$	154.4	0.065	161.01	0.078	4.281	19.749

Table 3-12 Total Emissions (g) and Emission Rates (g/VMT) of All Pollutants in Existing Network and Proposed Network for PM Peak Period

Pollutant Name	Existing Network		Proposed Network		% Increase in Total Emission	% Increase in Emission Rate
	Total Emission (g)	Emission Rate (g/VMT)	Total Emission (g)	Emission Rate (g/VMT)		
PM Peak (4 PM – 5 PM)						
GHG	1517410.73	611.859	1924826.9	867.821	26.849	41.833
CO	11759.72	4.742	14059.59	6.339	19.557	33.679
NOx	2774.93	1.119	3198.72	1.442	15.272	28.889
SO_2	27.72	0.011	35.64	0.016	28.571	43.768
PM_{10}	145.91	0.059	160.37	0.072	9.910	22.893
$PM_{2.5}$	132.97	0.054	146.09	0.066	9.867	22.845

It is observed that, total emissions and emission rates are higher in the proposed network with respect to the existing network. For instance, in the existing network (business-as-usual scenario), the total amount of NOx emission is 2774.93 g with an emission rate of 1.119 g/VMT during PM peak period. On the other hand, the total amount of NOx emission is 3198.72 g in the PM peak period of the proposed network with an emission rate of 1.442 g/VMT. Also note that the increased percentage of emission rate is comparatively higher than the increased percentage of total emissions. For example, the increased percentage of NOx emission rate is 28.889 % whereas, the increased percentage of total NOx emission is 15.272% during PM peak period. This indicates that vehicles are experiencing a significant change in driving cycle with higher frequency of acceleration and deceleration due to the increased congestion and changed road configuration in the proposed network.

To visualize the spatial change of emissions across the network, link-level emission variation in the proposed network compared to the existing network is illustrated using Arc GIS in Appendix D. Map D1 to Map D18 demonstrate the percentage change in emissions in the proposed network compared to the existing network. It is clearly observed that the highest increase in emissions occurs at the links immediately adjacent to the roundabout area. This is due to the fact that, these links serve as major connector links to the roundabout area. The increase in emissions in these connector links results from an extended idling hour and large queue length in congestion prior to accessing the roundabouts. Moreover, the increase in congestion in these links causes spillover effect in the whole network.

In order to better illustrate this point, Figure 3-59 and 3-60 demonstrate the simulated instantaneous speed profile of each link for 110 seconds in the existing and proposed network respectively. It is interesting to find that although demolition of interchange reduces long waiting time at the immediate vicinity, it is distributing congestion over the other areas of the network.

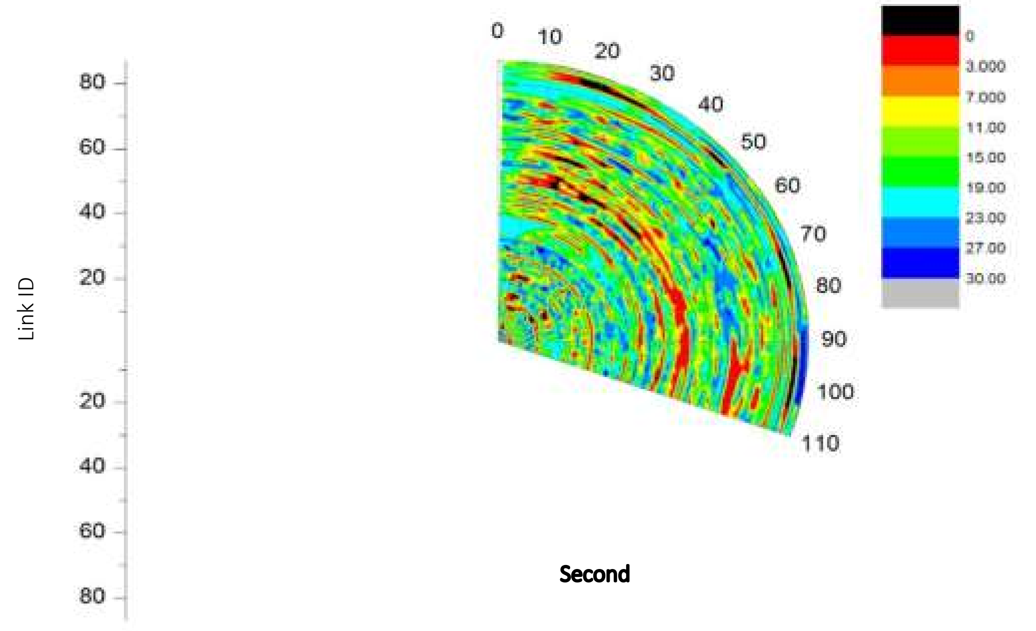


Figure 3-59 Simulated Instantaneous Speed Profile in the Existing Network

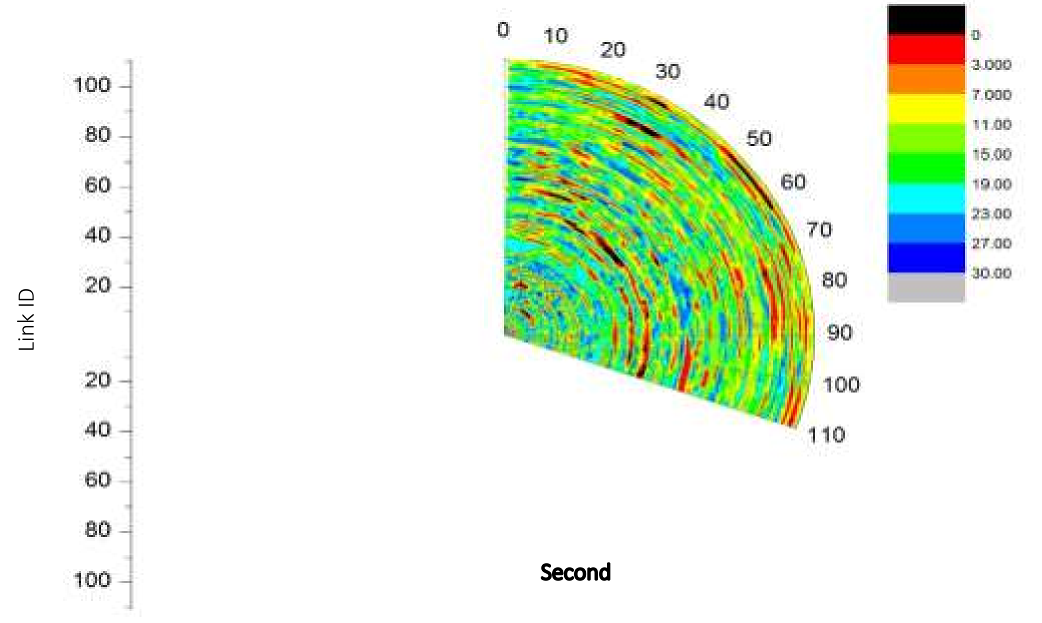


Figure 3-60 Simulated Instantaneous Speed Profile in the Proposed Network

Figure 3-61 and Figure 3-62 presents the frequency distribution of simulated instantaneous speed of the existing network and the proposed network. In the existing network, 5.44 % links have average speed less than 5 mph, 17.69% between 5-10 mph, 23.47% between 10-15 mph, 29.25% between 15-20 mph, and 24.15% links have speed greater than 20 mph. On the other hand, in the proposed network, 12.31% links have average speed less than 5 mph, 19.82% between 5-10 mph, 27.33% between 10-15 mph, 24.92 % between 15-20 mph and 15.62% links have speed greater than 20 mph. Figure 3-63 sheds more insights in comparing the speed distribution of the two networks. It reveals that frequency distribution of speed has shifted to the left in the proposed network in comparison to the existing network. It is observed that speed range of highest frequency is shifted from 15-20 mph to 10-15 mph in the proposed network. This investigation leads to the fact that, higher percentage of links run at lower average speed in the proposed network.

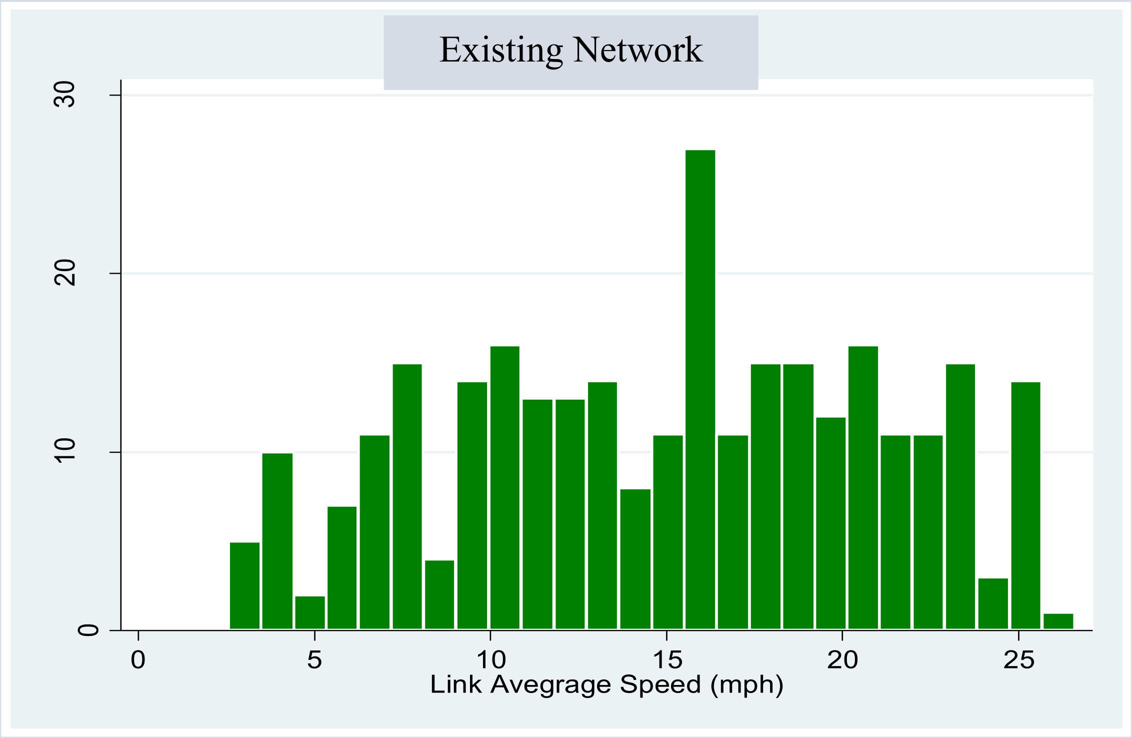


Figure 3-61 Frequency Distribution of Speed in the Existing Network

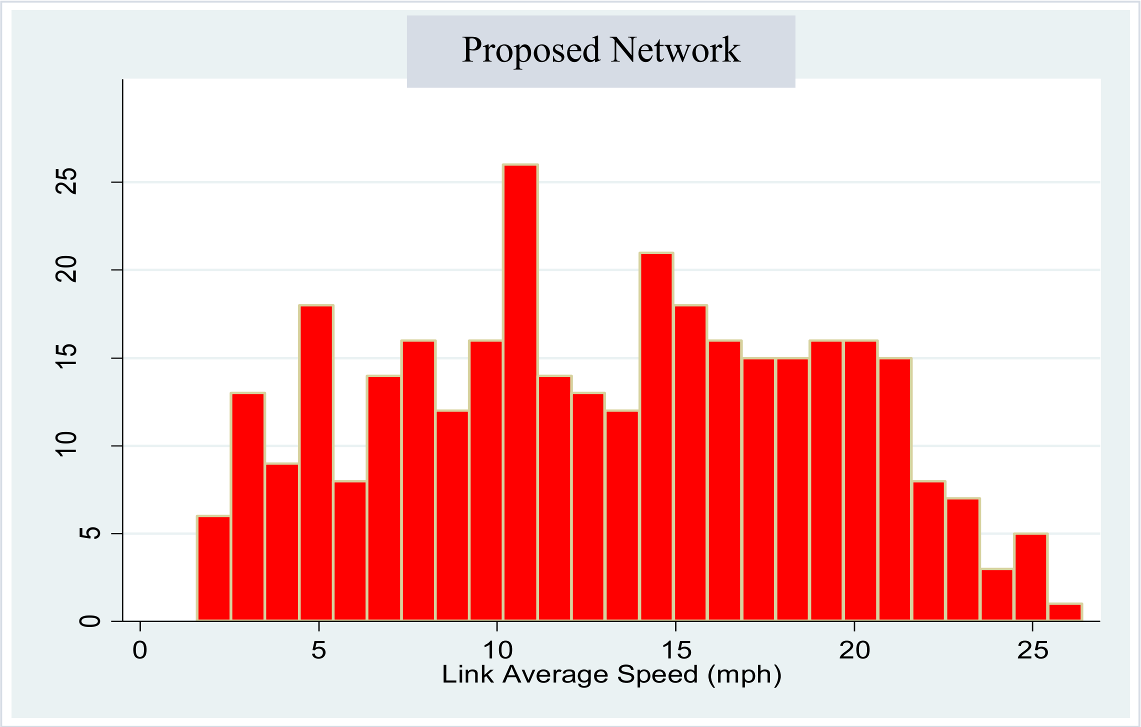


Figure 3-62 Frequency Distribution of Speed in the Proposed Network

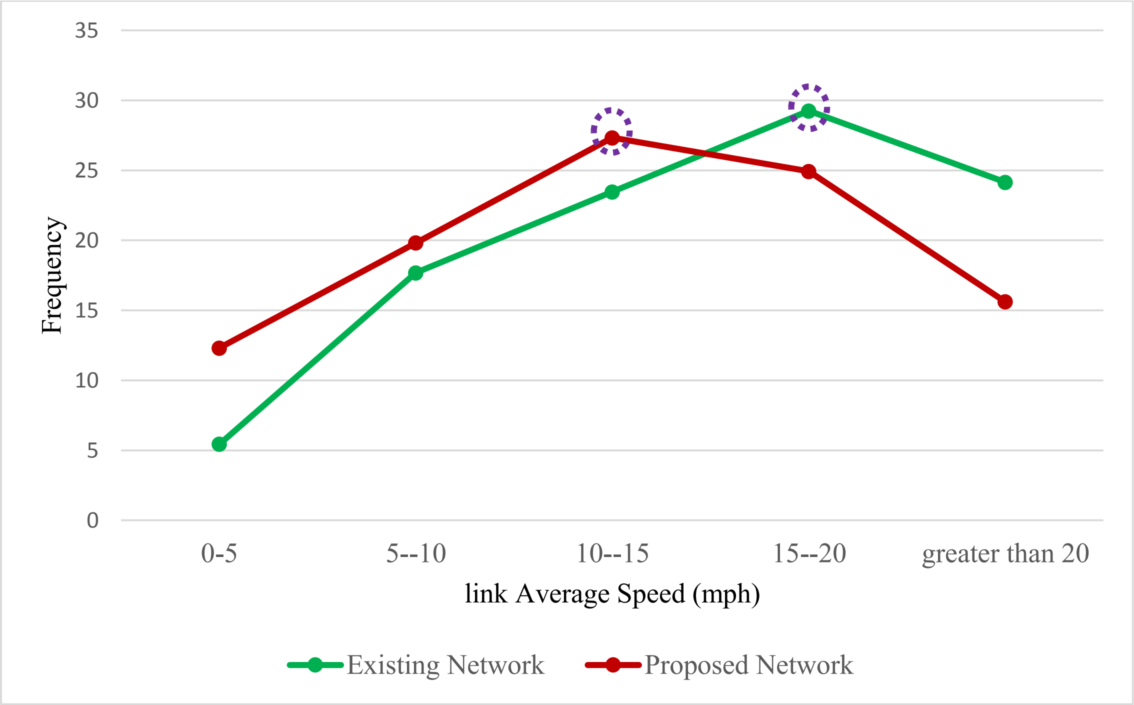


Figure 3-63 Comparison of Speed Frequency between Existing Network and Proposed Network

Table 3-13 compares the percentage of time spent in cruising, acceleration, deceleration and idling mode in existing and proposed network for each simulation hour. Results from traffic simulation model suggest that the percentage time spent in deceleration and idling is higher in proposed network due to the increase of traffic congestion.

Table 3-13 Percentage of Time Spent in Cruising, Acceleration, Deceleration and Idling mode in Existing and Proposed Network

	Percentage Time Spent in Cruising	Percentage Time Spent in Acceleration	Percentage Time Spent in Deceleration	Percentage Time Spent in Idling
AM Peak				
Existing Network	4.71	37.86	40.85	16.58
Proposed Network	4.54	36.78	41.45	17.23
Off Peak				
Existing Network	7.11	38.18	42.1	12.61
Proposed Network	6.07	37.1	43.16	13.67
PM Peak				
Existing Network	6.61	38.21	41.87	13.31
Proposed Network	4.67	36.02	39.92	19.39

Interestingly, results from Table 3-10, and Table 3-12 reveal that the increased percentage of emissions is higher in PM peak period than AM peak period. For instance, the increased percentage of emissions is ranging from 9.867% to 28.571% in PM peak period. On the other hand, the increased percentage in AM peak period is ranging from 4.246% to 12.079%. The increase in emissions observed in the PM peak period results from commuting traffic from the busy Downtown Core converging on common exit points, leading to longer queue length and idling time. This phenomenon can be explained by the results shown in Table 3-14 derived from the traffic simulation model.

Table 3-14 exhibits the average network speed (mph), and average network delay (minute) of the existing network and proposed network for AM peak, off peak and PM peak periods. It is found that the entire network speed is decreased in proposed scenario by 13.38%, 15.21%, and 22.45 % in the AM peak, off peak, and PM peak periods respectively. This decrease in speed leads to increase average travel time in the proposed network by 12.839%, 28.061% and 42.013% respectively. Moreover average network delay in the proposed network is increased by 2.4 minutes, 2.2 minutes, and 4.5 minutes in the AM peak, off peak, and PM peak periods respectively.

Table 3-14 Comparison of Average Network Speed and Delay between Existing Network and Proposed Network

	AM peak		**Off peak**		**PM peak**	
	Existing Network	**Proposed Network**	**Existing Network**	**Proposed Network**	**Existing Network**	**Proposed Network**
Average Network Speed (mph)	15.965	13.829	17.498	14.836	17.382	13.479
Average Network Delay (minute)	5.5	7.9	2.5	4.7	4.5	9

It is also interesting to find that the change in emissions varies significantly across pollutants. For example, in the PM peak period, the increased percentage of emissions is maximum for SO_2 (28.571%) and minimum for $PM_{2.5}$ (9.867%). In the case of other pollutants, including GHG, CO, NOx, and PM_{10}, the increased percentage varies from 9.910% to 26.849%. According to the combined effect of emission rate, speed and grade analysis, $PM_{2.5}$ emission rate decreases significantly at zero grade compared to the other pollutants (Figure 3-42 to Figure 3-47). Since, the grade at roundabout is zero; therefore, the increased percentage of emission for $PM_{2.5}$ is found to be the minimum in the proposed network with roundabouts. However, SO_2 emission rate shows the minimal decrease at zero grade among all pollutants (Figure 3-45). Hence, the increased percentage of emission for SO_2 is found to be the maximum in the proposed network. Therefore, the variation in the increased percentage of emission by pollutant suggests that same policy of introducing roundabout has different impact on different pollutants. Therefore, it is important to select the target pollutant which needs to be reduced and then implement the policy accordingly.

Finally, it can be concluded that the redistribution of traffic to reduce the waiting time at roundabouts and ensuring free-flowing traffic can improve the effectiveness of the infrastructure renewal.

3.6.3.2 Area Level Emission Evaluation

Although an increase in emissions is observed in the network level evaluation, a reduction of emissions is observed in the area level evaluation, where most of the development has happened as a result of infrastructure renewal. Table 3-15 to Table 3-17 compare the total emissions between the Cogswell Interchange area (that includes multi-grade signalized intersections, a remnant of the never-built expressway) and the newly proposed roundabout-based at-grade area for AM peak, off peak and PM peak periods. For instance, total NOx emissions in the roundabout area is 1070.62 g in AM peak period, which is 16.667% lower than the total NOx emissions (1284.75 g) in the Cogswell Interchange area. Emission reduction percentages of other pollutants are reported in Table 3-15 to Table 3-17. It is found that the percentage of emission reduction in the roundabout area is maximum for $PM_{2.5}$ (19.855%) and minimum for SO_2 (13.485%) in AM peak period.

Table 3-15 Percentage of Emission Reduction in Roundabout Area in AM Peak Period

Pollutant Name	Total Emissions in Cogswell Interchange Area (g)	Total Emissions in Roundabout Area (g)	Percentage of Emission Reduction
GHG	666042.687	573967.948	-13.824%
CO	4449.688	3730.72	-16.158%
NOx	1284.75	1070.62	-16.667%
SO_2	12.05	10.425	-13.485%
PM_{10}	70.37	56.456	-19.773%
$PM_{2.5}$	64.35	51.573	-19.855%

Note: Negative sign indicates emission reduction

Table 3-16 Percentage Emission Reduction in Roundabout Area in off Peak Period

Pollutant Name	Total Emissions in Cogswell Interchange Area(g)	Total Emissions in Roundabout Area (g)	Percentage of Emission Reduction
GHG	525359.118	511396.089	-2.658%
CO	3501.034	3369.73	-3.750%
NOx	1256.31	1256.09	-0.018%
SO_2	9.12	8.8	-3.509%
PM_{10}	70.15	70.127	-0.033%
$PM_{2.5}$	64.25	64.21	-0.062%

Note: Negative sign indicates emission reduction

Table 3-17 Percentage Emission Increase in Roundabout Area in PM Peak Period

Pollutant Name	Total Emissions in Cogswell Interchange Area(g)	Total Emissions in Roundabout Area (g)	Percentage of Emission Increase
GHG	556139.59	694124.35	24.811%
CO	4051.14	4539.22	12.048%
NOx	1051.68	1204.30	14.512%
SO_2	10.12	12.73	25.791%
PM_{10}	56.42	62.41	10.616%
$PM_{2.5}$	51.52	56.99	10.617%

It is interesting to note that the roundabouts are more effective at reducing emissions in AM peak period than in off peak period. For instance, in the off peak period, total amount of NOx emission in the Cogswell Interchange area is 1256.31 g, while the amount is 1256.09 g in the roundabout area which is only 0.018% lower than the Cogswell Interchange area. It is observed that emissions are reduced around 13.485% to 19.855% in the AM peak period, while a nominal percentage of reduction (ranging from 0.018% to 3.750%) has been achieved in the off peak period. The reason behind this can be explained by the fact that roundabouts increase the efficiency of the area during AM peak period by reducing idling time and queue length at intersection. However, this is not applicable for off peak period since the overall traffic volume is low in the off peak period of both scenarios compared to the AM peak period.

To identify the reason of lower emission reduction in off peak period than AM peak period in more details, percentage of time spent in acceleration, deceleration, cruising and idling are calculated separately for the Cogswell Interchange area and the roundabout area. According to Figure 3-64, it is evident that the percentage of time spent in acceleration and deceleration is increased by 5.8% and 1.7% respectively in the roundabout area compared to the Cogswell Interchange area. However, roundabout area decreases the percentage of time spent in cruising by 36.05% and idling time by 4.4%.

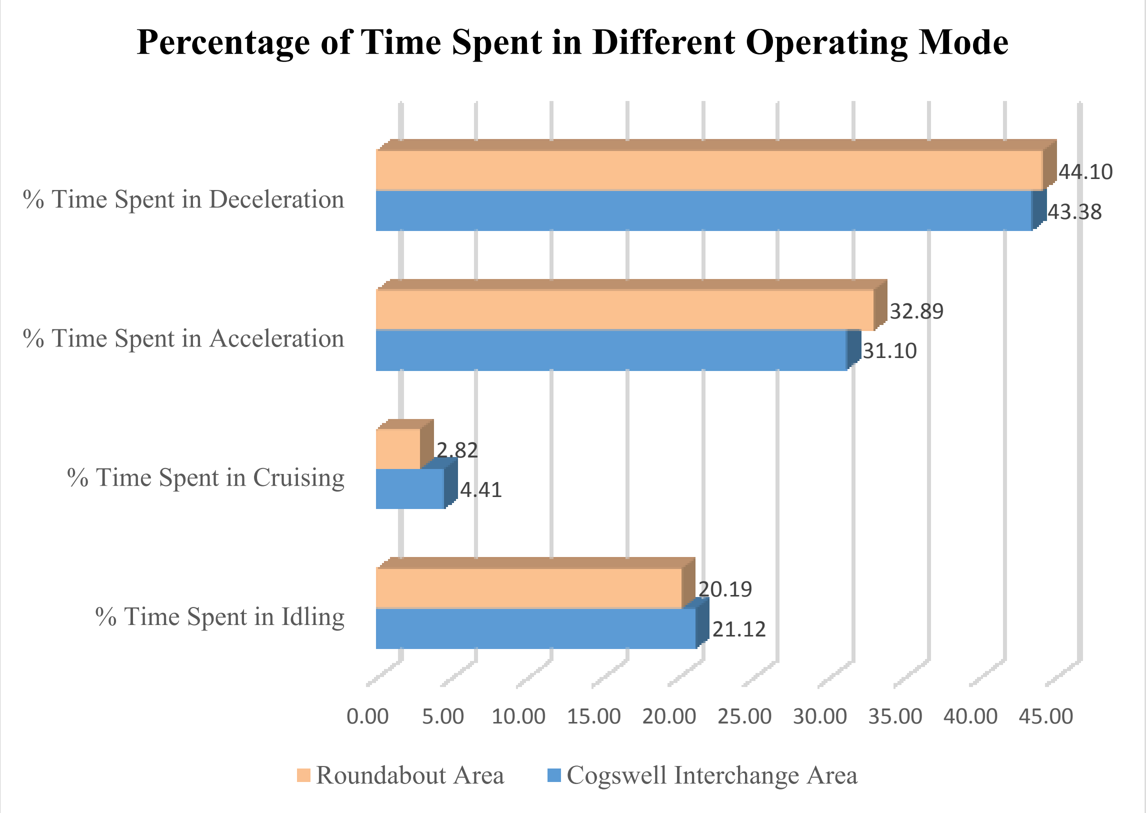


Figure 3-64 Percentage of Time Spent in Different Operating Mode by Roundabout Area and Cogswell Interchange Area

From Figure 3-36 to Figure 3-41, it is clear that trucks produce more emissions compared to the passenger cars while accelerating. Moreover, acceleration frequency of trucks increases while trucks are running through the roundabout area. As mentioned earlier, higher percentage of trucks enters in the downtown area during off peak period (4.13%) compared to the AM and PM peak periods (2.47% and 1.73%). This higher percentage of trucks running with high acceleration frequency consequences an increase in emissions in the off peak period even though the congestion level is low. This investigation reveals that the emission reduction potential not only depends on the network congestion level but also types of vehicle running through the network.

It can be concluded that reducing the percentage of trucks running through the roundabout area by shifting them to alternative routes can be a solution to make the roundabouts more effective in off peak period.

To explore the reasons behind the emission reduction in roundabout area, link level investigation has been conducted based on GHG (as a representative pollutant) emission rate trajectories for the signalized intersection and the roundabout (Figure 3-65 and Figure 3-66). Emission rate trajectories show the correlation of emission rates with key variables such as vehicle speed, acceleration, deceleration, and queue length. These trajectories also illustrate the stop and go frequency, number of stops, and time gaps between two consecutive acceleration and deceleration cycles in specific time periods.

Trajectory of the signalized intersection reflects that emission rates increase as speed decreases. Although idling operating mode has associated emission rates, the consequence of idling mode requires reacceleration on greens which causes increase in emissions at signals. Highest queues also build in this stage which leads to an increase in the stop and go frequency which strongly influences the addition of vehicular emissions. As queue lengths decrease emission rates decrease accordingly.

On the other hand, trajectory of the roundabout suggests that emission reduction is occurred due to the demolition of queue length, and smaller fluctuation in speed (average 11.596 mph) in the roundabout. Moreover, a road grade of zero in roundabout is also a contributing factor in emission reduction since the combined effects of speed, grade, and emission rate (Figure 3-42 to Figure 3-47) reveal the lowest emission rates at a zero road grade for all pollutants.

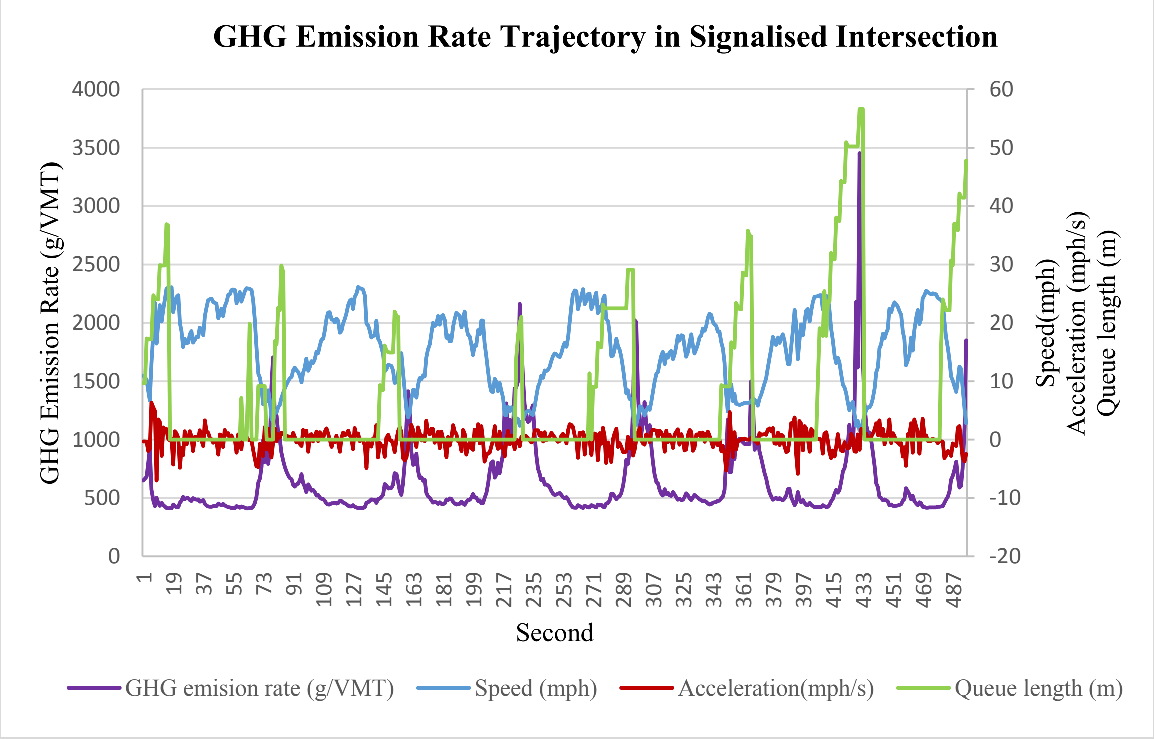


Figure 3-65 GHG Emission Rate Trajectory in Signalised Intersection

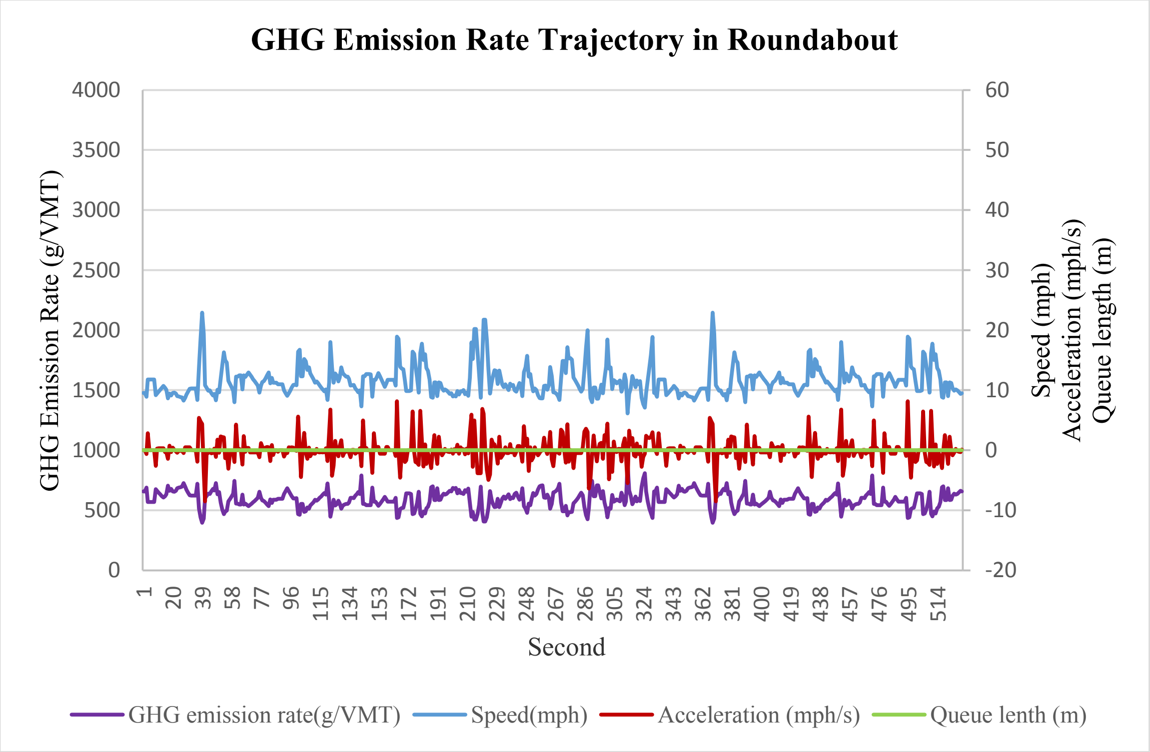


Figure 3-66 GHG Emission Rate Trajectory in Roundabout

One of the interesting findings is that emission increases (ranging from 10.616% to 25.791%) in the roundabout area in the PM peak period while it decreases in the AM peak and off peak periods. The oversaturated condition in the PM peak period causes queue spillover effect in the whole network. The queue spillover effect and additional congestion in roundabouts during the PM peak period result the increased emissions.

In this chapter, results of changing emissions due to the replacement of multi-grade signalised intersections with at-grade roundabouts are presented at both network level and area level. The results suggests that although roundabout area causes less emissions compared to the business-as-usual multi-grade signalized intersections, it is evident that Cogswell Transformed Plan increases total emissions in the entire network.

3.6.4 Statistical Analysis

3.6.4.1 Land Use Regression Model

The sequential emission model developed in this study is mainly based on traffic and network attributes. On the other hand, land use and built environment characteristics also significantly influence vehicular emissions (*Houston et al., 2004; Kanaroglou et al., 2005*). Therefore, it is imperative to evaluate the impacts of land use and built environment characteristics on emission rates, which could not be effectively incorporated in the microsimulation-based emission model. This study evaluates a land use regression model to reveal the effects of land use separately based on the estimated emissions at link level.

First, a multivariate regression model is developed using street and traffic attributes called as reduced model. Later, another regression model is developed accommodating the effect of built environment and land use characteristics in addition to the street and traffic attributes called as full model. The goodness-of-fit measures of the two models suggest that full model improves the R-squared and Root Means Square Error (RMSE) value and thus fits the data best compared to the reduced model (shown in Table 3-18 to Table 3-23). Therefore, the full model outperforms the reduced model in terms of goodness-of-fit measures. Moreover, the full model has the potential to predict emission rates at a higher precision, since it captures the effects of majority of the influential factors. Thus, the full model capturing the effect of street and traffic attributes, built environment, and land use characteristics is considered as the final model.

A total of six land use regression models are developed for the six pollutants considered in this study. The results of the final model for GHG, CO, NOx, SO_2, PM_{10}, and $PM_{2.5}$ pollutants are presented in Table 3-18 to Table 3-23 respectively. In addition, the results of the reduced model for each pollutant are also reported in corresponding tables respectively.

Table 3-18 Land Use Regression Model Results for GHG Emission Rates (kg/mile)

Variables	Land Use Regression Model for GHG	
	Reduced Model	Full Model
	co-efficient (t-stat)	*co-efficient (t-stat)*
Street and Traffic Attributes		
Traffic Volume	0.49764 (**24.99)	0.49501 (**26.70)
Road Grade (%)	4.68399 (**7.57)	4.59334 (**8.25)
Average Speed (mph)	-9.45961 (**-10.70)	-8.72033 (**-10.35)
Percentage Time Spent in Acceleration	1.65916 (**3.11)	1.65895 (**3.33)
Percentage Time Spent in Idling	0.15449 (0.41)	0.35007 (1.00)
Percentage of Heavy Duty Vehicle	3.98761 (**4.58)	3.79239 (**3.97)
Land Use and Built Environment Attributes		
Number of Commercial Establishment		0.09385 (*1.69)
Number of Educational Institution		-0.48374 (*-1.67)
Percentage of Residential Area		-0.86276 (**-3.08)
Percentage of Green Park Area		-38.43765 (**-2.79)
Land Use Mix Index		-0.17160 (**-4.13)
Number of Bus Stops		1.73018 (0.29)
Constant	103.3454 (**3.79)	203.2157 (**4.96)
Goodness-of-fit Measures		
R-Squared	0.7780	0.8185
Root MSE	52.057	46.666

** 95% confidence interval; * 90% confidence interval

Table 3-19 Land Use Regression Model Results for CO Emission Rates (kg/mile)

Variables	Land Use Regression Model for CO	
	Reduced Model	**Full Model**
	co-efficient (t-stat)	***co-efficient (t-stat)***
Street and Traffic Attributes		
Traffic Volume	0.00327 (**17.84)	0.00325 (**18.05)
Road Grade (%)	0.05167 (**9.08)	0.05059 (**9.35)
Average Speed (mph)	-0.068664 (**-8.45)	-0.06641 (**-8.11)
Percentage Time Spent in Acceleration	0.00675 (1.38)	0.00787 (*1.63)
Percentage Time Spent in Idling	-0.00822 (**-2.37)	-0.00694 (**-2.04)
Percentage of Heavy Duty Vehicle	-0.01077 (-1.34)	-0.01604 (*-1.73)
Land Use and Built Environment Attributes		
Number of Commercial Establishment		0.00094 (*1.75)
Number of Educational Institution		-0.00484 (*-1.72)
Percentage of Residential Area		-0.00742 (**-2.73)
Percentage of Green Park Area		-0.37485 (**-2.81)
Land Use Mix Index		-0.00151 (**-3.73)
Number of Bus Stops		0.04124 (0.72)
Constant	1.46563 (**5.84)	2.39146 (**6.01)
Goodness-of-fit Measures		
R-Squared	0.6498	0.6864
Root MSE	0.47872	0.45343

** 95% confidence interval; * 90% confidence interval

Table 3-20 Land Use Regression Model Results for NOx Emission Rates (g/mile)

Variables	**Land Use Regression Model for NOx**	
	Reduced Model	**Full Model**
	co-efficient (t-stat)	***co-efficient (t-stat)***
Street and Traffic Attributes		
Traffic Volume	0.83797 (**14.43)	0.84437 (**14.14)
Road Grade (%)	15.20714 (**8.43)	15.24826 (**8.50)
Average Speed (mph)	-13.94006 (**-5.41)	-15.28139 (**-5.63)
Percentage Time Spent in Acceleration	4.46509 (**2.87)	4.64418 (**2.90)
Percentage Time Spent in Idling	2.11674 (*1.93)	1.81669 (*1.61)
Percentage of Heavy Duty Vehicle	38.79908 (**15.27)	35.27228 (**11.46)
Land Use and Built Environment Attributes		
Number of Commercial Establishment		0.20203 (1.13)
Number of Educational Institution		-0.88958 (-0.96)
Percentage of Residential Area		-1.53075 (*-1.70)
Percentage of Green Park Area		-21.24743 (-0.48)
Land Use Mix Index		-0.32963 (**-2.46)
Number of Bus Stops		7.03877 (0.37)
Constant	-32.70902 (-0.41)	201.657 (1.53)
Goodness-of-fit Measures		
R-Squared	0.6977	0.7162
Root MSE	151.79	150.28

** 95% confidence interval; * 90% confidence interval

Table 3-21 Land Use Regression Model Results for SO_2 Emission Rates (g/mile)

Variables	Land Use Regression Model for SO_2	
	Reduced Model	**Full Model**
	co-efficient (t-stat)	*co-efficient (t-stat)*
Street and Traffic Attributes		
Traffic Volume	0.00919 (**25.82)	0.00914 (**28.64)
Road Grade (%)	0.07907 (**7.15)	0.07713 (**8.05)
Average Speed (mph)	-0.17475 (**-11.06)	-0.15846 (**-10.93)
Percentage Time Spent in Acceleration	0.02825 (**2.97)	0.02852 (**3.33)
Percentage Time Spent in Idling	0.00134 (0.20)	0.00542 (0.97)
Percentage of Heavy Duty Vehicle	0.018116 (1.16)	0.01922 (1.17)
Land Use and Built Environment Attributes		
Number of Commercial Establishment		0.00179 (*1.87)
Number of Educational Institution		-0.00941 (*-1.89)
Percentage of Residential Area		-0.01576 (**-3.27)
Percentage of Green Park Area		-0.79968 (**-3.38)
Land Use Mix Index		-0.00311 (**-4.36)
Number of Bus Stops		0.01814 (0.18)
Constant	2.20492 (**4.52)	3.95598 (**5.61)
Goodness-of-fit Measures		
R-Squared	0.7821	0.8311
Root MSE	0.9308	0.80302

** 95% confidence interval; * 90% confidence interval

Table 3-22 Land Use Regression Model Results for PM_{10} Emission Rates (g/mile)

Variables	Land Use Regression Model for PM_{10}	
	Reduced Model	**Full Model**
	co-efficient (t-stat)	***co-efficient (t-stat)***
Street and Traffic Attributes		
Traffic Volume	0.04322 (**13.37)	0.04333(**12.98)
Road Grade (%)	0.68702 (**6.84)	0.68498 (**6.83)
Average Speed (mph)	-0.65496 (**-4.56)	-0.74699 (**-4.92)
Percentage Time Spent in Acceleration	0.17249 (*1.99)	0.16129 (*1.80)
Percentage Time Spent in Idling	0.08420 (1.38)	0.05697 (0.90)
Percentage of Heavy Duty Vehicle	2.4014 (**16.97)	2.19567 (**12.76)
Land Use and Built Environment Attributes		
Number of Commercial Establishment		0.00679 (0.68)
Number of Educational Institution		-0.03129 (-0.60)
Percentage of Residential Area		-0.08287 (*-1.64)
Percentage of Green Park Area		-0.85391 (-0.34)
Land Use Mix Index		-0.01689 (**-2.26)
Number of Bus Stops		1.35156 (1.27)
Constant	-1.85459 (-0.42)	11.58433 (1.57)
Goodness-of-fit Measures		
R-Squared	0.6880	0.7030
Root MSE	8.4499	8.4045

** 95% confidence interval; * 90% confidence interval

Table 3-23 Land Use Regression Model Results for $PM_{2.5}$ Emission Rates (g/mile)

Variables	**Land Use Regression Model for $PM_{2.5}$**	
	Reduced Model	**Full Model**
	co-efficient (t-stat)	***co-efficient (t-stat)***
Street and Traffic Attributes		
Traffic Volume	0.03949 (**13.35)	0.03959 (**12.95)
Road Grade (%)	0.62666 (**6.82)	0.62496 (**6.81)
Average Speed (mph)	-0.59631 (**-4.54)	-0.68044 (**-4.90)
Percentage Time Spent in Acceleration	0.15829 (**2.00)	0.14772 (*1.80)
Percentage Time Spent in Idling	0.07822 (1.40)	0.05311 (0.92)
Percentage of Heavy Duty Vehicle	2.21367 (**17.10)	2.02529 (**12.86)
Land Use and Built Environment Attributes		
Number of Commercial Establishment		0.00613 (0.67)
Number of Educational Institution		-0.02819 (-0.59)
Percentage of Residential Area		-0.07542 (*-1.64)
Percentage of Green Park Area		-0.73442 (-0.32)
Land Use Mix Index		-0.01535 (**-2.24)
Number of Bus Stops		1.23478 (1.26)
Constant	-1.89641 (-0.47)	10.34332 (1.53)
Goodness-of-fit Measures		
R-Squared	0.6893	0.7041
Root MSE	7.7313	7.692

** 95% confidence interval; * 90% confidence interval

The regression model results in Table 3-18 to Table 3-23 reveal that higher road grade and lower speed have a significant impact on increasing emission rates of all pollutants. Higher amount of traffic, higher percentages of time spent in acceleration and idling, and higher percentage of heavy duty vehicles exhibit a higher probability on increasing emission rates.

Among the land use and built environment attributes, an increase in percentage of green park area (for recreational purposes), and residential area has a higher impact on reducing emission rates for all pollutants. Interestingly, an increase in the number of educational institution establishments reveals higher propensity of reducing emission rates. This reflects the fact that an increase in educational institution establishments indicates higher number of the individuals living close by, who might choose alternative modes of transportation such as walking or biking to drop off and pick up their children from educational institutions. A higher number of commercial establishments reveal a higher propensity of increasing emission rates. A higher number of bus stops reflect a higher frequency of stopping for transit bus, which indicates a higher probability of increasing emissions due to idling. Land use mix index reveals a significantly negative relationship with emission rates for all pollutants. This indicates that heterogeneous land use increases the probability of higher rate of emission reduction. Note that heterogeneous land use refers to the well mixture of residential, commercial, industrial, and green park area.

Although the relationship of different attributes for all pollutants is similar, the magnitude of effect of the attributes is different for different pollutants. For instance, higher percentage of green park area is more likely to reduce the highest amount of emission rates for all pollutants. Moreover, higher grade of roads exhibit a higher probability to increase maximum amount of emission rates for GHG, CO and SO_2. In the case of NOx, PM_{10}, and $PM_{2.5}$, higher percentages of heavy duty vehicles reveal a higher probability to increase maximum amount of emission rates. Interestingly, higher percentages of heavy duty vehicles exhibit a higher probability to reduce emission rates for CO. This can be explained by the fact that passenger cars are primarily responsible for the CO emission rather than heavy duty vehicles. Therefore, higher percentages of heavy duty vehicles will in turn reduce the percentage of passenger cars in the street resulting in a reduction in emission rates of CO.

Majority of the variables in the final model exhibits a statistical significance of above 95% confidence interval. Few variables retained in the final model are below the threshold statistical significance of 95% confidence interval. These variables offer important insights to understand the factors affecting the emission rates and have significant policy implications. These variables are retained in the final model with an assumption that if a larger data set were available, they might exhibit statistical significance.

3.6.4.2 Implications of Land Use Regression Models

This study utilizes the land use regression model to evaluate the effect of proposed changes in land use scenario on emission rates due to the infrastructure renewal. An empirical land use scenario after the infrastructure renewal is generated according to the consulting report by HRM (*Halifax Regional Municipality, and Ekistics Planning and Design, 2014*). For instance, the renewal plan proposes to develop 2.5 million sq.ft. of new area (which includes 573,275 sq.ft. of commercial area and 1,975,080 sq.ft. of residential area) and three new green park areas. The potential emissions generated from the regression model could be a proxy, particularly to assess the effect of land use improvement scenarios on emissions. Table 3-24 and Table 3-25 show the change in emission rates in the proposed network based on microsimulation-based emission model and land use regression model respectively. The land use regression model confirms the increase of emissions in the proposed network as found in the microsimulation-based emission model. However, the land use regression model exhibits a lower percentage of increase in emissions and minimal variation among pollutants. For example, while considering only road infrastructure change, the increased percentage of emission rates ranges from 21.067% to 30.165% in AM peak period based on microscopic emission model. On the other hand, the range is 21.025% to 21.982% when change in both road infrastructure and land reclamation has been considered based on land use regression model. This result presumably suggests that the finer details cannot be captured in the land use regression model since it does not account for the acceleration, deceleration, and idling effect at micro level. However it could be an alternative to assess the effect of land use variability on emission rates. The findings of the regression model also can be extended to identify the most effective variable which can cause maximum emission reduction of target pollutants.

Table 3-24 Increased Percentage of Emission Rates in Proposed Network Based on Microsimulation-based Emission Model

Pollutant Name	**AM peak**	**Off peak**	**PM peak**
GHG	29.136%	26.787%	41.833%
CO	30.165%	25.651%	33.679%
NOx	23.811%	23.004%	28.889%
SO_2	29.607%	27.722%	43.768%
PM_{10}	21.168%	19.789%	22.893%
$PM_{2.5}$	21.067%	19.749%	22.845%

Table 3-25 Increased Percentage of Emission Rates in Proposed Network Based on Land Use Regression Model

Pollutant Name	AM peak	Off peak	PM peak
GHG	21.607%	23.292%	26.848%
CO	21.982%	23.704%	27.221%
NOx	21.544%	23.237%	26.648%
SO_2	21.704%	23.405%	26.984%
PM_{10}	21.036%	22.613%	25.939%
$PM_{2.5}$	21.025%	22.601%	25.928%

3.7 Conclusion

This study presents the findings of a sequential emission model for Downtown Halifax using a microscopic traffic simulation model and emission estimation tool in order to evaluate vehicular emissions at micro-scale. The study area became an interesting case study following the proposed infrastructure renewal plan that replaces the multi-grade road network of the current infrastructure with an at-grade network. The project area has a high environmental value as it focuses on the redevelopment of a mixed land use area in the downtown core and in close proximity to existing residential neighbourhood. The model results reveal that demolition of interchange reduces emissions in the immediate vicinity. However, the Cogswell Transformation Plan has a potential to increase emissions in the entire network due to the spillover effect in the other areas of the network. Therefore, a mitigation plan is required, for instance to reduce queue building due to the spillover effect. Thus, the renewal project could ensure network efficiency as well as emission reduction targets.

Overall, this study contributes to the existing literature by estimating the change in emissions at the micro-level due to the major infrastructure renewal. This study also confirms the importance of developing traffic simulation models, including local instantaneous drive cycles to estimate emissions more accurately by capturing acceleration, deceleration and idling effect. Finally, a land use regression model has been developed in order to quantify the effect of street attributes, traffic attributes, land use, and built environment attributes on emission rates. The statistical analysis confirms that the regression model can be a reasonable proxy to incorporate and evaluate the effects of the land use attributes on emissions. However, the study concludes that an integrated transportation, land use, and emission model will be required to reveal the full extent of land use and traffic effects. The next step of this research will be to combine these models with a forthcoming integrated Transportation, Land Use, and Energy Modeling System (iTLE) for Halifax. Nevertheless, this microscopic emission model provides useful insights on emissions, which will assist planners and policy makers to consider strategies on mitigating air pollution in the final design process and implementation of the infrastructure renewal plan.

Chapter 4

Conclusion

4.1 Summary of Chapters

The impact of the urban transportation related air pollution is becoming an increasing concern, since majority of people resides in busy urban area experiencing significant air pollution. Despite vehicular emission is becoming an alarming issue, transportation engineers, planners and policy makers have focused on improving traffic operation systems and developing alternative technologies to enhance network efficiency and safety. Although these strategies are beneficial in improving road efficiency and safety; however, limited studies have assessed the environmental impact of these strategies at micro scale. Particularly, studies focusing on examining the effect of instantaneous drive cycle and traffic volume variations on emissions due to the strategy implementation are more limited.

Therefore, the first stage of this thesis develops an emission modelling framework for a major truck route in Halifax Downtown core, Canada. The model utilizes information from field surveys in conjunction with emission simulation platform to examine alternative policy scenarios under different traffic operation schedules for emission reduction. The model results provide useful insights into the effects of different policy strategies and scenarios on the emissions of criteria pollutants and air quality. The results suggest that emission rates are significantly affected by the traffic volume and time of the day.

Existing truck traffic significantly contributes to the total emissions in the busy road segment through the downtown core. Two alternative strategies are tested to reduce emissions in the route. Limiting trucks at certain time periods will reduce CO, NOx, PM_{10} and $PM_{2.5}$ emissions by 4.889 %, 27.207%, 21.158% and 22.522% respectively, which can be a reasonable solution in addressing the public concern regarding this truck route running through Halifax's urban core.

The second stage of this thesis demonstrates a comprehensive emission modelling framework that combines a microscopic traffic simulation model with emission simulation platform. The traffic simulation model generates instantaneous driving cycle profiles based on local context that facilitates the opportunity to estimate vehicular emissions and emission rates at a finer resolution with higher accuracy. The emission model developed in this stage captures the effect of two operational scenarios on vehicular emissions (i.e. an existing network with multi-grade signalized intersections at Cogswell Interchange and a proposed network based on the infrastructure renewal plan of introducing at-grade roundabouts by replacing multi-grade signalized intersections). The developed emission model explores the isolated and combined effect of network attributes at both network and link levels. It is observed that roadway grade and vehicle speed have significant impact on emission rate of all pollutants.

The model results suggest that the introduction of roundabouts at the Cogswell Interchange increases emissions for GHG, CO, NOx, SO_2, PM_{10} and $PM_{2.5}$ by 11.194%, 12.079%, 6.609%, 11.607%, 4.333 % and 4.246% respectively in the entire network. On the other hand, area level evaluation suggests that emissions of GHG, CO, NOx, SO_2, PM_{10} and $PM_{2.5}$ is decreased by 13.824%, 16.158%, 16.667%, 13.485%, 19.773 % and 19.855% respectively in the roundabout area compared to the business-as-usual multi-grade signalized intersections. The increase in emissions in the entire network is observed to be the maximum in PM peak period than AM peak and off peak periods. Interestingly, the variation in the magnitude of reduction and increase in emissions for different pollutants indicates that similar policy has different impacts on emissions depending on pollutant types. The increased percentage of emissions is maximum for SO_2 (28.571%) and minimum for $PM_{2.5}$ (9.867%) compared to other pollutants. This finding indicates the importance of selecting the target pollutant which needs to be reduced and then implement the policy accordingly.

Finally, a land use regression model is developed for each pollutant to examine the potential effect of land use and built environment attributes on vehicular emissions. This model results suggest that land use and the built environment attributes have significant influence on emission rates in addition to street and traffic attributes, which could not be effectively incorporated in the microsimulation-based emission model. The model results will assist transportation planners to predict vehicular emissions prior to the implementation of any infrastructure renewal plan in an area with limited instantaneous speed information.

In Conclusion, the findings of this research is expected to assist transportation planners and policy makers to identity proper transportation management policies and examine their effectiveness in mitigating air pollution. The sequential model developed in this study has the potential to be replicated in other projects to estimate emissions for different policy scenarios.

4.2 Summary of Contributions

This research enhanced the knowledge in the area of emissions. A list of contributions of this thesis is given below:

1. Demonstrates a comprehensive emission modelling framework based on Canadian context that combines microscopic traffic simulation model with emission simulation platform.
2. Explores the effect of traffic and network attributes on emissions for all criteria pollutants.
3. Offers an in-depth understanding of the resulting emissions for two major planning decisions: Truck route and Cogswell re-design.

4.3 Limitations

This study has some certain limitations, mostly associated with data unavailability, computational complexity and limited scope for model result validation. One of the major limitations of the models developed in this research is the lack of traffic count data in majority of the intersections for calibration and validation.

Another limitation exists due to insufficient computer power, since it takes significant amount of time to run the model and generate expected result. On average, microscopic traffic simulation model takes approximately ten hours to generate instantaneous speed and traffic volume data, and emission model takes around twenty hours to generate emission results.

Moreover, there is limited local drive cycle information data in the study area to validate instantaneous speed data obtained from the microscopic traffic simulation model. Introduction of GPS technology in traffic data collection can be a reasonable solution for local drive cycle data collection.

Another limitation of this research is the use of static user equilibrium algorithm for traffic assignment.

There is also limitation with respect to the assumption that traffic demand will remain same after the implementation of the infrastructure renewal plan.

4.4 Recommendations for Future Research

This research develops a microsimulation-based traffic emission model with a focus to capture the effects of a major infrastructure renewal plan on air quality at the micro scale. Recently, a large number of infrastructure renewal plans are undertaken in Canada to increase network efficiency and reduce maintenance cost for aging infrastructure. Therefore, emission estimation requires to be carried out "before and after" the implementation of renewal plan by using emission measurement devices for the validation of the emission model results with the real-world data. Moving forward, assessment of air pollutant exposer to people, and compare that with air quality standards are also recommended. Stochastic user equilibrium approach is recommended as future work which allows route choice distribution based on perceived travel times. Moreover, this emission modelling framework could guide the inclusion of emission components within the proposed integrated Transportation, Land Use, and Energy Modelling System (iTLE) for Halifax, which is expected to evaluate the effects of land use variability on vehicular emissions.

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Appendix A: Relative Difference in Emission Rates from Link Average Emission Rate

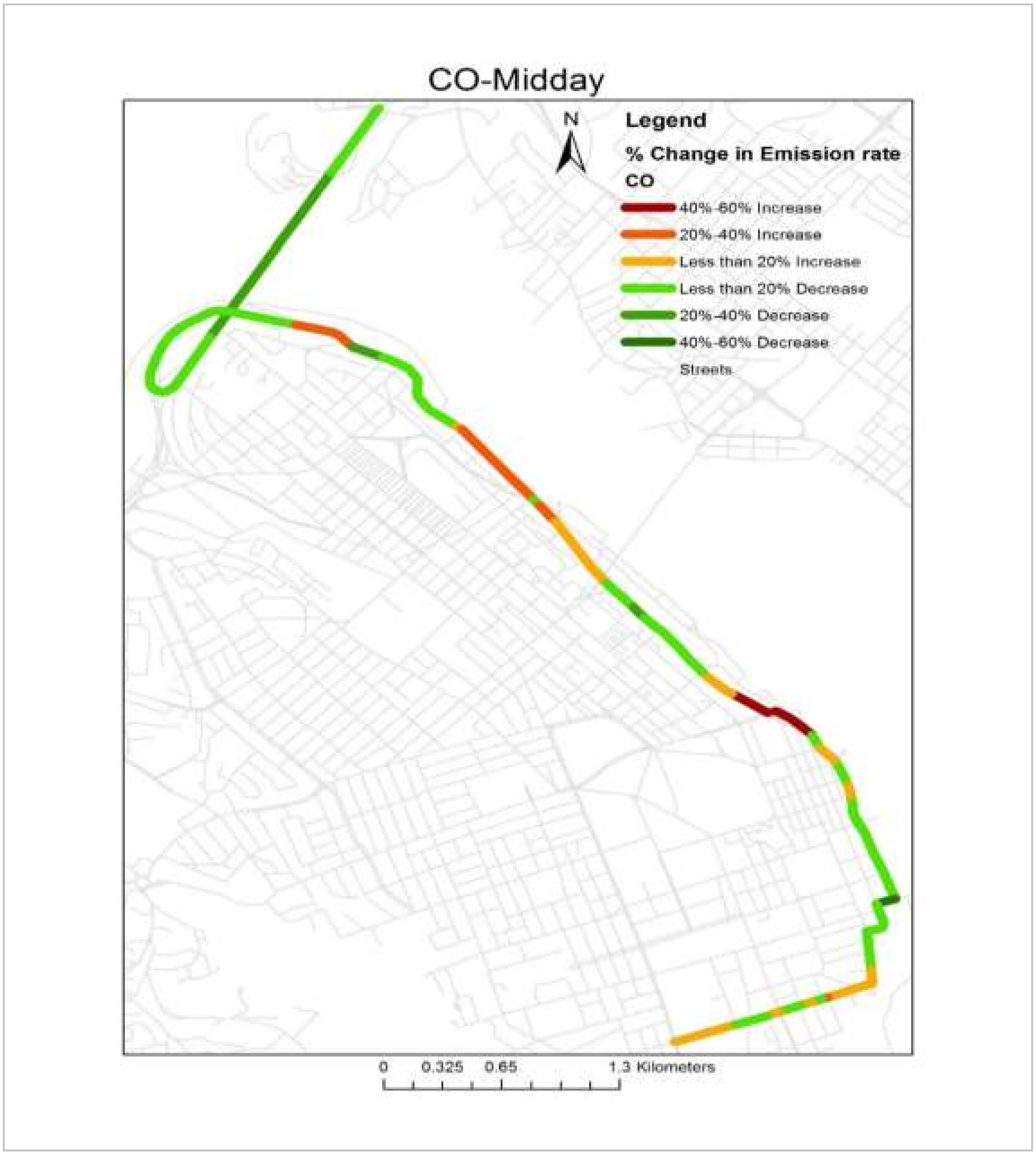

Figure A1 Relative Difference in CO Emission Rates from Link Average Emission Rate in Midday

Figure A2 Relative Difference in NOx Emission Rates from Link Average Emission Rate in Midday

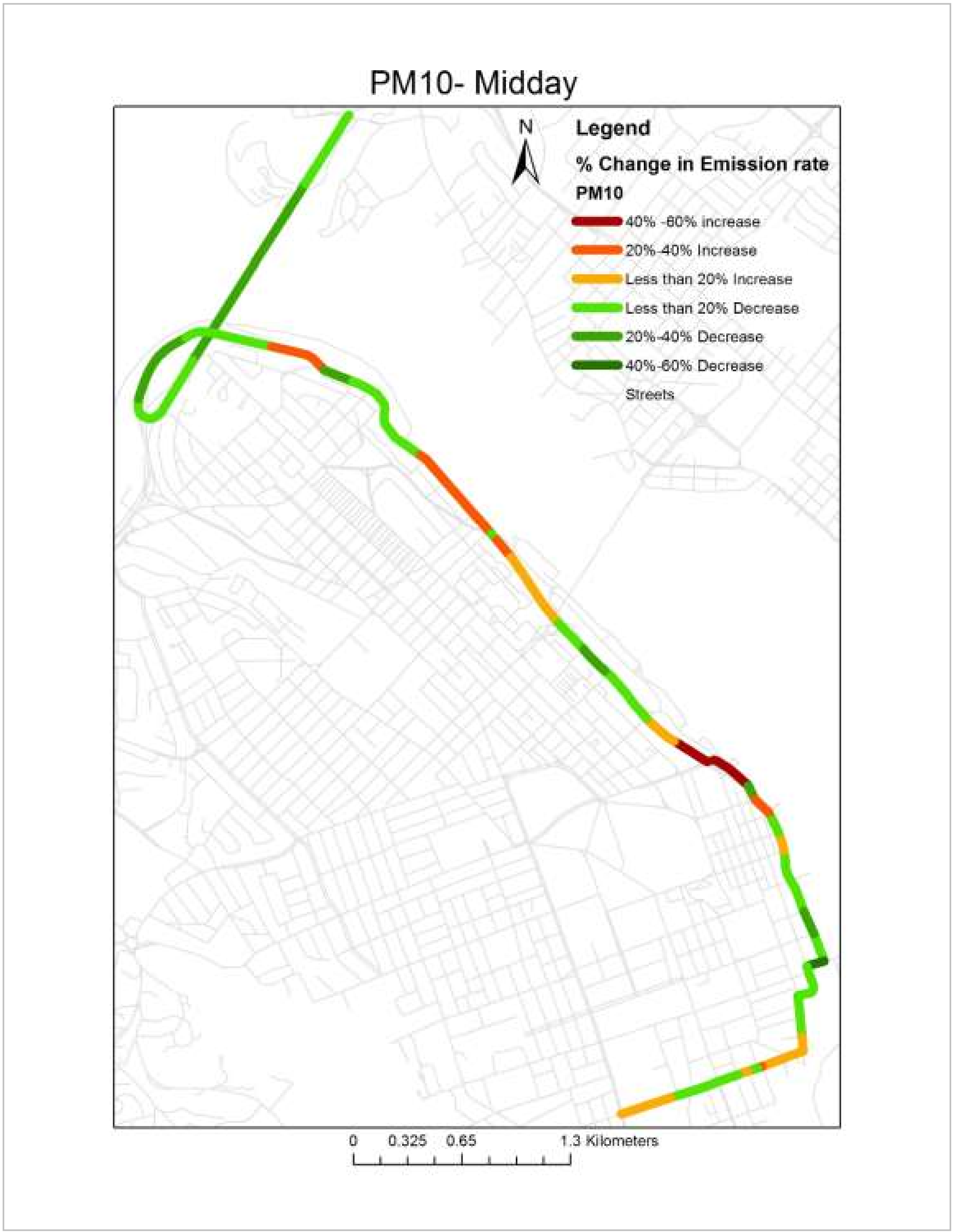

Figure A3 Relative Difference in PM_{10} Emission Rates from Link Average Emission Rate in Midday

Figure A4 Relative Difference in $PM_{2.5}$ Emission Rates from Link Average Emission Rate in Midday

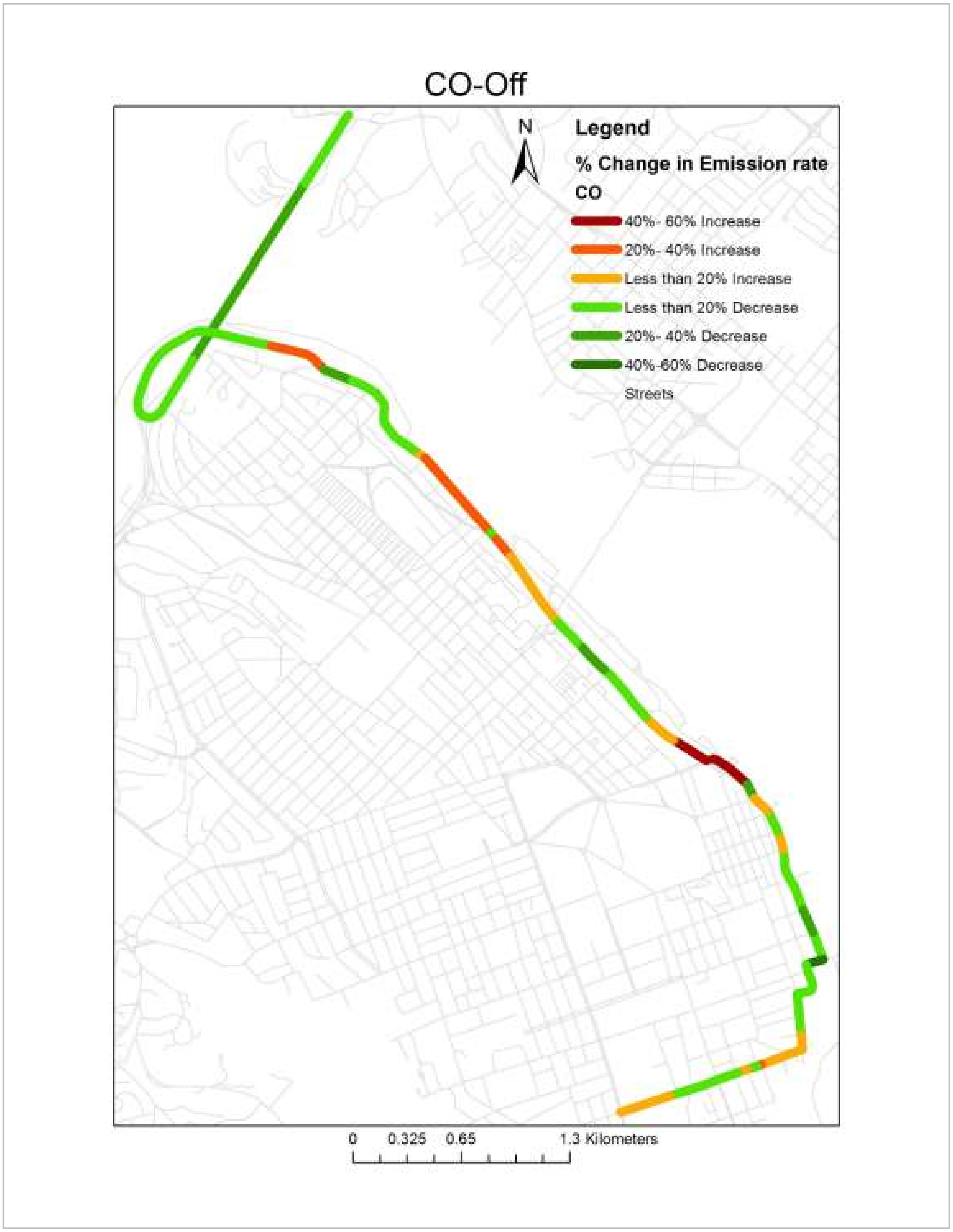

Figure A5 Relative Difference in CO Emission Rates from Link Average Emission Rate in Off Peak

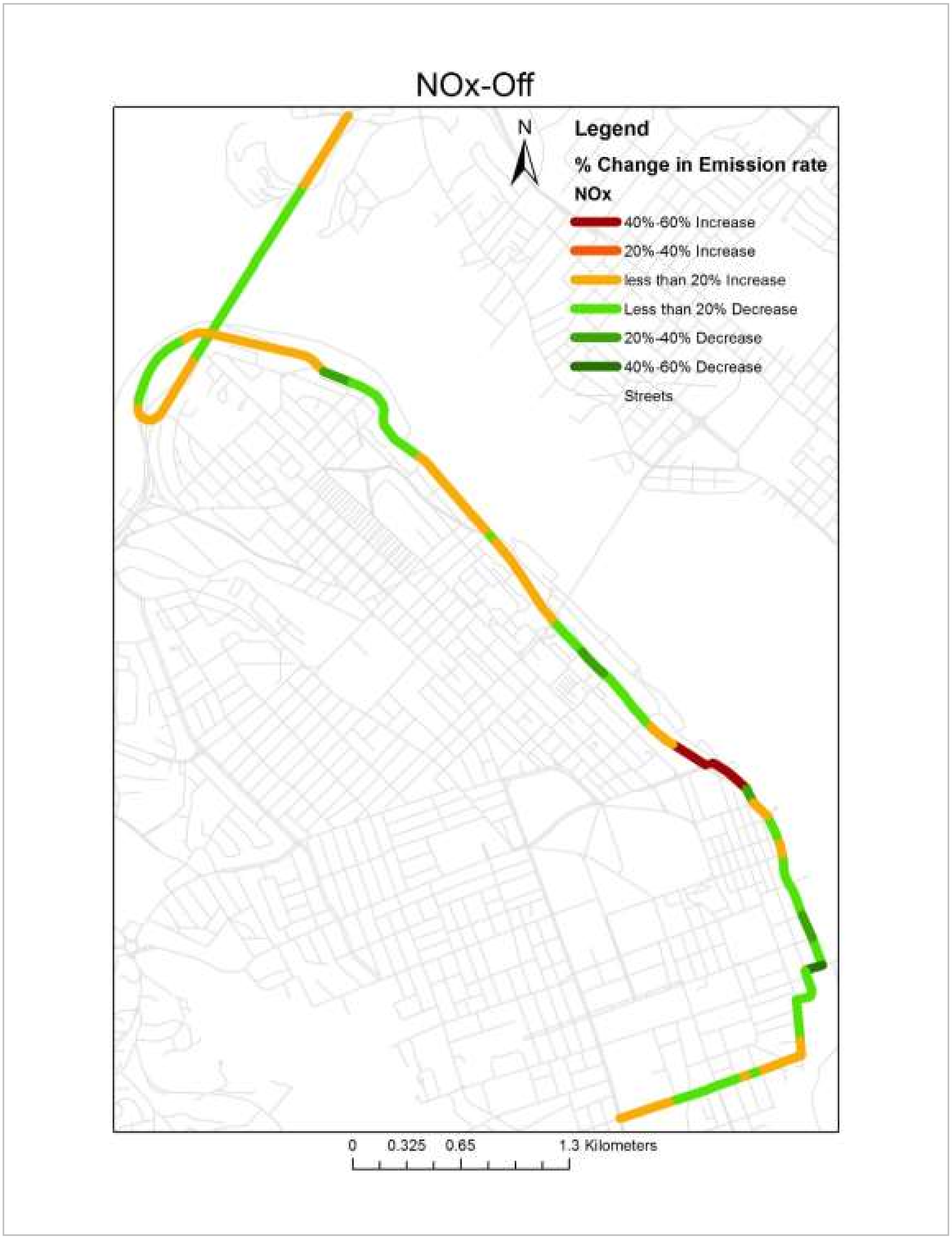

Figure A6 Relative Difference in NOx Emission Rates from Link Average Emission Rate in Off Peak

Figure A7 Relative Difference in PM_{10} Emission Rates from Link Average Emission Rate in Off Peak

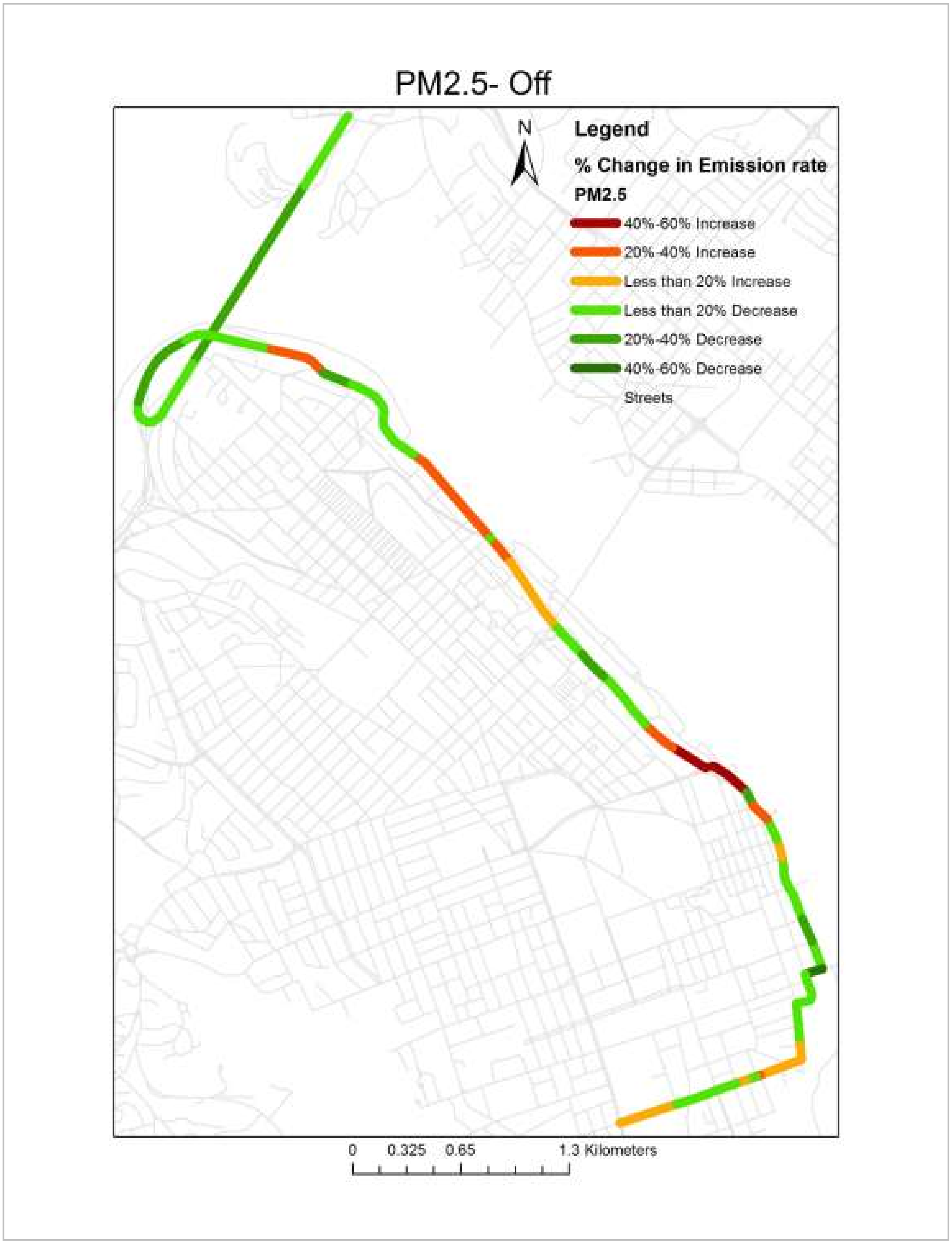

Figure A8 Relative Difference in $PM_{2.5}$ Emission Rates from Link Average Emission Rate in Off Peak

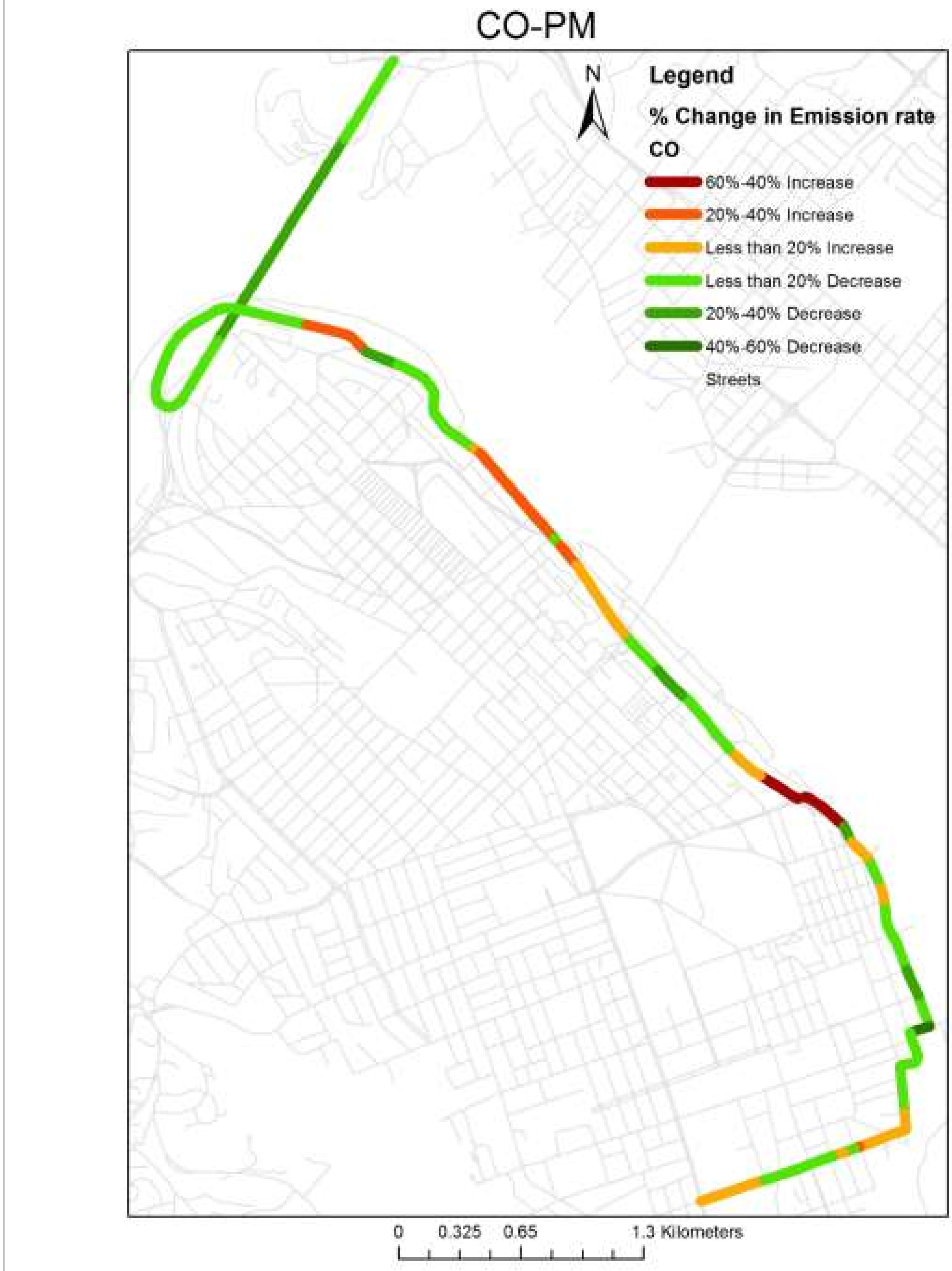

Figure A9 Relative Difference in CO Emission Rates from Link Average Emission Rate in PM Peak

Figure A10 Relative Difference in NOx Emission Rates from Link Average Emission Rate in PM Peak

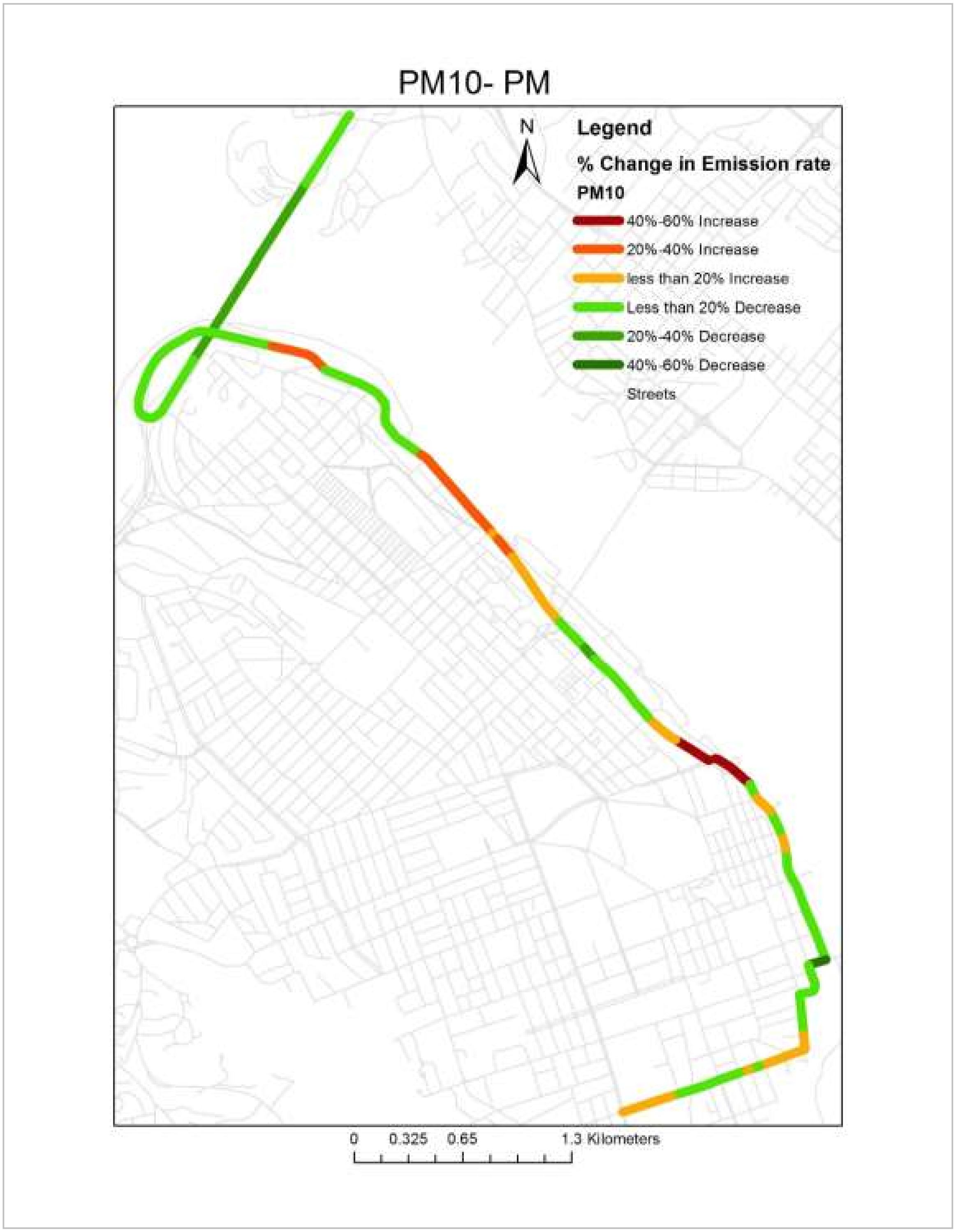

Figure A11 Relative Difference in PM_{10} Emission Rates from Link Average Emission Rate in PM Peak

Figure A12 Relative Difference in $PM_{2.5}$ Emission Rates from Link Average Emission Rate in PM Peak

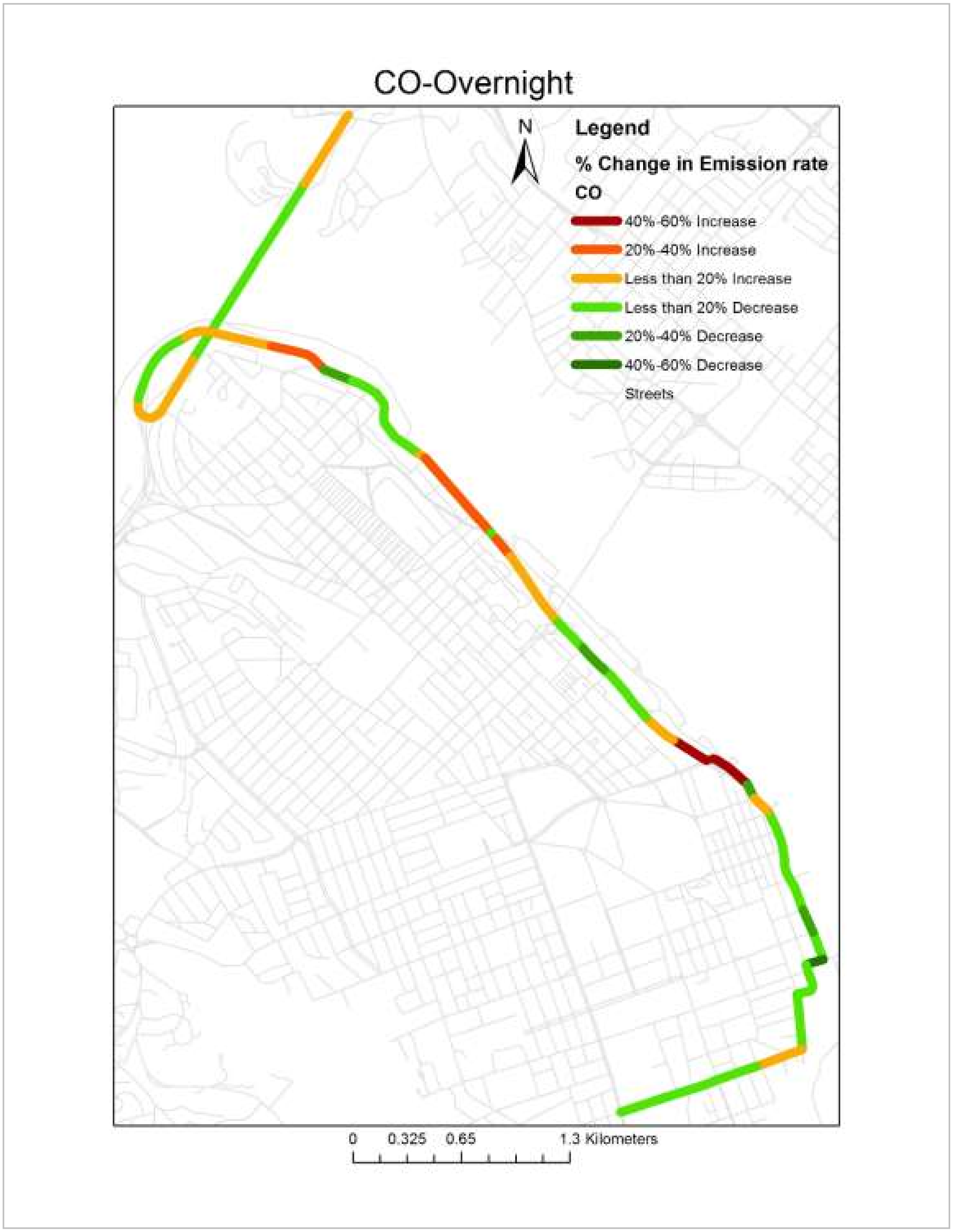

Figure A13 Relative Difference in CO Emission Rates from Link Average Emission Rate in Overnight

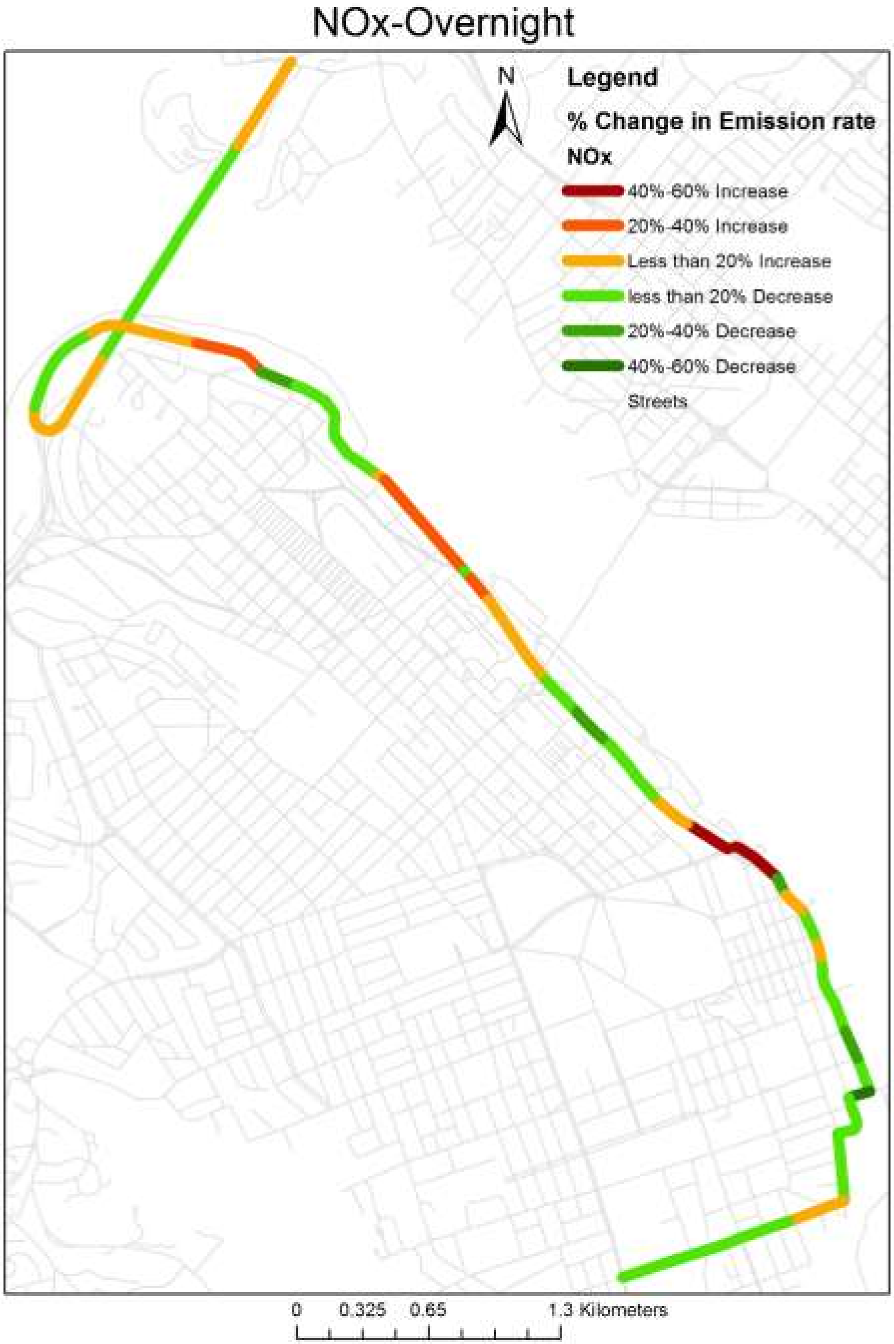

Figure A14 Relative Difference in NOx Emission Rates from Link Average Emission Rate in Overnight

Figure A15 Relative Difference in PM_{10} Emission Rates from Link Average Emission Rate in Overnight

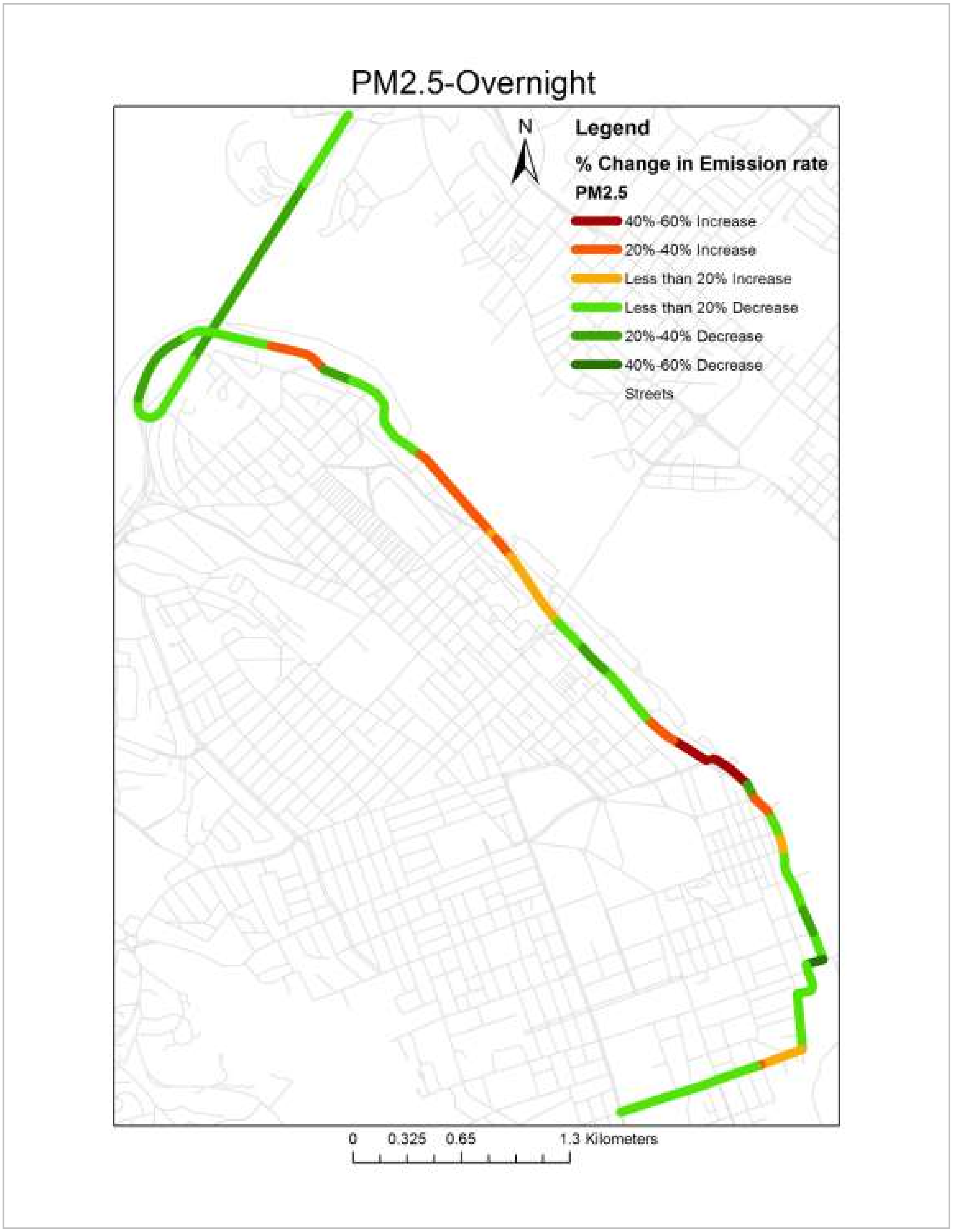

Figure A16 Relative Difference in PM$_{2.5}$ Emission Rates from Link Average Emission Rate in Overnight

Appendix B: Spatial Distribution of Total Emissions of Pollutants

Figure B1 Total Emissions (g) of GHG in AM Peak Period

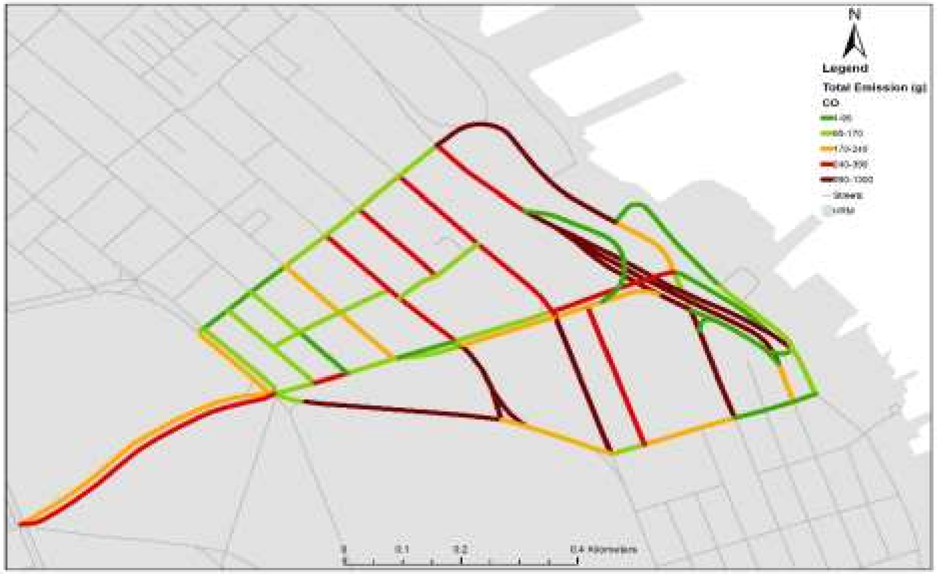

Figure B2 Total Emissions (g) of CO in AM Peak Period

Figure B3 Total Emissions (g) of NOx in AM Peak Period

Figure B4 Total Emissions (g) of SO_2 in AM Peak Period

Figure B5 Total Emissions (g) of PM_{10} in AM Peak Period

Figure B6 Total Emissions (g) of $PM_{2.5}$ in AM Peak Period

Figure B7 Total Emissions (g) of GHG in Off Peak Period

Figure B8 Total Emissions (g) of CO in Off Peak Period

Figure B9 Total Emissions (g) of NOx in Off Peak Period

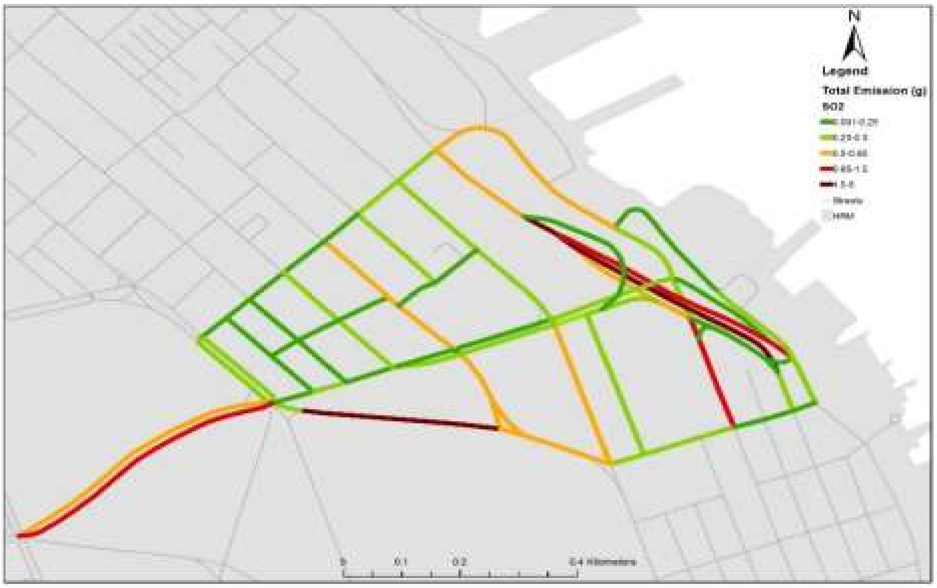

Figure B10 Total Emissions (g) of SO_2 in Off Peak Period

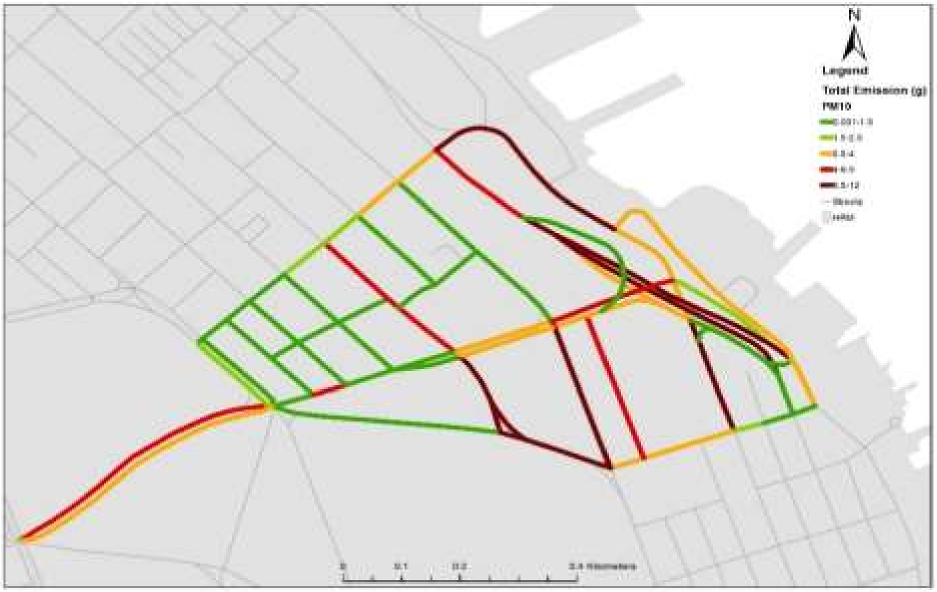

Figure B11 Total Emissions (g) of PM_{10} in Off Peak Period

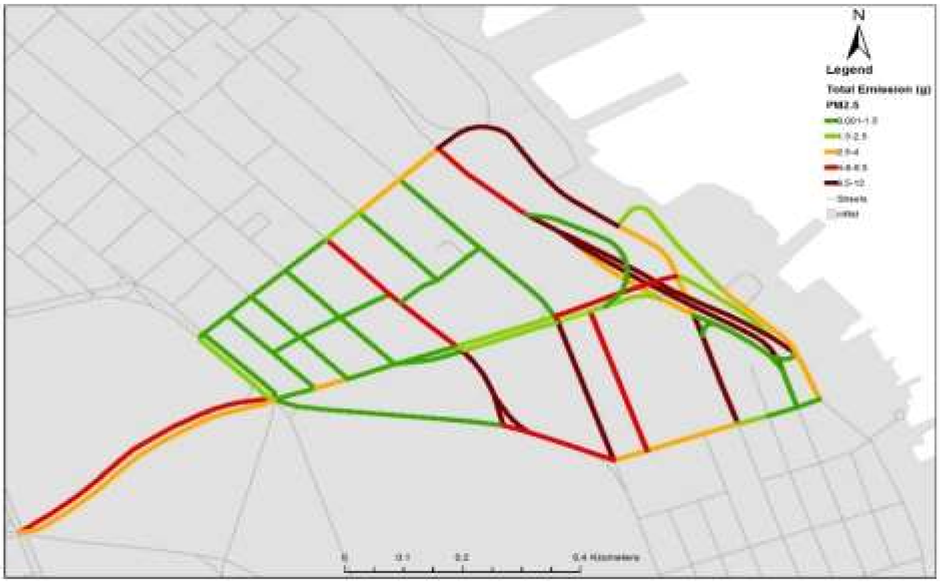

Figure B12 Total Emissions (g) of $PM_{2.5}$ in Off Peak Period

Figure B13 Total Emissions (g) of GHG in PM Peak Period

Figure B14   Total Emissions (g) of CO in PM Peak Period

Figure B15   Total Emissions (g) of NOx in PM Peak Period

Figure B16 Total Emissions (g) of SO_2 in PM Peak Period

Figure B17 Total Emissions (g) of PM_{10} in PM Peak Period

Figure B18 Total Emissions (g) of $PM_{2.5}$ in PM Peak Period

Appendix C: Spatial Distribution of Total Idling Emissions of Pollutants

Figure C1 Total Idling Emissions (g) of GHG in AM Peak Period

Figure C2 Total Idling Emissions (g) of CO in AM Peak Period

Figure C3 Total Idling Emissions (g) of NOx in AM Peak Period

Figure C4 Total Idling Emissions (g) of SO_2 in AM Peak Period

Figure C5 Total Idling Emissions (g) of PM_{10} in AM Peak Period

Figure C6 Total Idling Emissions (g) of $PM_{2.5}$ in AM Peak Period

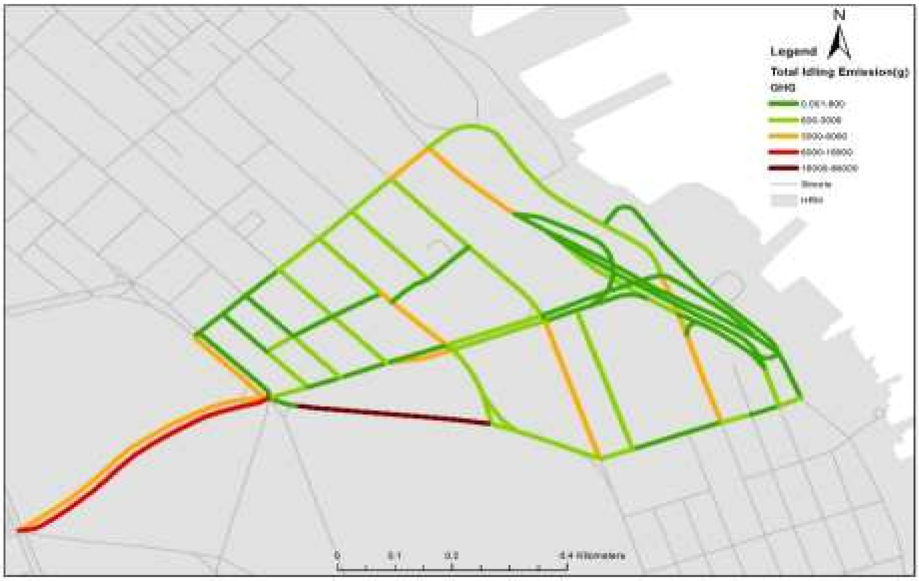

Figure C7 Total Idling Emissions (g) of GHG in off Peak Period

Figure C8 Total Idling Emissions (g) of CO in off Peak Period

Figure C9 Total Idling Emissions (g) of NOx in off Peak Period

Figure C10 Total Idling Emissions (g) of SO_2 in off Peak Period

Figure C11 Total Idling Emissions (g) of PM_{10} in off Peak Period

Figure C12 Total Idling Emissions (g) of $PM_{2.5}$ in off Peak Period

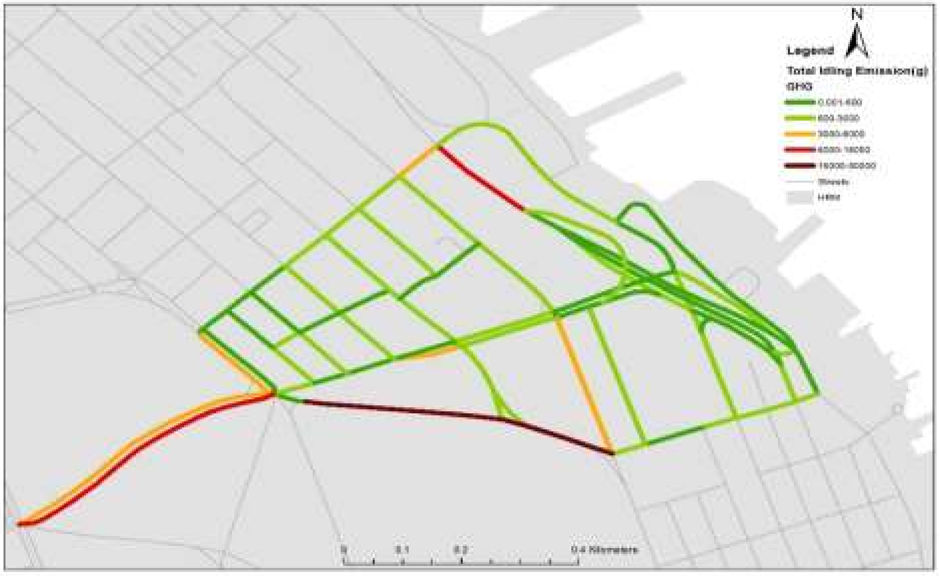

Figure C13 Total Idling Emissions (g) of GHG in PM Peak Period

Figure C14 Total Idling Emissions (g) of CO in PM Peak Period

Figure C15 Total Idling Emissions (g) of NOx in PM Peak Period

Figure C16 Total Idling Emissions (g) of SO_2 in PM Peak Period

Figure C17 Total Idling Emissions (g) of PM_{10} in PM Peak Period

Figure C18 Total Idling Emissions (g) of $PM_{2.5}$ in PM Peak Period

Appendix D: Changes in Total Emissions of Pollutants in Proposed Scenario

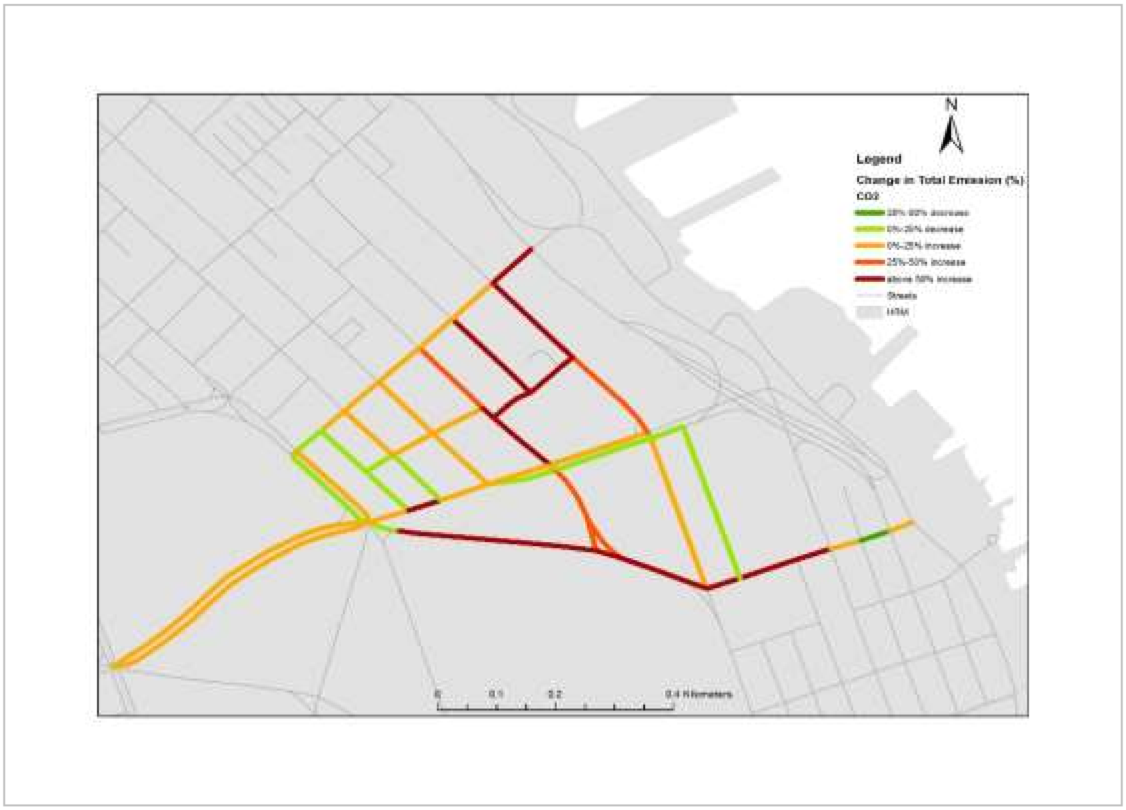

Figure D1 Changes in Total Emissions (g) of GHG in AM Peak Period

Figure D2 Changes in Total Emissions (g) of CO in AM Peak Period

Figure D3 Changes in Total Emissions (g) of NOx in AM Peak Period

Figure D4 Changes in Total Emissions (g) of SO_2 in AM Peak Period

Figure D5 Changes in Total Emissions (g) of PM_{10} in AM Peak Period

Figure D6 Changes in Total Emissions (g) of $PM_{2.5}$ in AM Peak Period

Figure D7 Changes in Total Emissions (g) of GHG in Off Peak Period

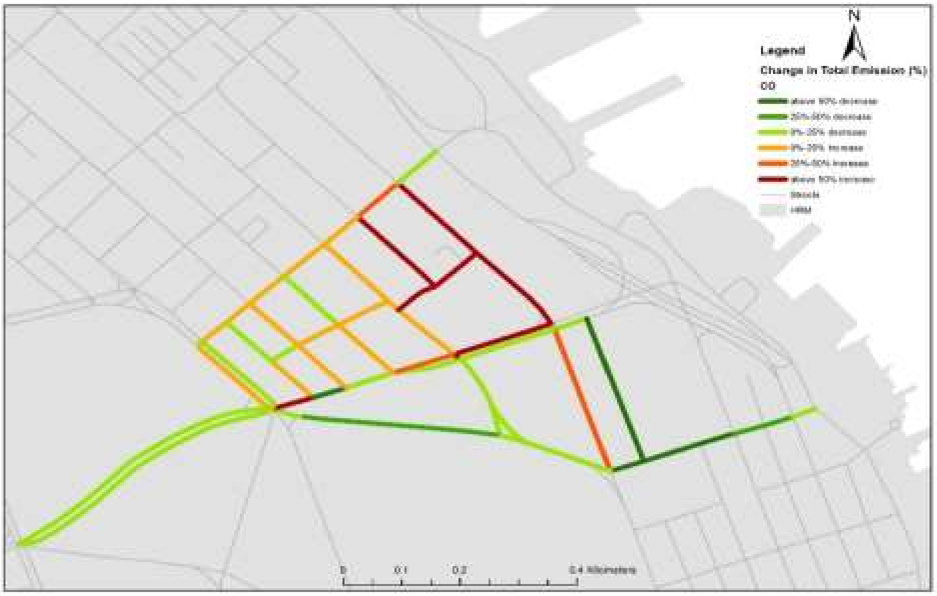

Figure D8 Changes in Total Emissions (g) of CO in Off Peak Period

Figure D9 Changes in Total Emissions (g) of NOx in Off Peak Period

Figure D10 Changes in Total Emissions (g) of SO_2 in Off Peak Period

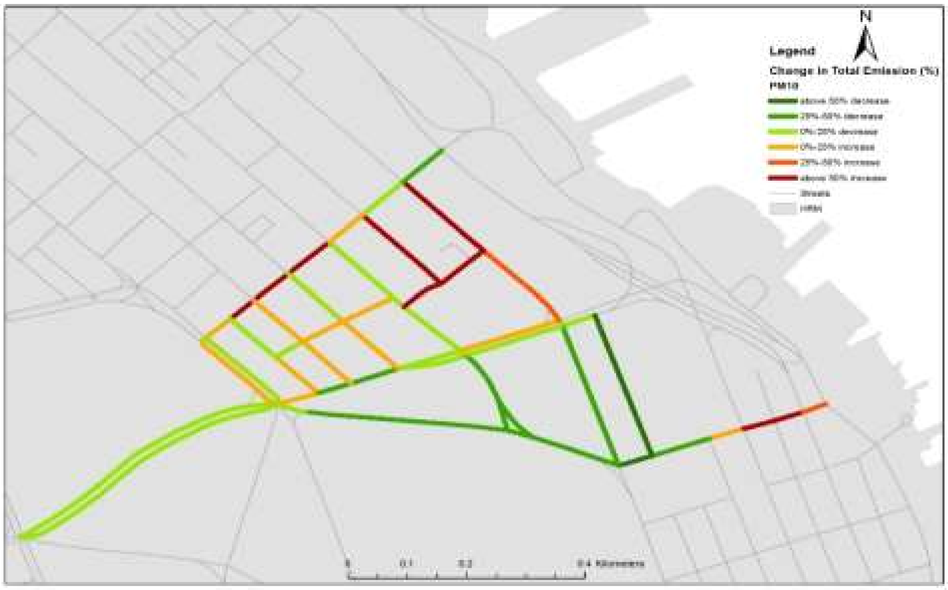

Figure D11 Changes in Total Emissions (g) of PM_{10} in Off Peak Period

Figure D12 Changes in Total Emissions (g) of $PM_{2.5}$ in Off Peak Period

Figure D13 Changes in Total Emissions (g) of GHG in PM Peak Period

Figure D14 Changes in Total Emissions (g) of CO in PM Peak Period

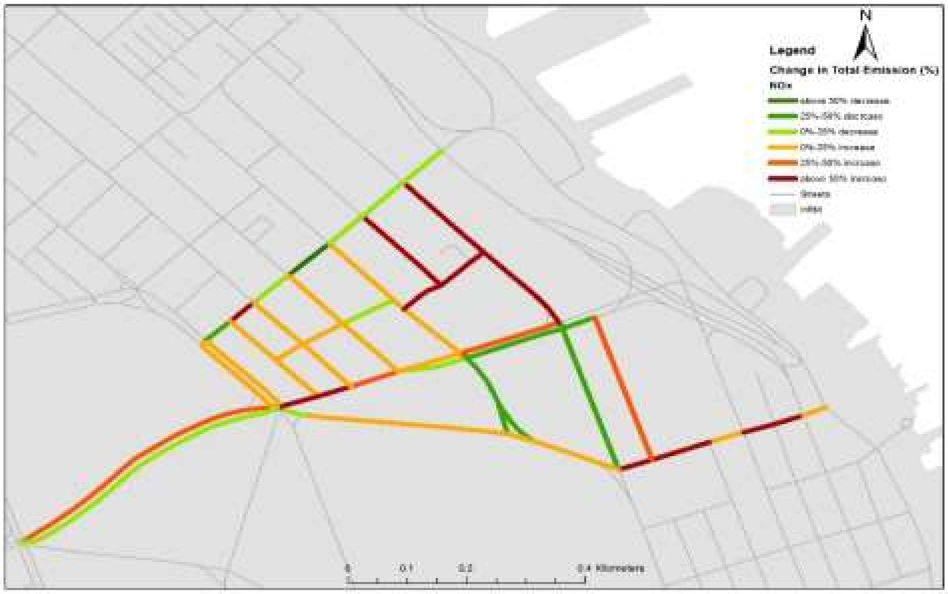

Figure D15 Changes in Total Emissions (g) of NOx in PM Peak Period

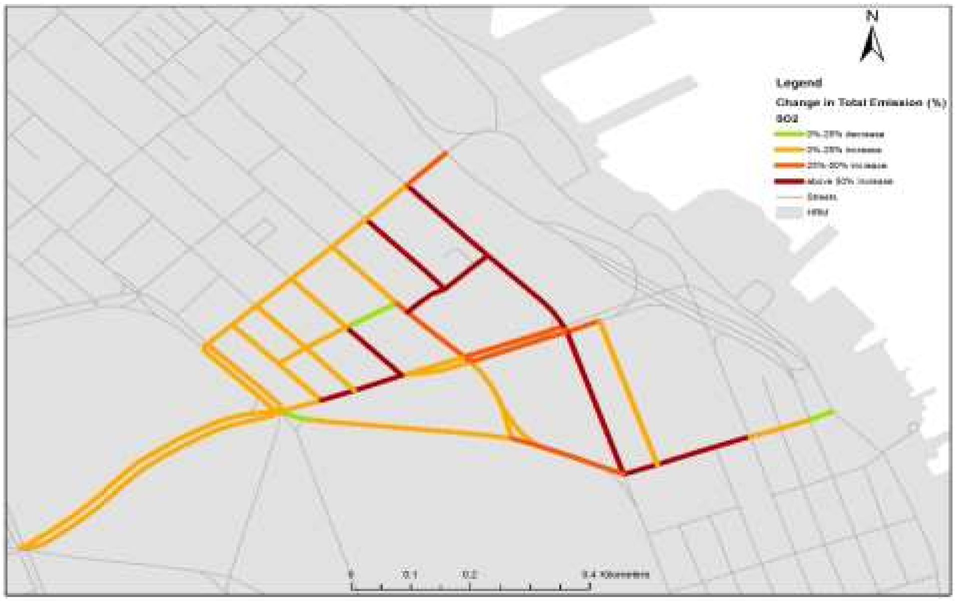

Figure D16 Changes in Total Emissions (g) of SO_2 in PM Peak Period

Figure D17 Changes in Total Emissions (g) of PM_{10} in PM Peak Period

Figure D18 Changes in Total Emissions (g) of $PM_{2.5}$ in PM Peak Period