Capturing the Effects of Urban Drive Cycles and Passenger Ridership on Transit Bus Emissions and Investigating the Potential of Emission Reduction Strategies

By

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ABSTRACT

Urban transportation is a major contributor to anthropogenic greenhouse gas (GHG) emissions and air pollution. Worldwide, planners and policy makers are consistently encouraging individuals to reduce their reliance on private vehicles while promoting the use of public transit. While transit buses reduce per-passenger emissions of GHG and air pollutants, they generate a large amount of emissions on a vehicle basis especially when they are fuelled by conventional diesel.

This research was motivated by the importance of reducing transit bus emissions in urban areas which can only be achieved after understanding the factors affecting transit bus emissions and exploring the effects of various emission reduction strategies. We started with exploring the emission estimation methods currently embedded within emission inventory models followed by a validation of the most commonly used model in North America, the Motor Vehicle Emissions Simulator (MOVES), in a local context by collecting instantaneous bus speed and passenger ridership data across a variety of transit routes (downtown and suburban/highway) and bus types (standard, articulated, old, and new). We observed a lack of transit bus drive cycles in MOVES and significant differences in emissions when MOVES uses it's embedded drive cycles to estimate emissions. To improve the estimates in MOVES, we then tested the effects of incorporating local drive cycles into the MOVES model by replacing embedded default drive cycles. A significant improvement was observed in emission estimation, showing a reduction of the average estimation error from 23% to 13%.

In order to understand how emissions are affected, we analyzed the spatial and temporal variability of transit bus emissions across the island of Montreal and investigated the isolated and combined effects of different factors affecting emissions (including the level of congestion, roadway grade, passenger load, and traffic variability). The level of congestion and higher road grade were found to be the most important factors. The trade-off between total and per-passenger emissions was also analyzed under varying passenger loads. While an increasing passenger load on the bus increases emissions, we observed that the addition of each passenger influences the per-passenger emissions differently, depending on the bus occupancy.

The reduction potential of using different fuels including ultra-low sulfur diesel or compressed natural gas; and of transit service operational improvements was also investigated. These included transit signal priority, queue jumper lane, and relocation of bus stops considering a wide combination of congestion, roadway grades, and passenger ridership. We observed that the effectiveness of the improvements could vary considerably depending on the level of congestion. While compressed natural gas could achieve 8-12% GHG reduction in both congested and uncongested networks, other transit improvements such as transit signal priority and queue jumper lanes could achieve an even higher reduction.

Finally, a corridor study was conducted to capture the changes in emissions as a result of the implementation of different transit service improvement strategies including smart cards, express bus service, and reserved bus lanes. Our results suggested that a reduction of 40% in GHG emissions could be possible by operating limited-stop express buses on reserved bus lanes compared to regular buses with no reserved lane.

This thesis addressed critical gaps in the current knowledge of transit bus emissions in four ways: it evaluated the most commonly used emission inventory model in a local context, it demonstrated a process to embed local drive cycles into the emission model, it quantified the individual and combined effects of different factors on transit bus emissions, and it quantified the emission reduction potential of different transit improvement strategies and alternative fuels, which would be crucial when implementing emission reduction strategies or modifying existing transit facilities.

RESUMÉ

Le transport urbain est un contributeur majeur de gaz à effet de serre d'origine anthropique (GES) et à la pollution de l'air. Dans le monde entier, les planificateurs et les décideurs politiques encouragent constamment les individus à réduire leur dépendance sur les véhicules privés tout en favorisant l'utilisation des transports en commun. Tandis que les bus de transit réduisent les émissions par passager de GES et de polluants atmosphériques, ils génèrent une grande quantité d'émissions sur une base d'un véhicule en particulier quand ils sont alimentés par du diesel conventionnel.

Cette recherche est motivée par l'importance de réduire les émissions des autobus de transport en commun dans les zones urbaines. Cette reduction ne peut être obtenue qu'après la compréhension des facteurs qui influent sur les émissions des autobus de transport en commun et d'explorer les effets de diverses stratégies de réduction des émissions. Nous avons commencé par comprendre les méthodes d'estimation des émissions actuellement intégrées dans les modèles d'inventaire des émissions, suivie d'une validation du modèle le plus couramment utilisé en Amérique du Nord, MOVES, dans un contexte local en recueillant la vitesse du bus instantanée et les données de l'achalandage de passagers à travers une variété de voies de transit (de centre-ville et de banlieue / autoroute) et types de bus (standard, articulé). Nous observons un manque de cycles de conduite de bus et des différences importantes dans les émissions quand MOVES utilise ses cycles de conduite intégrés pour estimer les émissions. Pour améliorer les estimations de MOVES, nous avons ensuite testé les effets de l'intégration de cycles de conduite locaux en remplaçant les cycles défaut. Une étude de validation représente une amélioration significative de l'estimation des émissions, ce qui réduit l'erreur d'estimation moyenne de 23% à 13%.

Nous avons analysé la variabilité spatiale et temporelle des émissions de bus de transit à travers l'île de Montréal et étudié les effets isolés et combinés de différents facteurs qui influent sur les émissions (y compris le niveau de congestion, le grade chaussée, nombre de passagers, le trafic et la variabilité). Le niveau de congestion et de grade de la route ont été trouvés être les facteurs les plus forts. Le compromis entre les émissions totales et par passager a également été analysé avec diverses charges de passagers. Bien que plus de passagers sur le bus augmente les

émissions, nous observons que l'addition de chaque passager influe sur les émissions par passager différemment en fonction de l'occupation du bus.

Nous avons également étudié le potentiel de réduction des différents combustibles dont les diesel à faible teneur en soufre, gaz naturel comprimé, et des améliorations opérationnelles de service, y compris la signalization qui donne priorité au transport, la file d'attente cavalier, et la relocalisation des arrêts de bus en envisageant une large combinaison de la congestion, des qualités routières, et d'achalandage. Nous avons observé que l'efficacité des améliorations peut largement varier en fonction du niveau de congestion. Alors que le gaz naturel comprimé pourrait parvenir à une réduction des émissions de GES de 8-12%, d'autres améliorations de transit tels que la priorité au transport en commun et de files d'attente cavaliers pourraient engendrer une réduction plus importante.

Enfin, une étude sur un corridor a été menée pour capturer les changements dans les émissions à la suite de la mise en œuvre des différentes stratégies d'amélioration du service de transport en commun, y compris les cartes à puce, un service d'autobus express et des voies réservées aux autobus. Nos résultats suggèrent qu'une réduction de 40% des émissions de GES pourrait être possible en exploitation d'autobus express sur les voies réservées par rapport aux autobus réguliers avec aucune voie réservée.

Cette thèse adresse des lacunes critiques dans les connaissances actuelles sur les émissions des autobus de transport en commun de quatre façons: elle a évalué le modèle d'inventaire des émissions le plus couramment utilisé dans un contexte local, elle a démontré un processus visant à intégrer les cycles locaux d'entraînement dans le modèle d'émission, lle a quantifié les effets individuels et combinés de différents facteurs sur les émissions des autobus de transport en commun, et elle a quantifié le potentiel de réduction des émissions des différentes stratégies d'amélioration du transport en commun et des carburants alternatifs, ce qui serait crucial lors de la mise en œuvre des stratégies de réduction des émissions ou de modification d'installations de transport en commun existantes.

ACKNOWLEDGEMENTS

This is the time when my journey ends. This journey over four years was like riding a bus. I started my ride as a PhD student while knowing very little about transit bus emissions. I was happy to ride the bus. Time was passing by and the bus was stopping at many locations where people boarded and alighted. Throughout the ride I met many individuals, heard about their experiences, read transit journals, and started realizing that I should continue my PhD aiming to reduce transit emissions. Now I feel this is the time to get off the bus and to thank the people without whom this journey would have never been complete. Even though it is not easy to acknowledge just by saying few words, I want to thank them from the very bottom of my heart. My appreciation extends to everyone who helped me in any capacity during this journey and apologies to those I may have forgotten to mention their name in the excitement of these last few stages.

First of all I am grateful to Allah, the most gracious and merciful, for His wisdom and blessing in my life. Then, I want to express my deepest gratitude to my professor, Dr. Marianne Hatzopoulou, for giving me the chance to work with her in the TRAQ group. Without her enthusiasm, moral advice, financial support, and continuous guidance this work would have never been complete. I also want to thank her for sending me generously to many conferences where I had the chance to meet new people and share experiences. Special thanks for replying to my endless emails within 30 minutes even on weekends and at midnight. I feel honoured to have been given the chance to learn many things over the last four years, especially how to think critically and write objectively. The way she teaches and supervises her students sets an example for me that I would like to carry in my future career.

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DEDICATION

To my parents, my wife, and my son

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LIST OF ABBREVIATIONS

BRT	=	Bus Rapid Transit
CACs	=	Criteria Air Contaminants
CARB	=	California Air Research Board
CH_4	=	Methane
CMEM	=	Comprehensive Modal Emissions Model
CNG	=	Compressed Natural Gas
CO	=	Carbon Monoxide
CO_2	=	Carbon Dioxide
EF	=	Emission factor
GHG	=	Greenhouse Gas
GIS	=	Geographic Information Systems
GPS	=	Global Positioning Systems
HCNG	=	Hydrogen-Natural Gas
IM	=	Inspection and Maintenance
ITS	=	Intelligent Transportation Systems
MOVES	=	Motor Vehicle Emission Simulator
NB	=	Northbound
NH3	=	Ammonia
NOx	=	Nitrogen Oxides
opmode	=	Operating Mode
PEMS	=	Portable Emissions Measurement System
PHEM	=	Passenger Car and Heavy Duty Emission Model
PLF	=	Passenger Load Factor
PM2.5	=	Particulate Matter less than or equal to 2.5 Microns
PM10	=	Particulate Matter less than or equal to 10 Microns
RBC	=	Ring Barrier Controller
RMSE	=	Root Mean Square Error
SB	=	Southbound
SOx	=	Sulphur Oxides
STM	=	Société de Transport de Montréal
TPM	=	Total Particulate Matter
TSP	=	Transit Signal Priority
ULSD	=	Ultra Low Sulfur Diesel
USEPA	=	US Environmental Protection Agency
VMT	=	Vehicle Miles Travelled
VOC	=	Volatile Organic Compounds
VSP	=	Vehicle Specific Power

AUTHOR CONTRIBUTIONS

This dissertation includes three manuscripts that have been published in peer-reviewed journals, and two other manuscripts that have been submitted to peer-reviewed journals and are currently under review. This work was completed with co-authors; details of author contributions are provided below:

Chapter 3-1: "*Modeling Transit Bus Emissions using MOVES: Validation of Default Distributions and Embedded Drive Cycles with Local Data.*" by myself as the first author and Dr. Marianne Hatzopoulou who contributed intellectually, provided comments, and edited the manuscript.

Chapter 3-2: *"Embedding Local Operating Mode Distributions into the MOVES Database To Estimate Transit Bus Emissions Across An Urban Network."* by myself as the first author and Dr. Marianne Hatzopoulou who contributed intellectually, provided comments, and edited the manuscript.

Chapter 4: *"Investigating the Isolated and Combined Effects of Congestion, Roadway Grade, Passenger Loading, and Alternative Fuels on Transit Bus Emissions."* by myself as the first author and Dr. Marianne Hatzopoulou who contributed intellectually, provided comments, and edited the manuscript.

Chapter 5: *"Reducing Transit Bus Emissions: Alternative Fuels or Traffic Operations?"* by myself as the first author and Dr. Marianne Hatzopoulou who contributed intellectually, provided comments, and edited the manuscript.

Chapter 6: *"A Simulation of Transit Bus Emissions along an Urban Corridor: Evaluating Changes across Several Years and Under Various Service Improvement Strategies."* By myself as the first author, with Dr. Ehab Diab, Dr. Ahmed El-Geneidy, and Dr. Marianne Hatzopoulou. Dr. Diab contributed by providing insights on transit operations along the corridor. Dr. Diab also contributed in designing and running the data collection campaign as well as in the development of statistical models. Dr. El-Geneidy and Dr. Hatzopoulou contributed intellectually, provided comments, and edited the manuscript.

PUBLICATION DETAILS

This dissertation is comprised of five papers. The details of the publications are listed below:

Chapter 3-1: Alam, A., and Hatzopoulou, M. (2015). "Modeling Transit Bus Emissions using MOVES: Validation of Default Distributions and Embedded Drive Cycles with Local Data." *Journal of Transportation Engineering (ASCE)*, under review.

Chapter 3-2: Alam, A., and Hatzopoulou, M. (2015). "Embedding Local Operating Mode Distributions into the MOVES Database to Estimate Transit Bus Emissions across an Urban Network." *95th annual meeting of the Transportation Research Board and Transportation Research Records journal,* under review.

Chapter 4: Alam, A., and Hatzopoulou, M. (2014). "Investigating the Isolated and Combined Effects of Congestion, Roadway Grade, Passenger Load, and Alternative Fuels on Transit Bus Emissions." *Transportation Research Part D: Transport and Environment*, 29, 12-21.

Chapter 5: Alam, A., and Hatzopoulou, M. (2014). "Reducing Transit Bus Emissions: Alternative Fuels or Traffic Operations?" *Atmospheric Environment*, 89, 129-139.

Chapter 6: Alam, A., Diab, E., El-Geneidy, A. M., and Hatzopoulou, M. (2014). "A Simulation of Transit Bus Emissions along an Urban Corridor: Evaluating Changes under Various Service Improvement Strategies." *Transportation Research Part D: Transport and Environment*, 31(0), 189-198.

1 CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1 Chapter Overview

This chapter starts with a discussion of transportation emissions and the recent trends in Canada. It also demonstrates the contribution of private vehicles to total emissions and highlights the need for public transit in Section 1.2. Section 1.3 outlines some of the negative health effects of diesel transit bus exhaust as well as the challenges in estimating transit bus emissions. The scope of work is then described in Section 1.4 and research significance is presented in Section 1.5. Section 1.6 describes the dissertation structure and how different chapters are integrated to address the research objectives. Finally, Section 1.7 gives rational of the unit system used in the dissertation.

1.2 Background and Motivation

The impact of transportation on greenhouse gas (GHG) emissions and air quality is a topic that needs little introduction. Worldwide, transportation is responsible for approximately 23 percent of total GHG emissions while in Canada, transportation accounts for about 24 percent of total GHG emissions (Environment Canada 2014; Li et al. 2011). Besides the potential impact on climate change, transportation emissions have been associated with a range of health effects including respiratory and cardiovascular outcomes as well as premature mortality (Health Effects Institute 2010). With an increasing portion of the Canadian population living, working, or travelling along busy streets, concerns over near-roadway exposure and its health effects remain pertinent. As a result, there is growing pressure on planners and policy-makers to reduce the amount of traffic emissions to improve urban air quality as well as to sustain climate change.

In Canada, transportation is the largest contributor to GHG emissions and Criteria Air Contaminants (CACs) which are composed of Total Particulate Matter (TPM), Particulate Matter less than or equal to 10 Microns (PM_{10}), Particulate Matter less than or equal to 2.5 Microns ($PM_{2.5}$), Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x), Volatile Organic Compounds (VOC), Carbon Monoxide (CO) and Ammonia (NH_3). In Canada, GHG emissions have been increasing significantly: in 1990 total GHG emissions amounted to 591 Mt and in 2012 they amounted to 699 Mt. In recent years the amount of annual GHG increase has slowed down, however it could become hard to achieve the Copenhagen target of 611 Mt whereby Canada committed to reducing its emissions by 17% from 2005 levels by 2020 (Environment Canada 2014). **Figure 1-1** shows the increase in GHG emissions from different economic sectors between 1990 and 2012. We observe that until 2001, transportation was consistently the leading sector in GHG emissions. In fact, GHG emissions from transportation have increased by 31%, from 128 Mt in 1990 to 168 Mt in 2005. This increase was promoted by strong economic growth and low oil prices between 1990 and 1999. Since 2005, GHG emissions from the transportation sector have been almost constant. Despite population growth, GHG emissions from transport remain almost stable because of improvements in the fuel efficiency of passenger cars as well as transportation policies. On average, the share of transportation to total GHG emissions remains above 21%. For the first time since 1990, the transportation sector became the second leading contributor to GHG in 2012 when the Oil and Gas sector became the first. A breakdown of Canada's annual GHG emissions in 2012 from different economic sectors is shown in **Figure 1-2**. The emissions can be attributed to seven key areas of the economy: Oil and gas (25% of total emissions); Transportation (24%); Electricity (12%); Buildings (11%); Emissions-intensive and trade-exposed industries (11%); Agriculture (10%); Waste and others (7%).

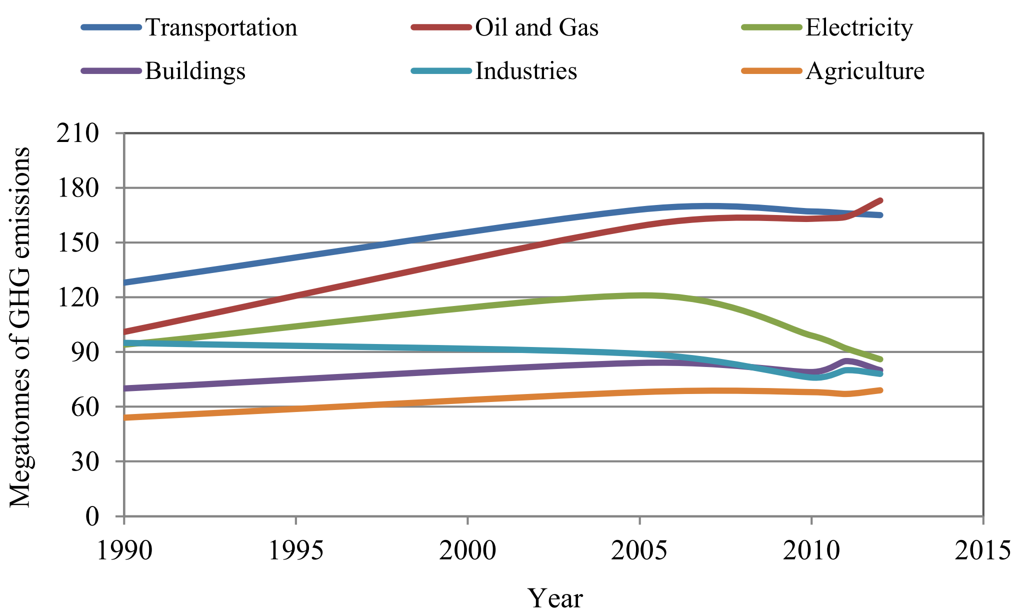

Figure 1-1. Trend of annual GHG emissions of different economic sectors in Canada (Environment Canada 2014)

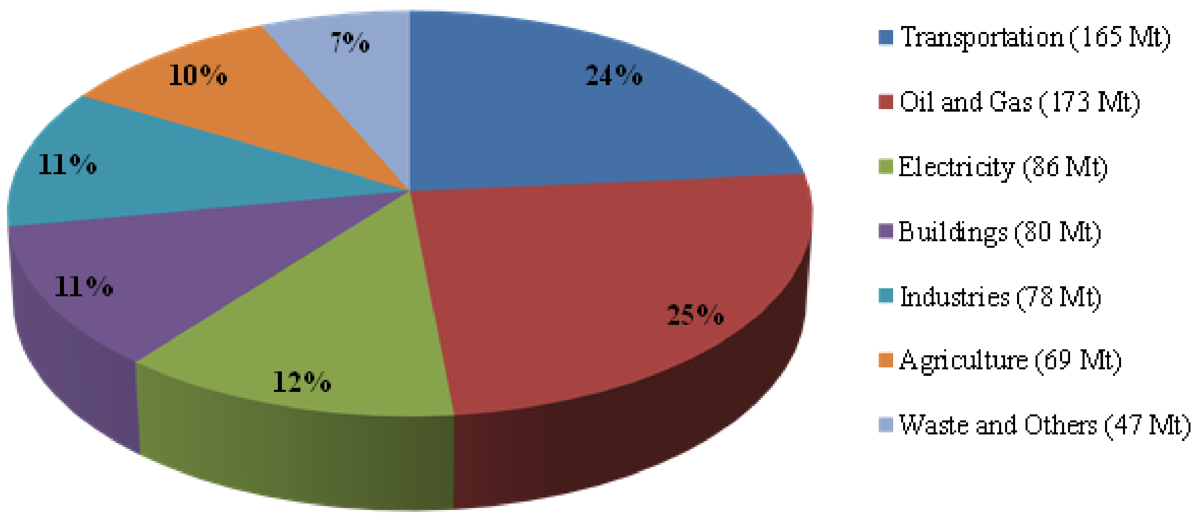

Figure 1-2. Contribution to total GHG emissions by different economic sectors in Canada in 2012 (Environment Canada 2014)

In Canada, road transportation is responsible for 69% of the total transportation GHG emissions (Environment Canada 2011). **Figure 1-3** prepared with Environment Canada data (Environment Canada 2011) shows the breakdown of road transportation GHG emissions across different modes in different years. It is clear that passenger vehicles which include light-duty gasoline vehicles and trucks are the main contributors accounting over 60% of total road based transportation emissions. Passenger vehicles are also responsible for emitting significant amounts of other pollutants. According to Transport Canada, passenger vehicles accounted for 2% of $PM_{2.5}$ emissions, 2% of SO_x emissions, 16% of NO_x emissions, 40% of VOC emissions and 55% of CO emissions in 2009 (Transport Canada 2012).

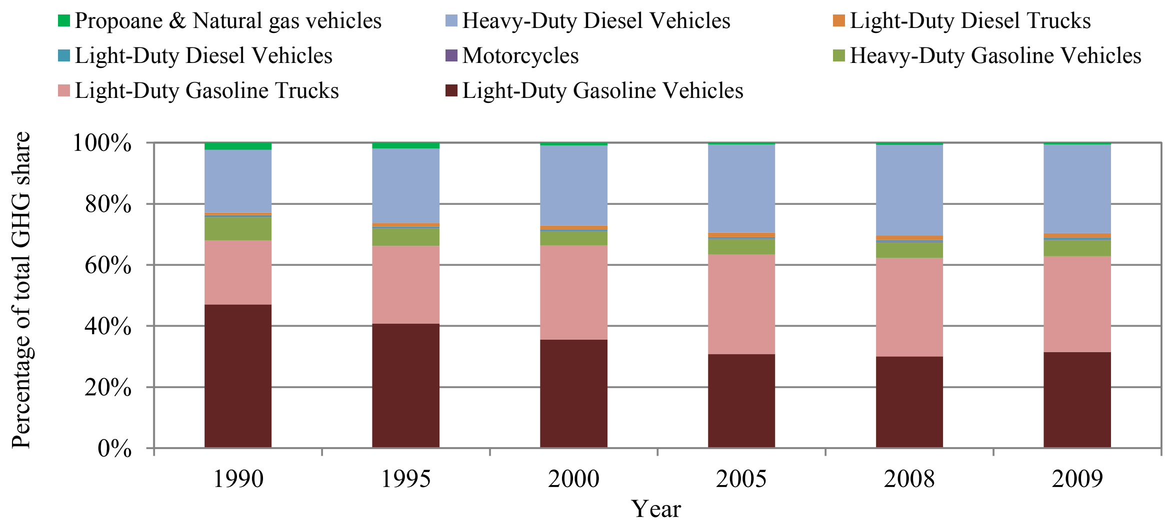

Figure 1-3. GHG emissions from different road transportation vehicles in different years (Environment Canada 2011)

Therefore, in order to reduce transportation related emissions, planners and policy makers are consistently aiming to reduce personal vehicle dependency while encouraging passengers towards public and active transportation modes. Because of the capability of achieving lower per-passenger emissions, public transit is considered as an environmentally friendly alternative. A transit rider can achieve up to 65% lower GHG emissions than an auto user for travelling the same distance. Commuters who take transit just twice a week can reduce their emissions by 25% (Canadian Urban Transit Association 2005). Besides GHG emission reductions, transit has many co-benefits such as reduced congestion, improved road safety, lower life-cycle environmental costs, a lower need for road infrastructure, improved air quality, improved social mobility, lower household costs, and positive impact on economic sectors (Chan et al. 2013; IBI Group et al. 2001; Nahlik and Chester 2014).

1.3 Problem Statement

In Canada, transit ridership has increased from 1.82 billion to 2.02 billion between 2008 and 2012, an increase of 11% while total transit kilometers driven increased from 1.07 million to 1.17 million km, an increase of about 10% (Canadian Urban Transit Association 2015). According to the Canadian National Household Survey, in 2011, 12% of commuters used public transit while 63.5% of them commuted by bus (Statistics Canada 2013). In larger metropolitan areas such as Toronto and Montreal, transit mode share is usually above 20% (Statistics Canada 2013). In order to meet the growing demand for bus service, transit agencies are expanding their network coverage as well as the size of their bus fleet. Often transit agencies prefer to use diesel fuelled buses because diesel requires less maintenance and generates more energy compared to other commonly available fuels. But diesel engines can produce significant amounts of GHGs, harmful aerosols, a range of hazardous air pollutants, and nitrogen oxides, which can contribute to ground level ozone formation or smog. Diesel exhaust emits over 40 toxic air contaminants (American Lung Association of California 2007). Exposure to these diesel-exhaust contaminants has both immediate health effects such as eye and nose irritation, headaches, light-headedness, nausea as well as long term health effects such as lung cancer, asthma, premature deaths and other chronic health conditions (Office of Environmental Health Hazard Assessment 2015). The risk of lung cancer among persons having been exposed to diesel exhaust is approximately 1.2 to 1.5 times more than the risk to those who are not exposed (Health Effects Institute 1995). Therefore, while the aim is to increase transit bus ridership, it is also very important to reduce conventional diesel bus exhaust by understanding the factors that significantly influence transit bus emissions as well as by investigating the potential of various strategies aimed to reduce transit bus emissions.

Emission inventory models can play a key role in the process of selecting suitable strategies that can achieve meaningful reductions in vehicle emissions. While in the US and many Europeans countries, vehicle emission inventories play a central role in transportation planning, Canadian cities are lagging behind. There is no formal process integrating emission modelling with transportation modelling and planning, and when emission models are adopted by certain cities, they are poorly calibrated, rarely updated and quickly become obsolete. To obtain improved emission estimates, local conditions including driving behaviour, fuel composition, fleet characteristics, and passenger ridership should be taken into account. In North America, the Motor Vehicle Emission Simulator (MOVES) developed by the US Environmental Protection Agency (USEPA) (US Environment Protection Agency 2010) is widely used both in planning and research. It has the capability of estimating emissions at different levels of spatial aggregation. When emissions are estimated at a neighbourhood or regional scale using average speeds, MOVES uses embedded driving characteristics obtained by instrumenting a limited number of vehicles running in US cities (Sierra Research Inc. 2009). Use of such default data could certainly under/overestimate emissions in a local Canadian context. Therefore, it is very important to understand how transit bus emissions are calculated in MOVES and the extent to which emission estimates could differ. At the same time, research efforts should include the development of alternative methods that could help local agencies achieve robust emission estimates without the reliance on resource intensive methods.

The use of vehicle drive cycles can provide more accurate estimates compared to average speeds, whereas a drive cycle is defined as the second-by-second speed profile of the vehicle. But even for smaller scale analyses, when drive cycles are used, emissions could vary largely depending on many factors such as passenger load, fuel type, bus type, fleet distribution, vehicle age distribution, and meteorology. The composition of diesel exhaust primarily depends on the composition of the fuel, the engine temperature, type of engine, and operating conditions (Nerella 2010). Transit bus emissions could vary with operation condition, bus age, and passenger loading; and on a per passenger basis depending on the situation, transit buses could be as polluting as private cars (Lau et al. 2011) . Most of the existing studies that focus on identifying factors behind transit bus emissions quantified the effects of individual factors. Very few studies have been conducted to date where the individual and combined effects of different factors as well as emission reduction strategies are investigated simultaneously. It is therefore crucial to understand the isolated and combined effects of the determinants of transit bus emissions in a local context and evaluate the potential of emission reduction strategies by considering local traffic conditions and geographic characteristics.

1.4 Research Questions

This research was driven by the following questions:

1) How do state-of-art emission inventory models estimate transit bus emissions? And what is the effect of incorporating local drive cycles as opposed to embedded default distributions?

2) How can traditional emission modelling techniques be improved without resorting to micro-simulation tools, especially when transit bus emissions are estimated for large urban areas?

3) What are the factors that can significantly affect transit bus emissions and what are their individual and combined effects along busy corridors?

4) What is the potential of alternative fuels and transit service improvements in the reduction of transit bus emissions?

By addressing the above questions, this dissertation filled the gap in the current literature on transit bus emissions regarding (i) understanding the methods used to estimate bus emissions, (ii) understanding the factors affecting emissions, and (iii) assessing the potential of emission reduction strategies. The four research questions are addressed in four chapters (Chapters 3-6). **Figure 1-4** outlines the structure of this thesis. Section 1.6 summarizes the contents of each chapter.

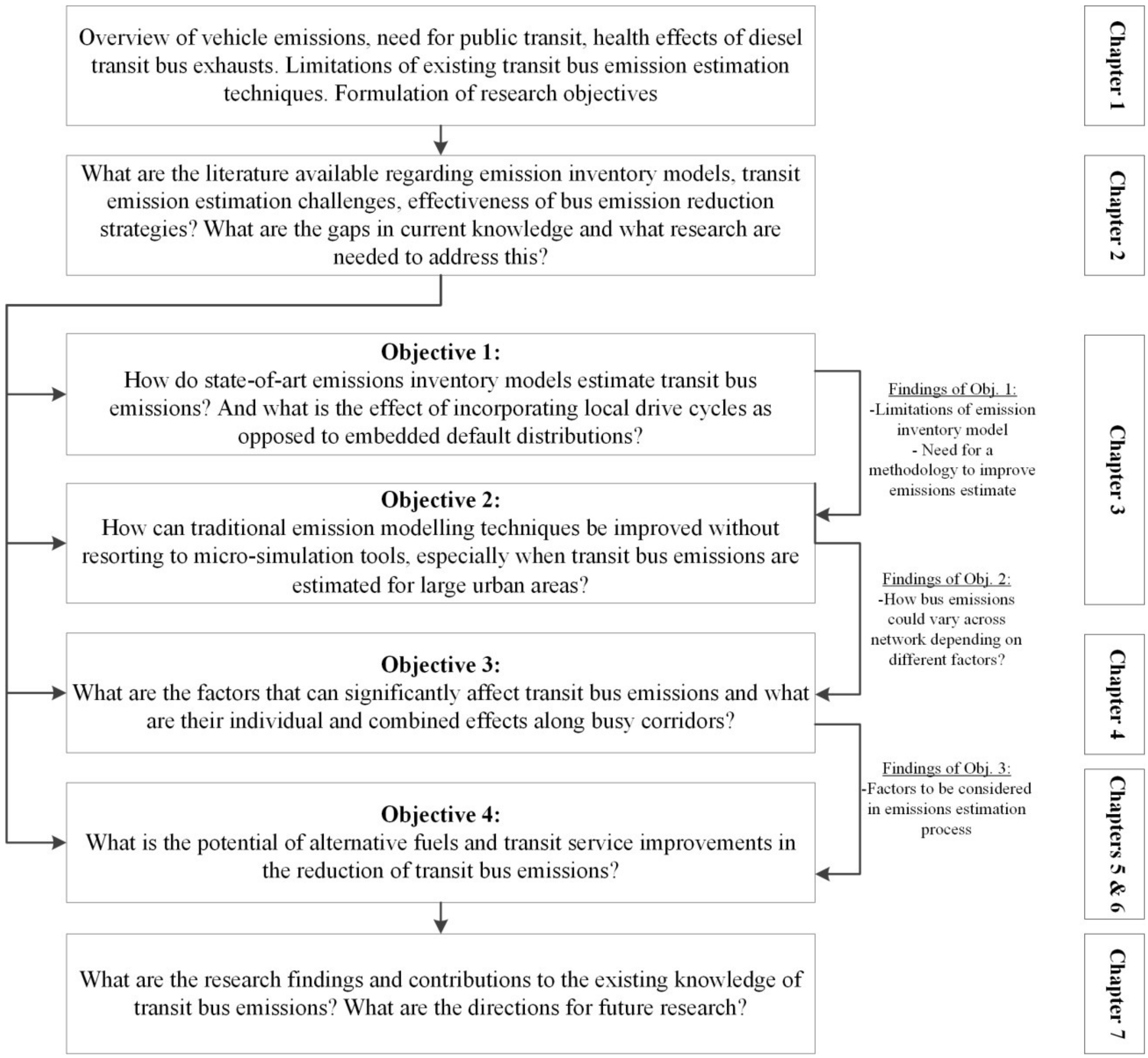

Figure 1-4. Overview of thesis structure

1.5 Research Significance

This research tackles three novel issues that are critical for understanding and improving the evaluation of transit service impacts on air quality: 1) understanding the accuracy of emission estimates conducted at different levels of aggregation and developing a methodology to achieve refined emission estimates, 2) exploring the association between transit bus emissions and traffic network variables, and 3) understanding the individual and combined effects of alternative fuels, traffic congestion, transit service improvement, passenger load, and road geometry on transit emissions. The aim of the research is to highlight the impact of different factors on transit bus emissions as well as to assess the potential of emission reduction strategies. The results could be very useful to transit planners before introducing or modifying transit routes as well as to policy makers before implementing or evaluating policies.

Another contribution of this study involves developing a procedure for the estimation of improved transit bus emissions using average speeds, which can be obtained from the bus schedule or from the output of a traditional traffic assignment model. The developed procedure will not require instantaneous speeds of vehicles (which is not easily available) but rather will take as input link-based average speeds and attributes from the regional traffic assignment model to generate link emissions with higher accuracy than what a traditional average-speed model would generate. The methodology can also be transferred to other vehicle types and modes.

1.6 Dissertation Structure and Overview of Chapters

This dissertation comprises five manuscripts that address the tasks outlined in **Figure 1-4**. **Chapter 2** starts with discussing different emission inventory models along with their usage and benefits. It discusses the most commonly used emission inventory model, MOVES, and the limitations of MOVES in estimating transit bus emissions. This chapter also discusses different methods of estimating transit bus emissions as well as the emission reduction potential of several transit service improvement strategies. It highlights the gaps in existing knowledge of transit bus emissions which motivated the research described in the succeeding chapters. **Chapter 3** investigates how transit bus emissions are estimated in MOVES, especially in average speed mode (**Objective 1**). To validate MOVES, we collected second-by-second bus speeds and stop-level passenger ridership information from 3,702 road segments covering 606 miles (970 km) in the City of Montreal (8 bus routes in total with repeated observations). Later, we compared the driving characteristics and emissions with those extracted from embedded MOVES inputs. The findings highlight the significant difference between MOVES and local data, and the need for a methodology for refining emissions that rely on average speeds. Later, this chapter uses the same second-by-second bus speed and passenger ridership data to generate average speed specific distributions that could be used to calibrate the model MOVES (**Objective 2**). This chapter also presents the temporal and spatial variations in emissions at a route level, link level, and bus stop level. **Chapter 4** investigates the isolated and combined effects of network speed, roadway grade, onboard passenger number, traffic variability, and alternative fuels on a corridor level (**Objective 3**). **Chapter 5** investigates the extent to which emissions could be reduced with the use of alternative fuels and improved transit operations by simulating transit buses. It presents an evaluation of emissions under different network speeds, roadway grades, and congestion levels (**Objective 4**). After observing the emission reduction potential of several transit improvement strategies in Chapter 5, **Chapter 6** presents a real case study in a busy corridor of Montreal to observe the reduction in emissions after the implementation of several transit improvement strategies by the local transit service provider, Société de transport de Montréal (**Objective 4)**. Finally, **Chapter 7** summarizes all findings and highlights the research contributions of this dissertation.

1.7 Note on the use of units in this document

It is important to note that throughout this dissertation, we use a combination of the International System of Units (SI) and Imperial units. This is done on purpose to remain faithful to the convention of the model MOVES (MOtor Vehicle Emission Simulator) that we use in each chapter. The model MOVES uses units of grams to reflect emissions and miles for distance; emission factors are in units of gram per mile.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Overview

This chapter starts with a review of emission inventory models in Section 2.2. We present available emission inventory models and discuss the structure and data requirements of the most commonly used emission inventory model in North America, MOVES. In Section 2.3 we present several existing emission estimation approaches as well as the limitation of MOVES in estimating bus emissions. In Section 2.4 we discuss several transit improvement strategies by focusing on their benefits in terms of travel time and identify the need for more research on quantifying their impacts on emissions. The potential of different alternative fuels in reducing emissions is then discussed in Section 2.5. Finally, in Section 2.6 we discuss some critical gaps in the current literature on transit bus emissions and highlight how this research addresses them.

2.2 Emission Inventory Models

With an increasing concern for improved air quality, vehicle emission reduction strategies have become a key component of the transportation planning process. Direct measurements of vehicle emissions often form the basis for emission models. Techniques for direct measurement include inspection and maintenance (IM) tests, on-road remote sensing, chassis dynamometer testing, and on-board emission monitoring. These techniques provide instantaneous emissions and engine performance, and are widely used in the development of databases for emission inventory models. Vehicle emission inventory models play a vital role in quantifying the potential of emission reduction strategies. At present, a considerable number of vehicle emission models exist to estimate and predict the amount of pollutants at macroscopic, meso-scopic, and microscopic levels (Abo-Qudais and Qdais 2005; Rakha et al. 2003; Sharma and Khare 2001). Macro-level models estimate emissions based on an average network speed for selected facility types. These models are often used when high-level emission inventories are conducted at the level of a state or province. They rely on facility specific average speeds and their corresponding emission factors (usually in g/vehicle mile); emissions are estimated for each facility type by multiplying the emission factors with total vehicle miles travelled (VMT) on the network (Wang et al. 2009). These macro models use only one average speed for each facility type and therefore, are unable to consider the spatial variability of average speeds and emissions across the network. Traditional meso-level models can capture the network wide spatial variability of traffic emissions by estimating link-based emissions. For each link, emissions are estimated using the average speed of the link rather than considering only one average speed for all links under the same facility type. However, these models do not have the capability of considering the effect of true behaviour of the vehicle and hence, they are insensitive to vehicle drive cycle. These models will estimate the same amount of emissions for the same average speed despite the presence of significant differences in driving behaviour. For the same average speed, different profiles for acceleration, cruising, idling, and deceleration, may be observed and may result in significantly different emissions. These models can be easily linked with regional transportation models whereby the link-based average speeds can be used as input to estimate emissions (Hao et al. 2010; Sider et al. 2013). Therefore, these models are widely used in regional emission inventories where the main focus is to assess the impacts of a broad range of policies and programs while ignoring the microscopic effects. But when emissions estimates are needed to observe the effects of activities at a smaller scale such as ramp metering, signal coordination, intelligent transportation system (ITS) strategies, reserved bus lane, passenger ridership; then micro-scale models are needed. Micro-scale models consider the instantaneous behaviour of the vehicles thus accounting for second-by-second speed profiles including acceleration, deceleration, idling and cruising (Barlow et al. 2007; Gokhale 2011). Therefore, these models estimate emissions by capturing the true behaviour of the vehicle and are preferred when changes in emissions at a smaller scale are investigated. The micro-scale emission models can be used with traffic microsimulation models that can simulate instantaneous vehicle movements within a road network and thus enable us to estimate second-by-second emissions for each and every vehicle on the network

A large number of average speed emission models exist including the USEPA MOVES series (US Environmental Protection Agency 2010), the California Air Research Board (CARB) EMFAC series (California Air Resource Board 2011), and the European COPERT model (Gkatzoflias et al. 2012). Most of the models rely on a database of base emission rates obtained by collecting real-world emission data using instrumented vehicles, chassis dynamometer tests, and on-board measuring devices. The emissions rates are associated with a particular average speed, vehicle type, meteorological conditions, fuel type etc. USEPA's MOVES and CARB's EMFAC models have been officially regulated by the federal and state agencies in the US for many years.

Significant efforts have also been made to improve the micro-scale models. Some of the most widely used micro-scale models include USEPA's MOVES model, the University of California-Riverside Comprehensive Modal Emissions Model (CMEM) (Scora and Barth 2006), the Virginia Tech microscopic (VT-Micro) model (Rakha and Ahn 2004; Rakha et al. 2004), the Finnish VERSIT+LD model developed by TNO Science and Technology, Netherland (Smit et al. 2007), and TU Graz's Passenger Car and Heavy Duty Emission Model (PHEM) based on European vehicle data (Eichlsede et al. 2009). In 2009, Transport Canada published a reference guide on emissions estimation tools for practitioners (Transport Canada 2009). The guide provides a short list of available tools that practitioners can consider and use to estimate emissions.

The Center for Clean Air Policy (CCAP) transportation emissions guidebook is an emissions calculator that estimates emission reductions due to policy implementations (Center for Clean Air Policy 2015). It can model changes in land use and traffic management and can estimate the changes in emissions. It is a Microsoft Excel spreadsheet where users need to input aggregated parameters such as total changes in VMT, total daily trips etc. and based on some predefined emissions factors, it calculates changes in emissions due to the policy. It is a macro model and hence, unable to consider the spatial distribution of emissions as well as vehicle driving characteristics.

The Canadian Mortgage and Housing Corporation (CMHC) has a tool called Greenhouse Gas Emissions from Urban Transit which is a Microsoft Excel spreadsheet that takes user input such as distance to central business district, number of households, employment density, vehicles per household, vicinity of public transit etc. (Canada Mortgage and Housing Corporation 2015). It can provide annual emission estimates of travel for both private and public transit. This tool is unable to estimate emissions at meso and micro scales.

GHGenius is a tool developed by Natural Resources Canada for assessing life cycle emissions of transportation fuels (Natural Resources Canada 2015). It is a Microsoft Excel workbook which requires large amount of input by users to estimate upstream and operational GHG emissions. It is a comprehensive model that captures all stages of fuel production and vehicle manufacture. On the operation side, it is a macro model that uses total mileage on the network for different vehicle types and estimates emissions using predefined rates. It does not have the capability of accounting for changes in emissions due to speed, age, grade, driving characteristics. This model is good for lifecycle emissions estimates for different fuels and vehicle types.

GREET is an another lifecycle emissions assessment model developed by Argonne National Laboratory in the US that can both upstream and downstream emissions (Argonne National Laboratory 2014). This model is also a macro model that is not capable of estimating changes in emissions due to traffic operational changes.

The Urban Transport Emissions Calculator (UTEC) is a tool developed by IBI group for Transport Canada. It estimates annual emissions by personal, commercial, and public transit vehicles (Transport Canada 2015). This is a user-friendly tool that can estimate emissions for different vehicle types under different future year scenarios. It takes VKT as the major input and estimates emissions at a macro level. Again this model is unable to capture operational changes and associated emissions.

The CMEM is a micro-scale emissions model that can estimate second-by-second tailpipe emissions (Scora and Barth 2006). Initially it was designed only for light duty vehicles and in the latest version three types of heavy duty diesel vehicles were incorporated. It is a physical, power demand model that considers vehicle physical condition including mass, engine size, torque information as well as operating conditions and vehicle driving characteristics. One of the drawbacks of this model is that it requires more detailed data on vehicle physical conditions. It also has a limitation related to predicting future years' emissions. Although it includes heavy duty vehicles, it lacks transit bus emissions data.

CORSIM is a traffic microsimulation model developed by the United States Federal Highway Administration (United States Federal Highway Administration 2015). It has two separate components: NETSIM for surface street simulation and FRESIM for freeway simulation. It requires external input such as transportation network topology, demand by mode, and emission rate for different vehicle types and speeds. One of the drawbacks of this model in estimating emissions is that it does not consider the effects of grade explicitly, especially on urban streets. It also incorporates a limited number of vehicle classes.

VISSIM is another traffic microsimulation tool widely used in North America. It can simulate private and public vehicles and can provide second-by-second speed profiles. Vehicle emissions can be estimated with an optional add-on module called EnViVer, which is based on the VERSIT+ exhaust emissions model (PTV Group 2015). VERSIT+ is also used as an add-on in another traffic microsimulation model, PARAMICS. VERSIT+ was developed by the Dutch Organization of Applied Scientific Research (TNO), in Delft, the Netherlands. It is based on statistical relationships developed for specific vehicle classes. The emissions database it uses is not for North American vehicles and it does not estimate emissions for different vehicle classes, and fuel types (Madireddy et al. 2012).

EMFAC is released by the California Environmental Protection Agency Air Research Board (California Air Resource Board 2011). It is a meso level model that estimates emissions based on the average speed of a vehicle. It takes the vehicle class, geographic area, calendar year, and fuel type as input. The vehicle distributions, emissions rates, and emissions standards were generated only for the vehicles that are operated in California.

MOBILE 6.2C was developed by the USEPA to estimate emissions for different combinations of vehicles, fuels, and facility types (US Environment Protection Agency 2003). It is a meso model that uses facility specific average speeds and estimates emissions by using look-up tables. This model cannot be used in micro-scale analysis to capture the changes in driving characteristics. It was replaced in 2004 by MOVES which is USEPA`s latest emission inventory model.

MOVES is the most commonly used emission inventory model in North America. It is developed by the USEPA’s office of Transportation and Air Quality (US Environment Protection Agency 2014). It is the official emission inventory model for all federal and state agencies in the US. It has the capability of estimating emissions at macro, meso, and micro level. Therefore, it replaces the need for different models at different scales. MOVES is a single comprehensive modeling system that can estimate emissions at macro, meso, and micro scales. This model has a very enriched database of vehicle trajectories and emissions rates for a wide combination of vehicle types, road types, and fuel types.

2.2.1 Motor Vehicle Emission Simulator (MOVES)

The latest version of MOVES is MOVES2014 which was released in July 2014. It has the capability of estimating emissions at levels of state, county, and project. When state level emissions are estimated, it works as a macro-model without the need for user supplied data. When it estimates emissions at the county level, it works as meso level with/without the need for user supplied data. On the other hand, when project level analysis is performed for small-scale networks it can operate at meso or micro scale depending on the user supplied data. MOVES is primarily a data driven model. Tailpipe emission data are collected from various sources including chassis dynamometer tests, remote sensing, and on-board emission measurement devices. **Figure 2-1** shows the structure of MOVES by highlighting its data requirements as well as the flow of data in the emission estimation process (Koupal et al. 2002). While for state and county level analyses the default database is available, users need to input data when project-level analysis is performed, especially if the emission modelling is carried out for places outside the US. Depending on the type of emission estimate (i.e. scale of analysis, time of analysis, fleet characteristics) all internal and external data are arranged into the DATA MANAGER where vehicle activities are classified into different operating mode (*opmode*) bins using the information on vehicle activity, fleet distribution, and speed information. To estimate emissions at a link level, MOVES generates an *opmode* distribution for each link. An *opmode* is defined as a combination of speed and vehicle specific power (VSP). The VSP calculation and *opmode* classification will be discussed further in the following chapters. Each *opmode* has a particular base emission rate that is updated using information on fuel, meteorology, IM data. Finally, total emissions per link are calculated by multiplying the emissions rates (g/total vehicle mileage) with total vehicle mileage. The final output can be disaggregated by vehicle type, vehicle model year, pollutant type, road type, and fuel type.

MOVES has the capability of estimating emissions for various vehicle types considering a wide variety of road types, model years, fuel types, and meteorology. At a project level analysis, when MOVES estimates emissions using average speeds, it relies on embedded drive cycles specific to each average speed, road type, and vehicle type. These embedded drive cycles are used to generate *opmode* distributions and hence, emissions are estimated. On the other hand, when MOVES estimates emissions at a micro-scale using second-by-second vehicle speeds, it calculates the VSP and defines an *opmode* for each second of the drive cycle. Later, an *opmode* distribution for each link is calculated and emissions are estimated. More details on emission estimation in MOVES are presented in the subsequent chapters.

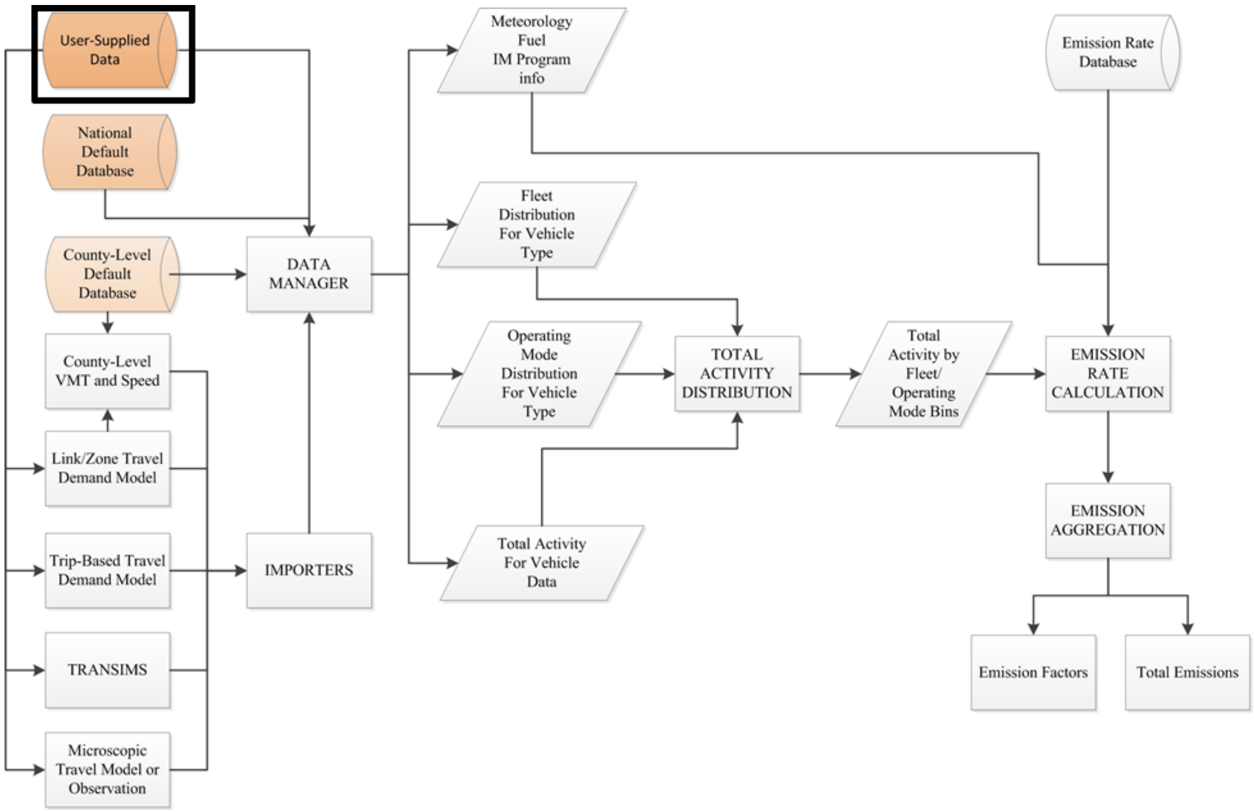

Figure 2-1. **Data flow diagram for MOVES**

2.3 Challenges in Transit Bus Emissions Estimation

2.3.1 Data requirement

It has been well documented that the use of instantaneous speed profiles has the capability of representing true driving behaviour to better estimate emissions. Such detailed data can be collected either using onboard data collection devices such Global Positioning Systems (GPS) devices or using traffic microsimulation models. While a number of studies have used GPS devices to collect instantaneous vehicle speeds and estimated emissions, they are often applied to small networks and they lack the capability of modelling the impacts of various policy interventions on traffic speeds (Ahn et al. 2002; Beckx et al. 2010; Jackson and Aultman-Hall 2010). It often becomes impossible to collect such detailed data using GPS devices, especially at a regional level. Another way of obtaining instantaneous speed profiles could be from simulating bus corridors in traffic simulation software packages. Capitalizing on the advances in traffic microsimulation, the use of microscopic emission models is gaining in popularity. However, a major concern emerging with the widespread use of microscopic emission modelling relates to the quality of the speed profile inputs obtained from traffic simulators. It is not yet clear whether direct use of traffic simulation outputs are valid for microscopic emission modelling. Therefore, it is very important to calibrate traffic simulation models as well as to validate the model output speed profiles by comparing with local bus speed data.

Concerns associated with the collection of both GPS and traffic microsimulation model outputs relate to the level of complexity, effort, and computational time they entail. When regional traffic emission estimates are needed, both GPS data collection and microscopic emission modelling often become impossible. Therefore, the following research question remains an active one: “How can the traditional regional transportation model output ‘average speed’ be used to estimate improved bus emissions without resorting to GPS data collection and micro-simulation models?”

2.3.2 Existing efforts in estimating emissions without emission inventory models

Modelling second-by-second emissions entails the collection of detailed speed information which becomes time and resource intensive and sometimes not feasible. Therefore, efforts have been made to construct drive cycles that can present the driving characteristics of vehicles at particular speeds. A common method to construct a drive cycle is to collect a large amount of second-by-second speeds and later, disaggregate them into microtrips. A microtrip is defined as the portion of the speed profile bounded by an idle mode (zero speed) at both ends. All microstrips are screened and sets of microtrips are combined together in such a way that they replicates the trend and driving characteristics of the desired cycle. While selecting microtrips some predefined criteria such as average speed, maximum speed, average acceleration, speed distribution etc. are used. Yu et al. (2010) developed a city specific drive cycle in the city of Huston, Texas for estimating GHG emissions for light duty vehicles by collecting emissions data using portable emissions measurement system (PEMS) and drive cycle data using GPS devices. They used a genetic algorithm approach to select the best candidate mictrotrips using some predetermined assessment criteria including: driving activity, operating mode distributions, and fuel consumption rate. They observed an error of 16.3%, 14.5% and 25% respectively for these assessment criteria compared to the MOVES estimate. Lai et al. (2013) developed city specific drive cycles for transit buses in Beijing, China. Instead of looking only at speed, idling, and acceleration they also considered VSP distributions. The microtrips were binned into three speed bins (i.e. 0-15 mph, 15-25 mph, and >25 mph). For each microtrip, the RMSE was calculated to find its similarity with the average VSP distribution of its speed bin. Then, the microtrips of each speed bin were ranked according to their RMSE (lower RMSE gets higher ranking) and the highest ranked microtrips were added until the desired speed profile was reached. One of the limitation of the study was they considered only three speed bins and emissions vary largely between speeds, especially in the lower speed range of 0-15 mph. The authors found an underestimation of 46% for CO_2 in the lower speed range and an overestimation of 7% in the higher speed range when compared to MOVES.

In general, most of the criteria used in the development of drive cycles present driving characteristics, not emissions characteristics. It was found that the VSP distribution has the ability to represent both driving characteristics as well as emissions characteristics (Song et al.

2011; Zhai et al. 2008). Song et al. (2011) analyzed the VSP distribution characteristics for light duty vehicles for urban restricted-access highways and developed a VSP distribution model to predict fuel consumption and emissions rates. To date, many studies in developing VSP distributions have been performed for light duty vehicles, but only a few models exist in the case of transit buses. Zhai et al. (2008) collected link level speed profiles from eight transit buses, calculated VSP distributions for each speed profile, and grouped them into eight VSP modes. Total emissions were calculated by applying a modal VSP specific emission rate to each VSP mode. It was observed that at a route level on average, compared to measured trip emissions, the estimates based on the VSP approach were within +/-2% for CO_2 and CO emissions, 17% for NOx emissions, and 35% for HC emissions. But the variability across buses were rather high: within -20% to 20% for CO_2, within -33% to 51% for CO, within -30% to 30% for NOx, and within -32% to 9% for HC. One of the main drawbacks of developing such model is the requirement of large amount of PEMS data to represent emission characteristics.

Because of the relatively easy availability of average speeds, considerable efforts have been made to develop speed correction factors (SCF) which can be applied on average speed based base emission rates to consider the variability in traffic conditions. The development of SCF has been attempted in the EMFAC and MOBILE models. Usually SCFs are developed by: 1) collecting average speed specific drive cycles, 2) constructing speed correction cycles, and 3) finally testing corresponding emissions. This SCF approach has been used in many cases, especially for considering facility specific drive cycles. Song et al. (2015a) collected second-by-second drive cycles for light duty vehicles and calculated a VSP distribution of each cycle. Later, VSP distributions were grouped into different VSP bins. Different regressions models were developed to predict VSP distributions as a function of average speed. These VSP distributions were used to estimate emission rates which were compared with the base emission rates to calculate average speed specific SCF. Using a similar principle to develop SCF, in another study by Song et al. (2015b) a delay correction model was developed to relate emissions with two most commonly used measures of intersection effectiveness (i.e. delay time and number of stops). The delay correction model was developed for only arterial and collector road types. On average, the absolute relative differences of the proposed model were 5.6%, 5.1%, 6.9%, and 8.7% for fuel, NOx, HC, and CO respectively, and 90% of prediction errors were lower than 10%. The limitation of this SCF approach is that the developed SCFs are limited to specific roadway and vehicle types. Also in the process of SCF development the effect of grade is not considered which might significantly change emission estimates if buses are operated in hilly areas.

Researchers also attempted to develop regression models that can eliminate the need for the collection of drive cycles. Most of the regression models identified vehicle average speed as the most important parameter in estimating emissions. Actually all macro and meso level emission models estimate emissions based on the average speed and VMT. But it is well established that average speed alone does not have the capability to represent drive cycle characteristics. Therefore, besides average speed, the impacts of percentage of idling, average acceleration etc. have been investigated in a few studies (Clark et al. 2007; Wayne et al. 2007). A correlation analysis between drive cycle characteristics and exhaust emissions was conducted by Tu et al. (2013). They concluded that along with average speed, the inclusion of stops per mile, percentage of idle, average acceleration, kinetic energy, and standard deviation of average speed can improve the efficiency of emissions prediction. Similar variables were identified by Delgado et al. (2011) in the development of linear regression models to predict fuel consumption and emissions. They observed an error of 8.5% in fuel consumption prediction and 20.4% in NOx emissions prediction. On the other hand, Sonntag and Gao (2009) developed a link based particle number predictor model using engine load and vehicle parameters. They found engine load, engine speed, and the exhaust temperature as the most significant parameters. They also developed vehicle parameter based model where VSP and vehicle speed were as two surrogate measures in the absence of engine parameters. The limitation of these regression models is that they are very specific to the data sample and might not be spatially transferrable. Also to get an improved regression model, many of parameters are be collected from the drive cycle and hence, these models do not eliminate the need for drive cycles.

Some studies also focused on the speed and acceleration portions of drive cycles as these two parameters are very important in the estimation of engine power demand. Clark et al. (2003) developed speed-acceleration matrices to predict emissions of heavy duty diesel vehicles. They used second-by-second speeds and emissions data generated by the West Virginia University-Transportable Heavy Duty Emissions Testing Laboratories. For each second, speed and acceleration data were related to the corresponding emissions data (g/sec). The developed speed-acceleration matrices could be useful to estimate bus emissions if second by second bus speeds are unavailable. In order to observe the effects of acceleration bins on the emissions, they categorized accelerations into three and seven categories. They observed that when only three acceleration categories are used, CO emissions could vary between 35% to 87% and NOx emissions could vary between -1% to 18%. On the other hand, having seven acceleration categories improved the estimates, although CO emissions could still vary between 18% and 87% and NOx emissions could vary between -0.6% to 20%. Along with the prediction error, the main limitation of this study is it does not consider grade in the development of matrices and hence, it underestimates emissions for buses moving uphill and vice versa. Yoon et al. (2005) developed acceleration-speed-grade matrices considering road grade in the matrices. They collected second-by-second bus speed data from transit buses operated by Metropolitan Atlanta Rapid Transit Authority and developed speed-acceleration- grade matrices at the route level as well as at the link level. It was observed that route based matrices are acceptable in regional estimates with a difference of 6% in engine power demand compared to second-by-second data based estimates. But when the same route based matrices were applied to estimate link level engine power, a difference between -56% and 105% was observed. These matrices are also specific to certain types of vehicles and roads. The authors also recommended considering the effect of passenger load in the development of such matrices.

2.3.3 Limitations of MOVES in estimating transit bus emissions

MOVES has an enriched database for estimating passenger vehicle emissions by using both average speed and instantaneous speeds. But in the case of transit buses, it has many limitations. When second-by-second speeds are provided, MOVES estimates emissions by calculating VSP and allocating them into *opmode* bins. But when only average speeds are provided, the MOVES database lacks transit bus specific data. Prior to the release of the latest version of MOVES (i.e. MOVES2014) in July 2014, MOVES was unable to estimate bus emissions for average speeds below 15 mph. In MOVES2014, two low speed urban drive cycles have been included to estimate emissions for speeds below 15 mph. When MOVES estimates emissions for buses running on 'urban unrestricted roads" (i.e. local and arterial roads), it uses different drive cycles from different sources. To estimate lower speed emissions, it uses two transit bus drive cycles specific to average speeds of 3.7 and 8.3 mph (US Environment Protection Agency 2014). To estimate bus emissions for average speeds of 15, 30, and 45 mph, it has drive cycles for average speeds of 15, 30, and 45 mph respectively. But the average speeds of 15, 30, and 45 mph do not represent the actual bus average speed, rather they represent the average speed of traffic the bus is moving with (US Environment Protection Agency 2010). To estimate higher average speeds emissions, MOVES uses light duty truck drive cycles that are available for average speeds of 55.4, 60.4, and 72.8 mph. To estimate emissions at any other average speed, MOVES conducts interpolations using the available drive cycles. The MOVES embedded drive cycles and the emission calculation methodology is briefly described in Chapter 3. The lack of transit bus specific drive cycles definitely questions the accuracy of transit bus emissions estimated using average speeds. Emissions could be under/over predicted compared to a local context. No studies to date have quantified the extent to which the estimates could be different when MOVES default data is used compared to local data. This definitely highlights the need for a validation of MOVES embedded drive cycles in a local context. It also emphasizes the importance of collecting transit drive cycles as well as developing a methodology to estimate refined bus emissions using average speeds only. To date, few studies have been conducted to compare MOVES default *opmode* distributions and emissions with city-specific drive cycles. In Texas, drive cycles for passenger cars, passenger trucks, and heavy duty diesel trucks were developed with GPS data; emissions were then estimated using MOVES and compared with average speed-based emission estimates (Farzaneh 2014). A significant difference was observed in the *opmode* distributions as well as in emissions. For heavy-duty diesel trucks the differences in NOx emissions ranged from -47% to +5%. To date, no study has focused particularly on transit buses.

2.4 Transit Service Improvement Strategies

Transit service providers adopt various strategies to improve transit service. Some of the most common strategies include transit signal priority (TSP), express bus service, reserved bus lanes, queue jumper lanes, articulated buses, and relocation of bus stops. There exists a large body of literature regarding the effectiveness of these strategies mostly in terms of travel time saving. However, little research has been conducted that quantifies the impact of these strategies on transit bus emissions.

2.4.1 Transit signal priority

Transit signal priority is one of the most widely implemented transit service improvement strategy. TSP is an operational strategy that provides priority to transit vehicles so that they can pass an intersection easily. Detectors are used to sense the presence of the bus and concurrent actions are followed to give the green phase to the bus. Usually TSP included two measures: 1) green extension that extends the green phase of the signal so that the bus gets enough time to pass the intersection, and 2) early green that shortens the length of green of the non-priority phase (i.e. truncate the red phase of the priority phase) to the minimum green time. Rakha and Zhang (2004) identified the impacts of TSP on a signalized intersection and concluded that (1) it provides benefits to transit vehicles, (2) at low level demand, it provides marginal benefits to the whole network, (3) the system wide impact of TSP is directly proportional to transit frequency, (4) benefits depend largely on the base signal timing plan and (5) near-side bus stop location has significant impacts on the TSP benefits. The most quantified benefit of TSP includes reduced travel time by minimizing delay at intersections (Baker et al. 2002; Sunkari et al. 1995). This potentially translates to reducing drivers' workload, fuel consumption, emissions, and maintenance costs (Wang et al. 2008). While a breadth of research on TSP has been conducted to evaluate travel time saving, very few studies exist on quantifying its impact on emissions. Dion et al. (2004) quantified the benefits of TSP in terms of delay and emissions, and found that emission reductions of HC, CO and NOx are not significant. The study concluded that vehicle emissions are not only a function of vehicle stops and travel time, but also of the individual driver behaviour and variability in travel speeds. Ji et al. (2014) developed an algebraic method to optimize TSP scheme and performed a case in study in China using VISSIM and CMEM. They observed that on average it can reduce 25% of transit bus emissions but it could increase emissions of other vehicles in the network. As the TSP strategy gives more advantages to the direction of bus travel, other approaches at the intersection achieve less green time and therefore, their travel time and emissions increase. Wijayaratna et al. (2013) observed that even though the amount of bus emission reduction due to TSP is small, it can increase overall traffic emissions by

11%. To minimize the negative impact on other traffic, Ma et al. (2013) proposed a rule-based integrated TSP system to obtain "system-optimal-performance" by focusing on: 1) maximum efficiency of TSP, 2) minimum impacts of TSP on other traffic, and 3) minimum number of bus stops. Using their approach they observed a reduction of 7%-16% of fuel consumption compared to "no TSP but traffic signal coordination system", and a reduction of 4%-14% compared to "conventional TSP and traffic signal coordination system". The limitation of the study is it does not consider any near side bus stops which are very common. They also considered only exclusive bus lanes in operation.

Even though most of the studies found TSP as an effective strategy in reducing travel time, transit service reliability and efficiency might decrease across the route. Kimpel et al. (2005) quantified the benefits of TSP across bus routes and observed that less than 50% links actually experience reduced running time compared to base running time. Similar findings were observed by Diab and El-Geneidy (2012) where they observed different amount of travel time savings across routes and time periods for a study conducted in Montreal. It was also observed that TSP can become ineffective during peak hours as the buses are not able to cross the signal due to longer queue lengths at intersections (Balke et al. 2000; Head 1998; Nowlin and Fitzpatrick 1997). To date, no studies have been performed that quantify the impact of TSP on emissions under various traffic conditions.

2.4.2 Queue jumper lanes

The installation of queue jumper lanes is another strategy that can reduce bus emissions at an intersection. Usually buses emit high amount of pollutants while idling at the intersection such as waiting in long queues. Queue jumper lanes entail a short stretch of a special lane (such as right turning lane) near an intersection so that buses can bypass the waiting queue. Nowlin and Fitzpatrick (1997) observed a delay reduction of 6.5 sec at high-volume intersections with the implementation of such lanes. In another study, Fitzpatrick and Nowlin (1997) observed that the effectiveness of queue jumper lanes increases with traffic and when traffic volume is between 250 and 1000 v/hr/lane the average speed could increase between 3 to 10 mph. On the other hand, when traffic volume at an intersection becomes very high such as a volume to capacity ratio over 0.9, buses start experiencing significant delays (Zhou and Gan 2005) and in such cases

Lahon (2011) recommended to design far side bus stops with queue jumper lanes at the intersection. Zhou and Gan (2009) evaluated the performance of jumper lanes with TSP under various traffic volumes and bus stop locations and found that the jumper lane with TSP can reduce delays by 3 to 17 percent compared to a mixed-lane TSP with a far-side bus stop.

One of the challenges of introducing such lanes could be the space availability along urban streets. Also the effectiveness of such lanes could be affected by the presence of right turning vehicles at the intersection such as the “no right turn on red” policy in Montreal. Zhou and Gan (2005) showed that in such cases, the intersection delay could be minimized with the use of TSP and placing detectors in the optimum place. One transit improvement project at 98-B line bus route in Vancouver, BC reported an annual reduction of 1,800 tons of CO_2e, 0.01 tons of PM, 4.9 tons of NOx, 59.36 tons of CO, and 5.09 tons of HC while the improvement includes: segregated median bus lanes (2.5 km of the total route length of 15.8 km), queue jumper lanes on bridge approaches, exclusive curbside bus lanes, traffic signal priority when vehicles are behind schedule, and extensive travelers information systems (IBI Group 2003).

2.4.3 Relocation of bus stops

The location of bus stops could potentially affect delays, travel time, and emissions. Often, bus stops are located at far-side (downstream of the intersection), at near-side (before the intersection) and at mid-block (between two intersections). When transit providers place bus stops, careful considerations are made on passenger’s safety, conflict with other vehicles, and the impact on bus travel time. In most of the cases bus stops are placed as “near-side stops”. The advantages and disadvantages of various bus stop locations has been discussed by USDOT Federal Transit Administration (2015). In a study conducted by Furth and SanClemente (2006), the authors observed that far side bus stops are safer as they carry almost zero net delay in travel time. On the other hand, near-side bus stops could cause delays when the signal design is not optimal or when long queues at intersections exist. Diab and El-Geneidy (2015) observed that stop time for near-side bus stops is 4.2 to 5 second slower than stop time occurring for far-side stops. In another study, El-Geneidy et al. (2006) observed that increasing bus stop spacing by bus stop consolidation has no effect on passenger activity and it could decrease travel time by 6%.

The location of bus stops is also an important consideration for bus emissions reduction as the bus approaches a bus stop three actions are completed: deceleration, dwell, and acceleration, and bus emissions during these events are high. Saka (2003) conducted a study to examine the effect of bus stop spacing on emissions in urban areas and suggested an optimal spacing of 700-800m. However, the study could not detect any plausible association between bus stop location and emissions. Recently, Li et al. (2012) observed that in the case of a far-side stop, if the bus receives a red light while approaching an intersection, the emissions could be increased by 100%. No studies have been found that quantified the impact of bus stop location on emissions under various traffic congestion levels as well as in conjunction with other transit improvements measures.

2.4.4 Limited stop express service and reserved bus lanes

Limited stop bus service has been considered as one of the effective strategies to reduce bus travel time. This type of service serves only few bus stops along a route and sometimes this could become a drawback of the service because of the increase in passenger waiting time (Furth and Day 1985). Therefore, transit agencies operate other regular bus routes to serve the intermediate bus stops. The effectiveness of this service is mostly quantified in terms of reducing travel time. Studies have observed above 10% of travel time saving due to the implementation of a reserved lane in Montreal (El-Geneidy and Surprenant-Legault 2010). It has been observed that the benefits of limited stop bus service could increase in the presence of a reserved bus lane (Diab and El-Geneidy 2012) which is an another common transit improvement strategy. Using AVL/APC data, Surprenant-Legault and El-Geneidy (2011) quantified a reduction of 1.3% to 2.2% in travel time due to the implementation of a reserved bus lane in a bus corridor in Montreal. The effectiveness of these two measures has been already proved in light of travel time saving, yet their impacts on emissions are still unquantified.

2.4.5 Introduction of articulated bus service

Articulated buses are frequently used in the bus rapid transit (BRT) system because of their high carrying capacity. Usually they can carry twice as many passengers during one trip. They also reduce the required number of buses and manpower for transit agencies. Passengers enjoy extra comfort as more spaces are available on the bus (Hemily and King 2008). Articulated buses have been found to spend less dwell time compared to regular buses because of the presence of a higher number of alighting doors. It was found that for articulated buses 1) running time increases due to increased time in various events such as acceleration, deceleration and merging with traffic, and 2) dwell time decreases with higher passenger activity, 4.5% saving for 30 passengers compared to 1.9% for 20 passengers (El-Geneidy and Vijayakumar 2011). The effect of articulated buses on emissions is still unknown.

In general, the main objective of transit improvement strategies is to improve existing bus service so that it attracts more transit riders. While the increased onboard passenger ridership effect on bus dwell time and running time has been quantified (Diab and El-Geneidy 2012), its impact on bus emissions has not been fully quantified. Frey et al. (2007) observed that on average, the diesel fuel consumption rates increase by 33% when the number of on-board passengers increase from less than 20 to more than 40. Tartakovsky et al. (2013) quantified the impacts of urban buses and passenger cars on energy and the environment and concluded that with increasing passenger loading, transit becomes more environmentally friendly than passenger cars. Clark et al. (2007) quantified the impacts of passenger loading on emissions and found that buses consume 9% more fuel when running at full weight compared to empty weight. None of the existing studies quantified the impact of incremental passenger loading on total and per passenger emissions. Also there is a lack of research that analyzes bus routes on the basis of per passenger emissions.

2.5 Potential of Alternative Fuels in Reducing Bus Emissions

While a breadth of research exists documenting the effects of various alternative fuels, of most interest to this research is recent work on the potential of compressed natural gas (CNG). The principal component of CNG is methane (85-99%), but it may also contain ethane, propane, nitrogen, inert gases, hydrogen sulphide and water vapor (Amrouche et al. 2012; Weaver C. S. 1989). As methane (CH_4) contains one carbon and four hydrogen atoms, the hydrogen/carbon ratio is high. On the other hand, gasoline (C_8H_{18}) and diesel ($C_{15}H_{32}$) have a lower hydrogen/carbon ratio (Semin et al. 2009). As CNG contains relatively less carbon in its chemical composition, it produces less Carbon dioxide (CO_2) compared to diesel during the combustion process (Aslam et al. 2006). CNG also has a higher octane number in the range of 110 to 130, compared to 95 and 98 for gasoline and diesel respectively (Amrouche et al. 2012). A higher octane number indicates increased compression ratio and hence increased engine efficiency without knocking or denotation. Indeed, CNG is considered as one of the fuels with most potential for application in transit especially that buses operate along fixed routes and therefore, it becomes relatively easy to install refueling stations along the routes (Nylund et al. 2004). Wang et al. (2011) compared on-road emissions and fuel consumption of Euro III, Euro IV, and CNG buses and observed that emissions from CNG buses were lower than Euro IV diesel buses by 72.0% and 82.3% for NOx and PM respectively. Reductions were even higher compared with Euro III diesel buses with 75.2% and 96.3% for NOx and PM respectively. Jayaratne et al. (2010) monitored exhaust emissions of CNG and ultra-low sulphur diesel buses on a chassis dynamometer. Emissions were measured under idle and steady state conditions with different engine loads at a fixed speed of 60 km/h. CO_2 emissions of CNG buses were found to be lower than diesel buses by 20% to 30%. However, emissions of NOx did not show significant differences due to the large variation between buses. Karavalakis et al. (2013) tested different fuel blends with different properties of methane number (a measure of fuel knock resistance) and Wobbe number (a measure of fuel interchangeability) and concluded that the composition of natural gas can strongly affect different pollutants. Blends having higher methane content showed lower NOx, CO and nonmethane hydrocarbons, but higher total hydrocarbons, methane, and formaldehyde emissions. The benefits of using bio-methane (bio-CNG) were examined by Ryan and Caulfield (2010) for a portion of the bus fleet in Dublin, Ireland. The authors found that converting from conventional diesel to bio-CNG would reduce emissions of CO_2, CO, $PM_{2.5}$, PM_{10} and NOx by 64%, 71%, 87%, 77% and 87% respectively. Genovese et al. (2011) experimented with a hydrogen-natural gas (HCNG) blend on CNG buses. The authors compared energy and emissions of CNG buses when fuelled with HCNG blends with different percentages of hydrogen (5%, 10%, 15%, 20% and 25% by volume). They observed (1) improved energy efficiency in urban driving due to higher hydrogen content in the fuel and (2) significant reduction of CO_2, CO and NOx emissions. Cozzolini et al. (2013) tested Diesel-Methane dual-fuel and observed a significant reduction of NOx and CO_2 and a drastic increase in hydrocarbons, PM, and CO. Hydrogen fuel cell buses are another attractive alternative with the benefits of zero emissions, less noise, and better energy efficiency compared to conventional internal combustion engines. But Barbosa (2013) pointed out that these buses are three to four times more costly than modern diesel buses and to commercialize such buses, many barriers need to be overcome, including the optimization of (i) fuel cell durability, (ii) purchase cost, and (iii) hydrogen production and delivery technology. All of these studies quantified the potential of alternative fuels under one condition. But transit bus emissions could vary depending on different situations such as congestion level, passenger ridership, and roadway grade. Studies that evaluate the effectiveness of alternative fuels under different conditions as well as in conjunction with other improvement measures are still lacking.

2.6 Identified Gaps in the Current Literature on Transit Emissions

Based on the literature discussed in the previous sections, we identify some critical gaps that should be addressed in order to improve the existing knowledge relating to transit bus emissions. The much needed work to fill the gaps can be classified into two streams: 1) estimation of transit bus emissions, and 2) strategies to reduce transit bus emissions.

MOVES is the most commonly used emission inventory model in North America. But MOVES does not include enough transit bus drive cycles to estimate emissions using average speeds, which is often the method adopted in regional emission inventories. No studies have been performed to validate the accuracy of MOVES estimates including emissions and *opmode* distributions. The lack of transit bus specific drive cycle highlights the need for collecting local bus speed data as well as for validating the default average speed based estimates of MOVES in a local context. It also identifies the need for developing a methodology for improved estimates of bus emissions using average speeds only without the need for second-by-second bus speeds obtained from traffic microsimulation models or extensive GPS data collection campaigns.

While a breadth of literature exists for passenger vehicles, little research exists on transit bus emissions. The individual effect on transit emissions of several factors such as travel speed, onboard passenger number, and fuel type has been discussed. But no studies have considered the simultaneous effects of different variables including congestion level, roadway grade, onboard passenger number, traffic variability, and fuel type. The consideration of simultaneous effects is important as in real bus operations different variables together could impact emissions differently. We also observe that the individual and combined impacts of transit improvement strategies such as transit signal priority, queue jumper lane, and bus stop location have not been studied under various traffic conditions. No studies have been found that quantify the impact on emissions of the most important transit service improvement strategies including limited stop bus service, reserved lanes, introduction of articulated buses, and use of smart cards. Finally, a lack of studies is identified where the potential of alternative fuels is investigated under various network conditions as well as under various transit improvement strategies. This clearly stresses the need for studies on the combined effect of different emissions reduction strategies and their effectiveness under varying traffic conditions.

3 CHAPTER 3: MODELING TRANSIT BUS EMISSIONS USING MOVES: VALIDATING DEFAULT DISTRIBUTIONS AND EMBEDDING LOCAL DRIVE CYCLES

3.1 Chapter Overview

This study focuses on the validation of operating mode distributions and other assumptions used in the estimation of transit bus emissions with the Motor Vehicle Emission Simulator, MOVES. Our study area is the City of Montreal, Canada where a single transit provider operates bus service along 209 routes. Instantaneous speeds and passenger ridership data were collected on-board for a total of 96 bus trips over 3,700 links during the summer and fall of 2013. Our data collection campaign covered eight bus routes in Montreal. The selected routes serve a range of corridor types capturing the variability in land use, road geometry, traffic flow, bus type, and transit service. Ultimately, we analyzed data from 3,702 road segments amounting to approximately 606 miles (970 km) with bus service. The resulting emissions exhibited network wide variations across different time periods, directions, land uses, passenger ridership, and transit service. The per-passenger emissions highlighted the importance of considering on-board passenger weight in the estimation process. These results are relevant to transit planners in the evaluation of plans to modify or introduce bus routes. We also observed large differences between locally derived operating mode distributions and MOVES2014 default distributions. The MOVES distributions assumed a significantly larger portion of idling than obtained from local data. In order to improve the emission estimation process using local data, this study also demonstrates a process to develop local operating mode distributions and to select average speed specific drive cycles that could be embedded into the MOVES2014 database. A validation test suggests that emission estimates can be improved by using our locally developed operating mode distributions compared to the MOVES default distributions. These embedded local drive cycles could be useful when instantaneous speed information is unavailable, especially when developing a regional inventory of bus emissions in Montreal.

3.2 Introduction

Public transit investments are often justified partly on the basis of their potential to reduce air pollutant and GHG emissions in urban areas. Public transit has undoubtedly been associated with a reduction in per-passenger emissions from travel compared to the private car (Lau et al. 2011). While a large portion of transit buses in North American cities remains diesel fuelled (running on ultra low sulfur diesel), local emissions along busy bus corridors can become a concern for near-road air quality. Transit bus emissions can vary widely with speed, roadway grade, passenger occupancy (contributing to load), bus age, fuel type, and bus type (Jayaratne et al. 2009; Lau et al. 2011; Tartakovsky et al. 2013). Therefore, in order to achieve accurate transit emissions, it is important to understand how they are simulated in existing emission modelling packages and whether the embedded drive cycles and default distributions are appropriate within local contexts.

MOVES is the latest USEPA (US Environment Protection Agency 2010) emission modeling tool and it is widely used in North America both in planning and research. It has the capability of estimating average and instantaneous speed-based emissions. In planning applications, especially when transit bus emissions are estimated at the level of the urban area serviced (with all bus routes and fleet), most studies model bus emissions at the level of the route (Diana et al. 2007) or link (Lau et al. 2011). In such average speed-based emission modelling applications, MOVES relies on default driving characteristics, also known as *opmode* distributions derived from instrumented vehicles (US Environment Protection Agency 2010). If the default *opmode* distributions are significantly different than the local distributions, emissions could be over/under estimated. Therefore, in order to improve emission estimates, local instantaneous drive cycles should be used, but this could be possible only at a smaller scale. When emissions are estimated at a regional scale it might not be possible to collect instantaneous bus speeds for every link under consideration either using GPS devices or by simulating regional network on a second-by-second basis. Drive cycles from certain corridors could be used as representative, but the main challenge lies in selecting representative drive cycles and in capturing the variability in bus operations and air emissions across a transit network. This variability can only be captured within emission studies that extend beyond a single corridor, capturing the range of factors affecting emissions across a diversity of roads, operations, services, and vehicles.

The study has three primary objectives: 1) capturing the variability in transit bus emissions across an urban network, 2) validating the default *opmode* distributions and embedded drive cycles of MOVES compared to local data, and 3) selecting local representative drive cycles which can be embedded within MOVES in order to achieve an improved estimation of transit bus emissions especially when second-by-second speeds are not available. For this purpose, this study focuses on collecting data on-board a range of bus types and routes across the City of Montreal, Canada and estimating emissions using instantaneous speeds. The data collected were used to develop local *opmode* distributions, and to select representative drive cycles. These were in-turn compared with MOVES embedded *opmode* distributions using MOVES2014. Emissions were estimated for GHG (in CO_2-eq).

3.3 Description of the Study Network

Our study area includes the island of Montreal, Canada where a total of 209 buses are operated by the Société de Transport de Montréal (STM), the local service provider, that runs the bus network covering 1,374 miles (2,194 km) of roads and serving an area close to 193.05 mile^2 494.21 km^2). In 2012, 412.6 million passenger trips were made on STM buses (Société de Transport de Montréal 2012). STM currently operates an integrated network of buses, underground metro, and shared taxibuses. The transit network includes four metro lines, 155 regular, 31 express, and 23 night routes. The bus network covers 1,346 miles (2,154 km) serving an area close to 195 mile^2 (500 km^2). In 2012, 412.6 million trips were made using STM buses (Société de Transport de Montréal 2012). The current bus fleet consists of 1,721 regular buses, 257 articulated buses, and 8 hybrid buses.

In this study, eight bus routes were selected for data collection covering a wide variety of built environments and road geometries as shown in **Figure 3-1**. Four routes (17, 80, 467 and 107) are operated along the north-south direction while another four (24, 161, 121 and 141) run in the east-west direction. Articulated buses are operated along three of the eight routes (121, 80 and 467). Also, two routes (80 and 467) have reserved lanes in operation during peak hours along the direction of commuter traffic. Route 467 also has limited express service with an average stop spacing of 0.35 mile (0.56 km) compared to 0.15 mile (0.24 km) for the other routes**. Table 3-1** presents the general characteristics of the selected routes.

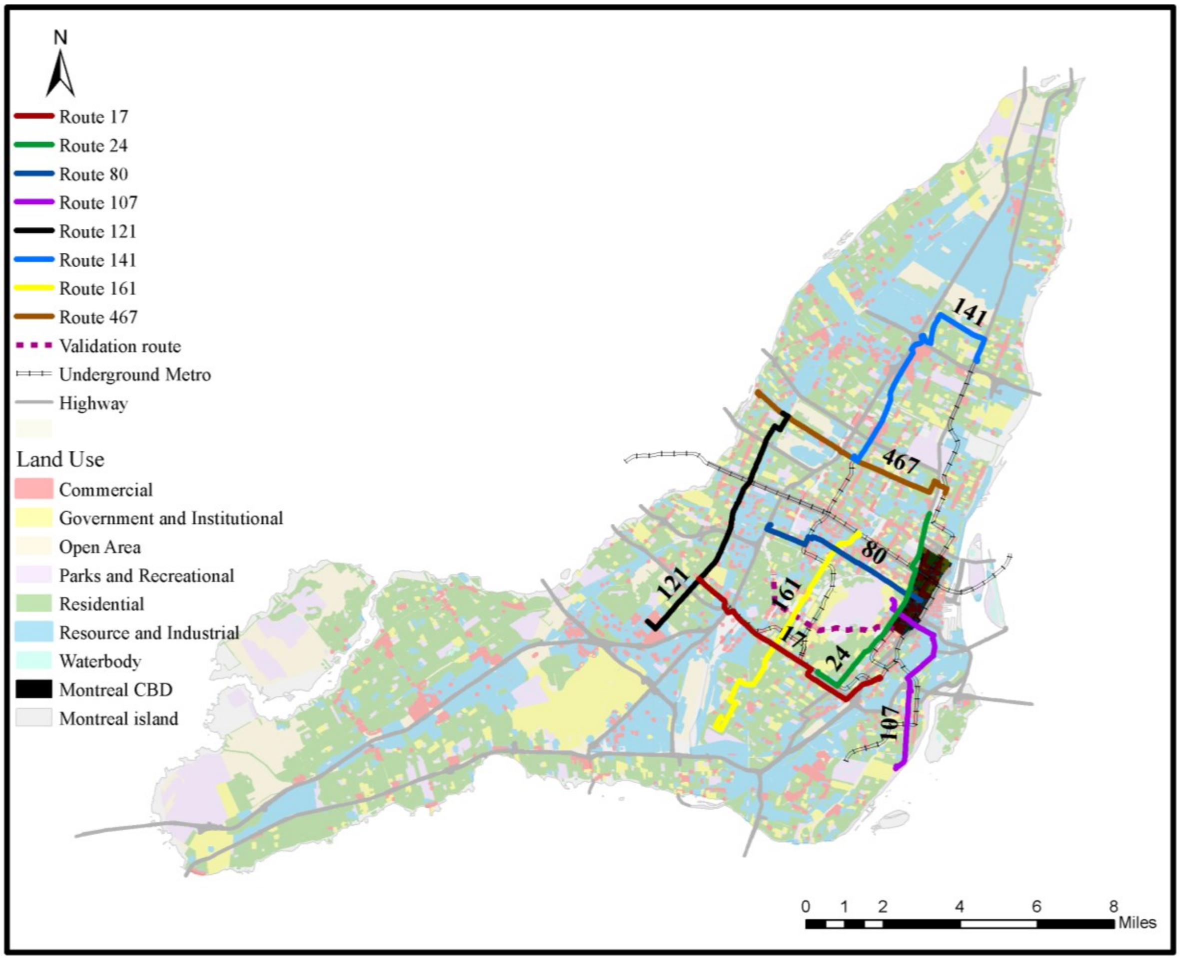

Figure 3-1. Selected transit bus routes

Table 3-1. General characteristics of the selected routes

Route No	Route Name	Bus type	Direction	Total length (mile)	No of bus stops	Avg. stop spacing (mile)
17	Décarie	Regular	North	6.59	38	0.173
			South	6.47	38	0.170
80	Avenue du Parc	Articulated	North	4.91	29	0.169
			South	4.86	29	0.168
467	Express Saint Michel	Articulated	North	5.70	16	0.356
			South	6.23	18	0.346
107	Verdun	Regular	North	5.67	41	0.138
			South	5.70	41	0.139
24	Sherbrooke	Regular	East	6.19	47	0.132
			West	6.01	47	0.128
161	Van Horne	Regular	East	6.40	44	0.145
			West	7.54	48	0.157
121	Sauvé / Côte-vertu	Articulated	East	7.01	48	0.146
			West	7.23	52	0.139
141	Jean-Talon Est	Regular	East	7.28	47	0.155
			West	7.25	50	0.145

3.4 Materials and Methods

Our methodology includes four main elements; 1) on-board data collection for a sample of buses, 2) development of *opmode* distributions based on instantaneous data, 3) simulation of bus, link, and route emissions and comparison with emissions and *opmode* distributions generated using MOVES defaults, and 4) selection and validation of representative local drive cycles to embed into the MOVES database (**Figure 3-2**).

3.4.1 Data collection and processing

A data collection campaign was designed and implemented over the span of the summer and fall 2013. Data were collected along eight routes on-board the buses for: 1) instantaneous speed and elevation using GPS, 2) number of individuals boarding and alighting per door at each bus stop, 3) number of passengers onboard (for verification), and 4) bus type. Instantaneous bus speeds were collected using Garmin 800 Edge GPS devices which can record speed and altitude at one second intervals. Two research assistants were present on each bus to record the number of individuals boarding and alighting from each door and at each stop as well as the idling time per stop. For quality control, two GPS units were used to collect data on the bus. After the routes were chosen, the choice of day of the week, time period, and GPS unit were randomized. For each route, data were collected in the morning and afternoon and in both directions. In addition, to account for the variability in traffic flows, data were collected three times for each route/direction/time period thus covering a total of 12 trips per route. In total, 96 trip-level observations were conducted whereby a trip is defined from the beginning to the end of one route in a single direction. Each trip consists of several links whereas a link spans between two successive bus stops. Data for a total of 3,702 links were collected: 2,586 links with regular buses and 1,116 with articulated buses. Trip-level second-by-second speed profiles were disaggregated into instantaneous speeds per link in such a way that each link drive cycle consisted of the initial dwell time at the upstream bus stop and the running time before stopping downstream. Therefore, the average speed of a link included bus running time and dwell time at the upstream stop. Road grade for each link was calculated based on the altitude recorded by the GPS devices and validated against topographic data for the City of Montreal.

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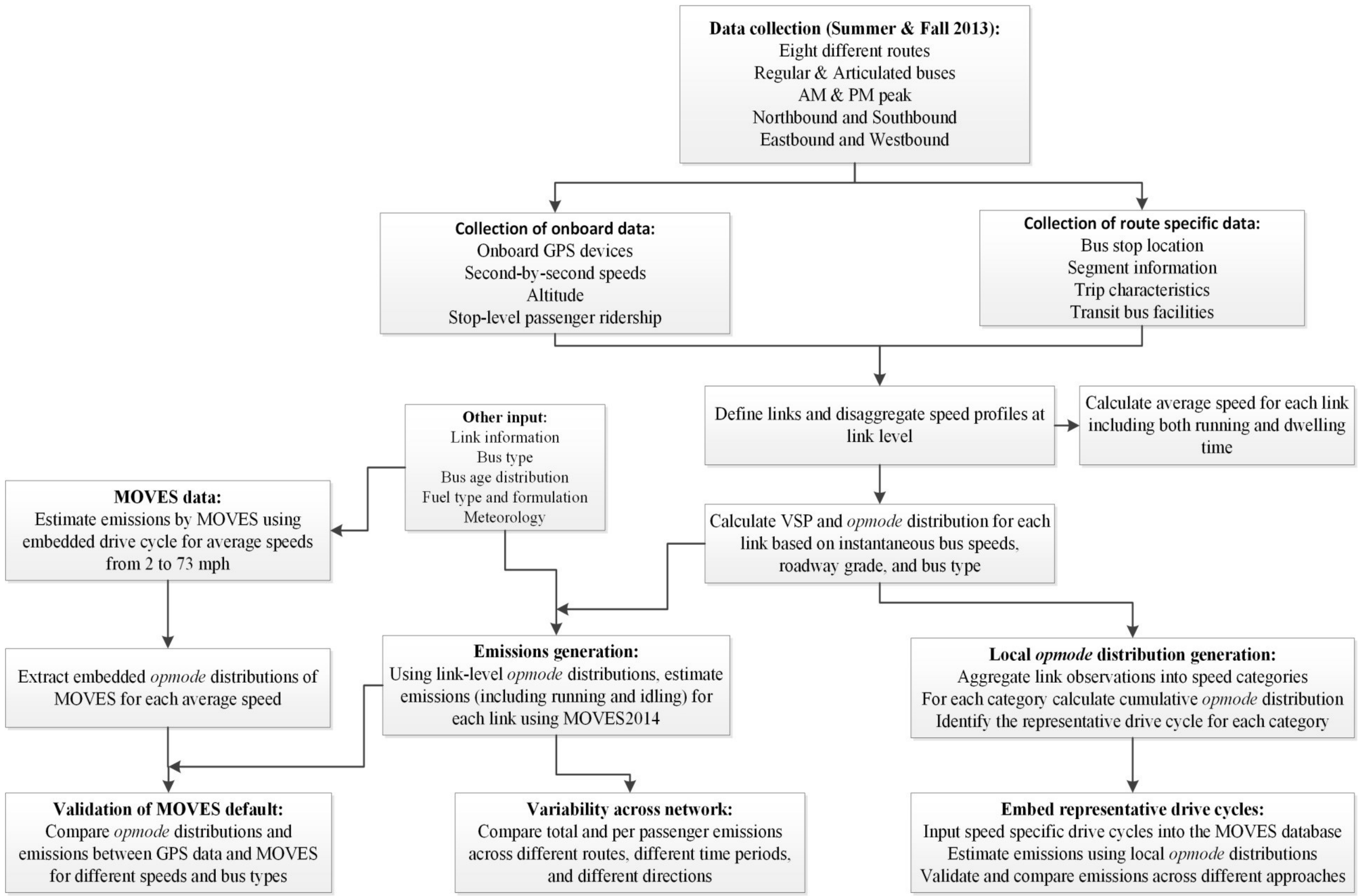


Figure 3-2. Study methodology

Data cleaning included removing incomplete trips associated with ambiguities regarding instantaneous vehicle location and dwell times at bus stops (since bus routes are known). Links where buses were not observed to stop at the bus stop were excluded (less than 1% of all links). In addition, links with running speeds less than 1 mph were also excluded; this situation often happened due to road construction or accidents. Other reasons for excluding links included: if the recorded dwell time was zero even though passenger activity occurred, and if the dwell time at a single stop was recorded as exceeding 240 seconds. Finally, following data cleaning, 2,474 link-level observations were retained for regular buses and 1,096 link-level observations were retained for articulated buses. Our maximum link average speeds for regular and articulated buses were found to be 34.43 mph and 29.49 mph respectively. Also in our dataset, link grades varied from -10% to 6%.

3.4.2 Generation of *opmode* distributions

When MOVES estimates emissions it relies on the *opmode* distributions and associated emission rates. For average-speed emissions, it uses default *opmode* distributions whereas for micro-scale analysis it generates the *opmode* distributions with user-specified instantaneous speeds. In this study we have generated link-specific *opmode* distributions externally and later, they were input into MOVES. This was done externally (1) to analyze the local *opmode* distribution of the bus fleets, (2) consider onboard passenger number, and (3) consider the effect of bus types. For transit buses, MOVES does not specifically differentiate between regular and articulated buses and does not consider the number of onboard passengers, rather it assumes a constant weight of 16.556 tons (representing the average weight of a standard bus). Due to the heavier weight of articulated buses, they need more tractive power; therefore we altered the bus weights within the equation for the VSP embedded in MOVES (Equation 1). The regular and articulated buses operating along our routes have an empty weight of 12.69 tons (with a seating capacity of 41 and total capacity of 80) and 18.86 tons respectively (with a seating capacity of 47 and total capacity of 112). Because we count the number of passengers on-board along each segment, the total weight of each bus is calculated as the sum of empty weight and number of on-board passengers multiplied by 70 kg per passenger. The bus weight is considered explicitly in the calculation of VSP. Therefore, we considered both bus type as well as passenger load in the VSP calculation which is a function of instantaneous speed, acceleration, vehicle weight, and road grade as illustrated in equation (1) (US Environment Protection Agency 2010).

$$\mathrm{VSP} = \left(\frac{\mathrm{A}}{\mathrm{M}}\right) * \mathrm{v} + \left(\frac{\mathrm{B}}{\mathrm{M}}\right) * \mathrm{v}^2 + \left(\frac{\mathrm{C}}{\mathrm{M}}\right) * \mathrm{v}^3 + (\mathrm{a} + \mathrm{gSin}\theta) * \mathrm{v} \quad \ldots\ldots\ldots \quad (1)$$

$$\mathrm{A} = (\text{bus weight in metric ton}) * 0.0643$$

$$\mathrm{B} = 0$$

$$\mathrm{C} = (\text{bus weight in metric ton}) * \left(\frac{3.22}{\text{bus weight in kg}} + 5.06 * 10^{-5}\right)$$

where A, B, and C are the rolling, rotating, and drag road load coefficients respectively in the units of (kiloWatt second)/(meter), (kilowatt second^2)/(meter^2), and (kiloWatt second^3)/(meter^3), respectively. The denominator term, 'M' represents the weight of the vehicle, 'g' is the acceleration due to gravity (9.8 meter/ second^2), 'v' is the vehicle speed in meter/second, 'a' is the vehicle acceleration in meter/second^2, and Sinθ is the (fractional) road grade.

To estimate emissions per link, using equation (1), we calculated the VSP for each second of the corresponding drive cycle. Then for each second, we determined the *opmode* using the combination of VSP and instantaneous speed (US Environment Protection Agency 2011). In the next step, the *opmode* distribution for every link was developed. The *opmode* distribution provides the amount of time that a vehicle has spent under different *opmode* categories such as idling, braking, and cruising. In MOVES, a total of 23 *opmodes* are defined. The first two represent braking (*opmode* 0) and idling (*opmode* 1) events. The other 21 *opmodes* (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. The running *opmodes* are divided into three speed categories: (1) six running *opmodes* for speeds between 1 mph and 25 mph, (2) nine running *opmodes* for speeds between 25 and 50 mph, and (3) six running *opmodes* for speeds over 50 mph (US Environment Protection Agency 2011). Each *opmode* is associated with a particular emission rate (gm/hr) which depends on a number of variables such as fuel type, meteorology, and vehicle age. Braking and idling *opmodes* have the lowest emissions rates. Within each *opmode* category, the emission rate increases as the *opmode* ID increases.

After the generation of link-specific *opmode* distributions using our collected data, link-level observations were classified into different average speed categories. Each trip/link constitutes an individual observation. Our maximum link average speeds for regular and articulated buses were found to be 34.43 mph and 29.49 mph respectively. Due to the small number of links with average speeds above 26 mph, in the generation of *opmode* distributions, only links with average speeds below or equal to 26 mph were considered (2,456 links for regular bus and 1,060 links for articulated bus). A total of 25 average speed categories were identified for speeds between 1 and 25 mph with increments of 1 mph. Between 3 mph and 20 mph at least 50 links for regular buses and 30 links for articulated buses are included in each category. For the other speed categories a minimum of 10 observations were available for both bus types. Under each average-speed category, an average fraction for each *opmode* ID was calculated by using the *opmode* distribution of all links in that category. Finally, cumulative *opmode* distributions were generated for each average-speed category.

On the other hand, MOVES was simulated in average-speed mode to estimate emissions for speeds ranging from 2 mph to 73 mph. In turn, the embedded *opmode* distribution used in the emission estimation process was extracted for each average speed. Note that the previous version of MOVES (e.g. MOVES2010b) was not capable of estimating emissions for below 15 mph average speeds. The latest version MOVES2014 (released in July, 2014) includes drive cycle data associated with 2 average speeds below 15mph (3.7 and 8.3 mph).

3.4.3 Emission modeling

Using the externally constructed *opmode* distributions in section 3.2, we estimated bus emissions for each link. Input was provided for a total of 2,474 links with regular buses and 1,096 links with articulated buses. In addition to speeds, MOVES also requires: (1) link information including link length (mile) and grade (%), (2) vehicle information including type and model year (age), (3) fuel supply including its type and formulation, and 4) meteorology including temperature (°F) and relative humidity (%). The length of each segment was calculated from Google Maps and validated against the road network layer in geographic information systems (GIS) and onboard-GPS data. Similarly, grade was derived from GPS data and corrected using topography data. Link type was set to ‘urban unrestricted road’ as all of our buses were running on arterial roads with signalized intersections. Data on bus ages were obtained from STM. The range of model years for regular buses extends from 2001 to 2011 and for articulated buses from 2009 to 2013. All buses run on Ultra Low Sulfur Diesel (ULSD) with a sulfur content of 15ppm. Meteorological data were collected from Environment Canada and input in the form of hourly temperature (°F) and relative humidity (%). Total Emissions (including running and idling) were estimated for GHGs (in CO2-equivalent). On the other hand, average-speed based emissions resulting from the default MOVES *opmode* distributions were estimated by running MOVES for average speeds ranging from 2 mph to 73 mph.

3.4.4 Comparison of o*pmode* distributions and emissions

Following the generation of *opmode* distributions from collected GPS data and the estimation of emissions using collected instantaneous speeds, a number of validation tests were conducted. First, we compared the cumulative *opmode* distributions at different average speeds to understand the differences in local vs. MOVES default distributions. We also compared emissions at different average speeds between those estimated using the average-speed mode in MOVES and the ones estimated using our collected data. Differences between regular and articulated buses were also captured in terms of emissions, *opmode*, and drive cycle characteristics.

3.4.5 Selection of local drive cycles to embed into the MOVES database

To estimate average speed based transit bus emissions on “urban unrestricted road”, MOVES uses embedded drive cycles for average speeds of 3.7, 8.3, 15, 30, 45, 55.4, 60.4, and 72.8 mph. The properties of the drive cycles are discussed in the results section. Each of these drive cycles are used to generate a specific *opmode* distribution at zero grade associated with its specific average speed. When MOVES is simulated to estimate emissions for a particular average speed, it generates an *opmode* distribution by interpolating the *opmode* distributions of the nearest two drive cycles for zero grade. If emissions are to be estimated for any link with non-zero grade, then MOVES adjusts the interpolated *opmode* distribution. Therefore, in order to embed local drive cycles into the MOVES database we considered only the drives cycles that were collected for zero-grade links. In our data sample, a total of 1,998 link observations were found having zero grade (1,389 for regular buses and 609 for articulated buses) and we grouped them into 25 speed categories considering average speeds between 1 and 25 mph. For each speed category, at least 50 observations were found between 3 and 17 mph, while for the other categories at least 10 observations were found.

A cumulative *opmode* distribution associated with each observation was generated and the variations within the same speed category were carefully observed. For each average speed category, a median cumulative *opmode* distribution was identified to represent the drive cycle characteristics of all the observations in that category. It was calculated using the cumulative *opmode* distribution of many different drive cycles within the category. In the next step, in each speed category, one drive cycle was selected in such a way that the calculated *opmode* distribution of that selected drive cycle is the closest to the median *opmode* distribution. To do so, we calculated the root mean square error (RMSE) for each drive cycle using equation (2)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad (2)$$

where, yi is the *opmode* fraction of the drive cycle at *opmode* ID ‘i’; $\hat{y}_i$ is the *opmode* fraction of the median *opmode* distribution at *opmode* ID ‘i’; ‘i’ is the *opmode* ID, and n is the number of total *opmode* ID which is 23 as MOVES has a total of 23 *opmodes*.

For each average speed category, the drive cycle having the lowest RMSE was selected as the representative drive cycle of that category. Then, the selected 25 drive cycles for 25 average speed categories were assigned a drivescheduleID, starting at drivescheduleID-410 for 1 mph and drivescheduleID-434 for 25 mph speed. Later, using the MySQL platform three files in the MOVES2014 database were modified to incorporate this drivescheduleID. These three files are “driveschedule”, “drivescheduleassoc”, and “driveschedulesecond”. In the “driveschedule” table new IDs (410 to 434) were defined along with their average speed. In the “drivescheduleassoc” table these 25 new driveschedules were assigned for transit buses (source type 42) running on urban unrestricted roads (road type 5). Also the second-by-second drive cycles of these new drivescheduleIDs were imported to the “driveschedulesecond” table. MOVES embedded drive cycles for speeds less than 25 mph (drivescheduleID 404, 405, 401) were removed from the database so that MOVES is forced to use only our local drive cycles to estimate emissions for speeds below 25 mph. Other MOVES embedded drive cycles for speeds greater than 25 mph (i.e. drivescheduleID 402, 403, 251, 253, 254, and 255) were kept in the database so that MOVES can use those to estimate emissions for speeds greater than 25 mph.

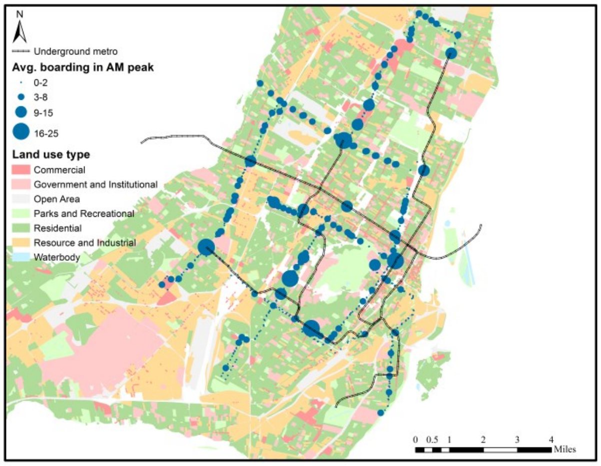
3.4.6 Validation of the embedded drive cycles

To validate the accuracy of our locally derived *opmode* distributions and embedded drive cycles, we selected route 165 which was not included in the original sample. This route runs along the Cote-des-Neiges corridor (represented with a dotted line in **Figure 3-1**) in the north-south direction with Montreal's downtown core located at the south end, making the southbound (SB) direction more congested in the morning peak. The corridor has one of the highest transit riderships in Montreal. The length of the corridor is about 5.1 km with various link grades ranging from +23% to -22% in the northbound (NB) direction and +19% to -28% in the SB direction. For each direction, second-by-second bus speed profiles were collected using GPS for two trips in the morning peak and two trips in the afternoon peak. In total, eight trip datawere collected containing 221 link-level instantaneous speed information along with passenger ridership. Bus emissions along the CDN corridor were estimated using three different approaches: (1) emissions based on collected instantaneous speed data, (2) emissions based on average speed using MOVES default *opmode* distributions, and (3) emissions based on average speed using our local *opmode* distributions embedded in MOVES. In the following sections these approaches will be referred as "instantaneous speed", "MOVES default", and "local *opmode*" respectively.

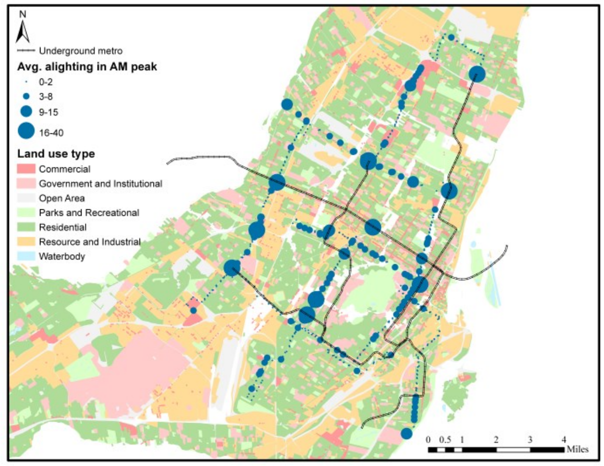
3.5 Results and Discussion

3.5.1 Descriptive analysis of on-board data and overall emissions

General characteristics of the eight routes were compiled and illustrated in **Figure 3-3**. **Figure 3-3(a)** presents the average number of boardings for each stop in the morning peak period overlaying the underground metro network. Clearly, the highest number of boardings occurs at the bus stops located at metro stations. Generally boardings that occur at the beginning of each route are lowest. **Figure 3-3(b**) shows that the average numbers of passengers alighting are highest at bus stops located in commercial areas and at metro stations.



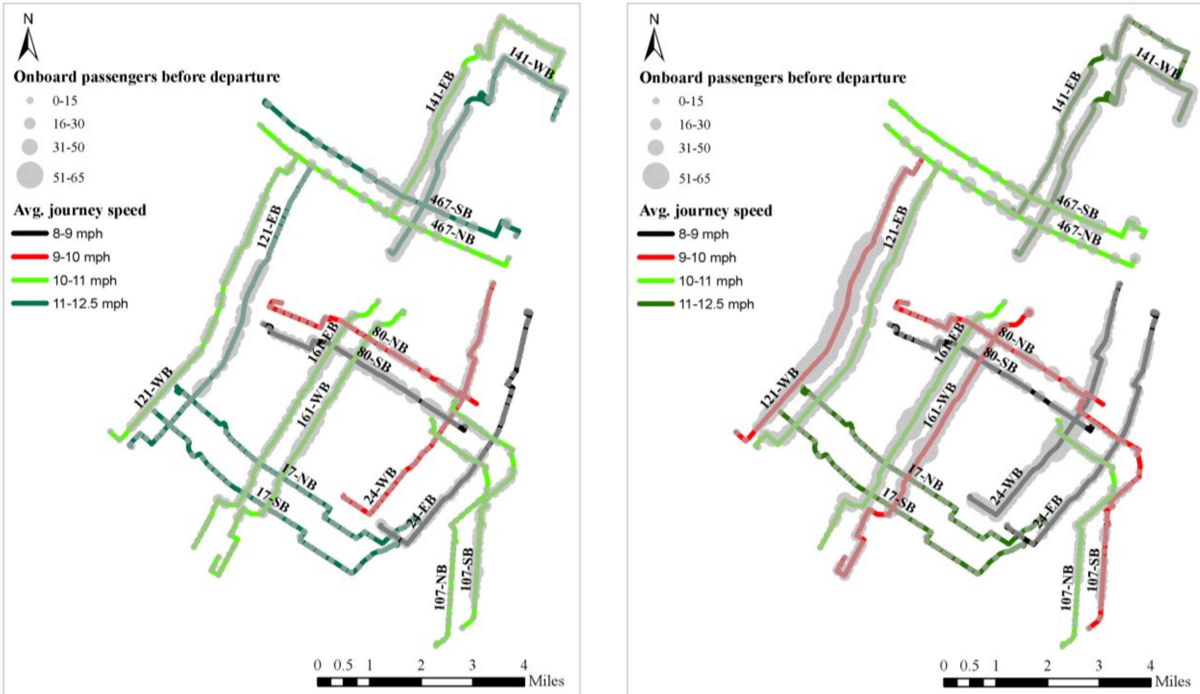
(a) Average passengers boarding



(b) Average passengers alighting

Figure 3-3. Boarding and alighting passengers in the morning peak period

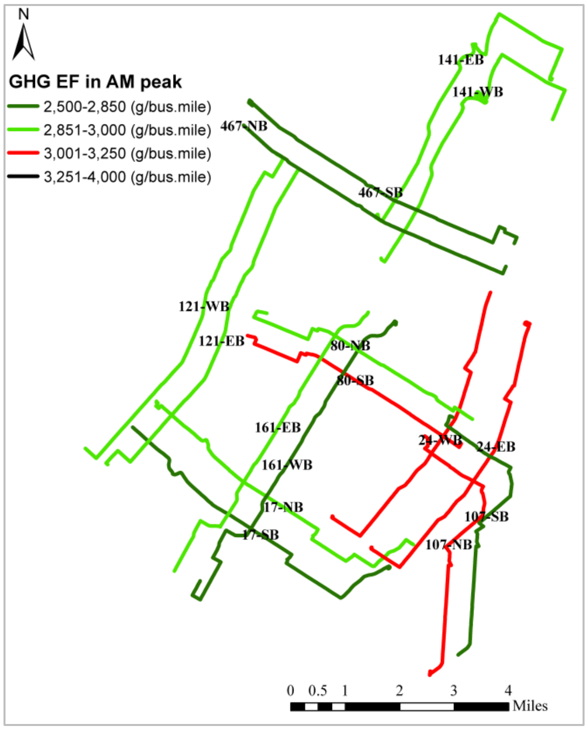
Figure 3-4 illustrates the average journey speed at a route-level for both peak periods. It also illustrates the average number of passengers on-board at a stop-level. In this figure, one direction for each route was offset so that bi-directional information can be visible. Both **Figures 3-4(a)** and **3-4(b)** show that the average speeds are lower in the direction of commuter traffic. Also, average speeds are lower in the afternoon where the number of onboard passengers is higher as well. In both the morning and afternoon peak periods, Routes 24 and 80 have the lowest speeds mostly because of the relatively small spacing between stops and because they go through dense downtown areas where the interaction with regular traffic is highest.



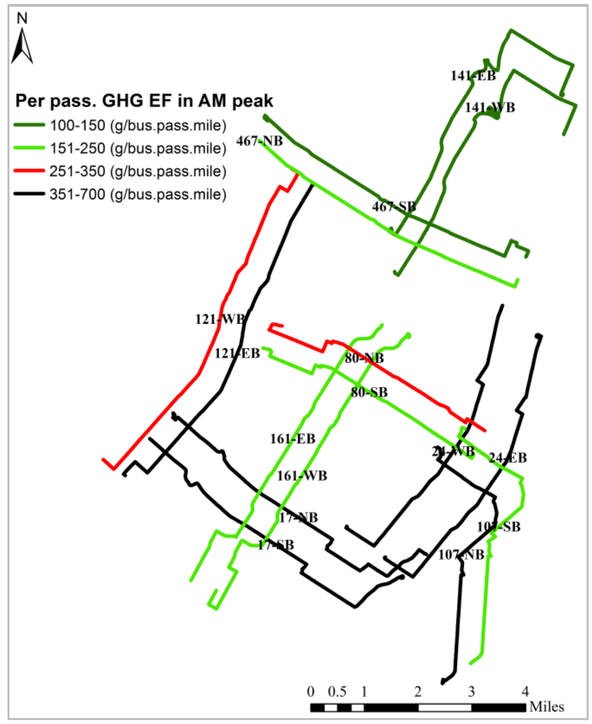
(a) AM peak period (b) PM peak period

Figure 3-4. Average journey speed and onboard passengers per route

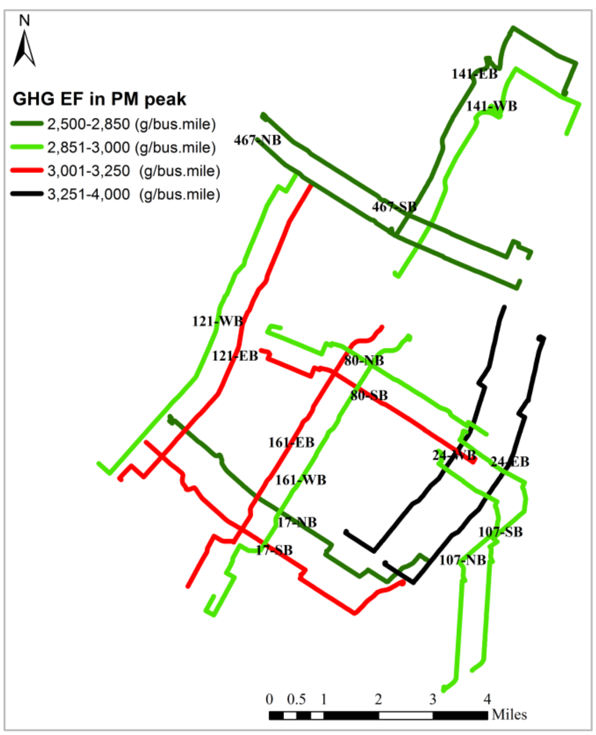
We also estimated total emissions per route for each trip and averaged over the multiple visits to simplify the visualization and enable route-level comparisons. **Figure 3-5** illustrates average route emissions (normalized by bus and mile) in g/bus.mile. We observe that PM peak buses produce higher emissions than AM buses because of lower speeds due to congestion and longer idling at bus stops. But it is also interesting to see that lower average speeds **(Figure 3-4)** do not necessarily translate into higher emissions. This is because emissions not only depend on average speeds, but also on factors like roadway grade, bus type, and driving characteristics. **Figure 3-5** also compares emissions on a per-passenger basis illustrating different trends than the ones observed for total emissions. For example, route 17, which produces relatively low emissions compared to other routes becomes one of the most polluting routes on a per-passenger basis. Similarly route 24, which generates one of the highest emissions during the PM peak period, on a per passenger basis it generates the lowest.



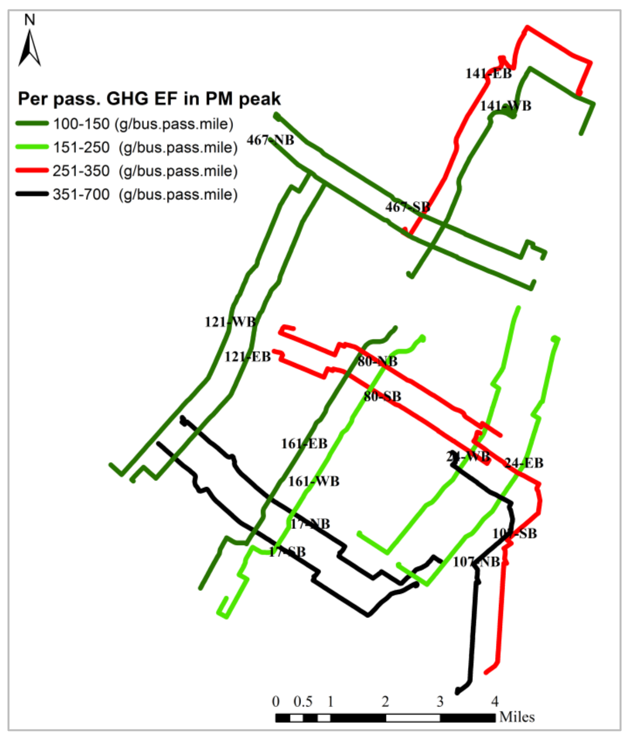
(a) Total emissions in AM peak



(b) Per passenger emissions in AM peak



(c) Total emissions in PM peak



(d) Per passenger emissions in PM peak

Figure 3-5. Total and per passenger route-level GHG emissions

When emissions are aggregated over the entire route, the effect of speed and grade could cancel-out. Therefore, the effects of these variables were investigated at a link-level. **Figure 3-6** illustrates how emissions are affected by the average speed of the bus at zero grade using data for regular buses only (1,389 observations). This figure also shows the variability in emissions for the same average speed due to the variation in drive cycles. The effects of speed and grade on emissions are also investigated in **Figure 3-7** using data for regular buses only. The fitted line (the dotted lines represent mean 95% confidence interval) shows how emissions vary across grades. At negative grades, emissions do not vary strongly with grades rather they are dominated by speed. At positive grades, the rate of increase in emissions with grade is higher but we also observe that the effect of speed dominates whereby segments with higher grades and higher speeds can generate less emission than segments with lower grades and lower speeds. Similar effects of grade and speed were observed for articulated buses.

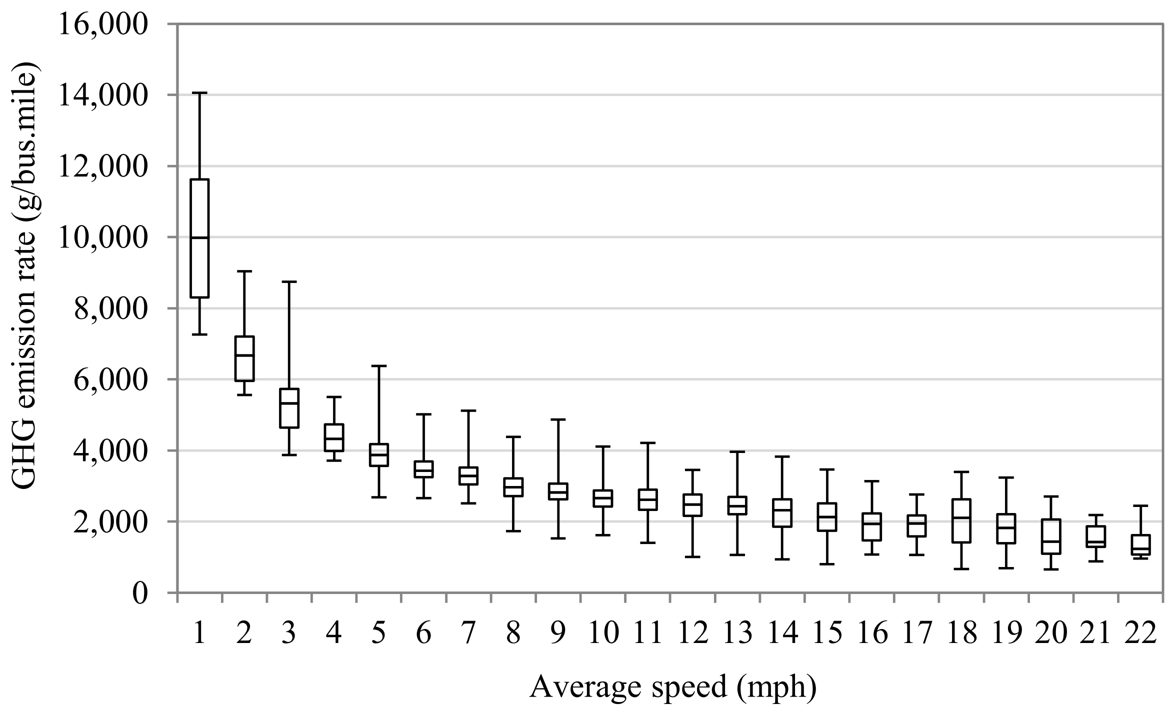


Figure 3-6. Observed relationship between bus speed and emissions at zero grade

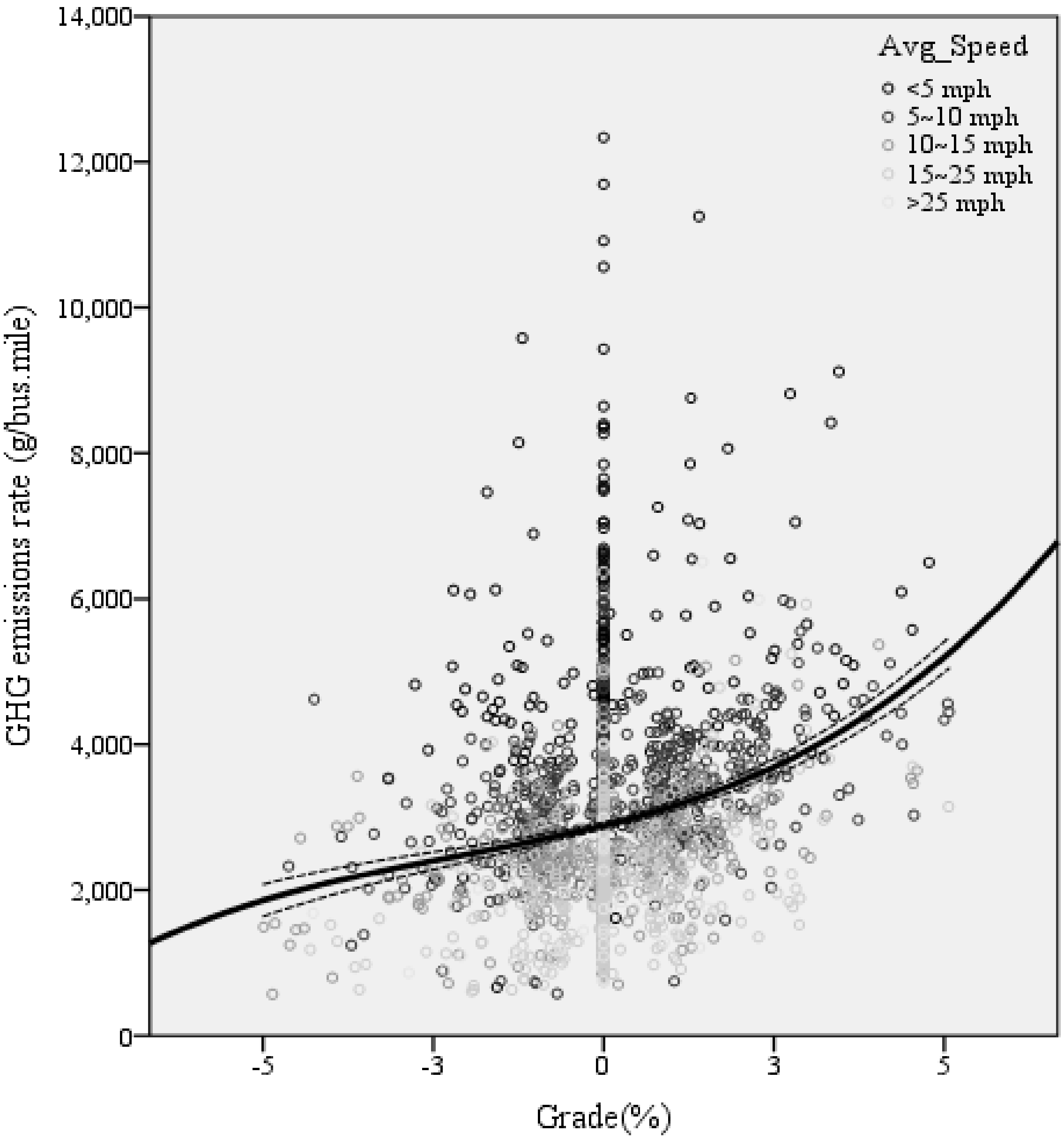
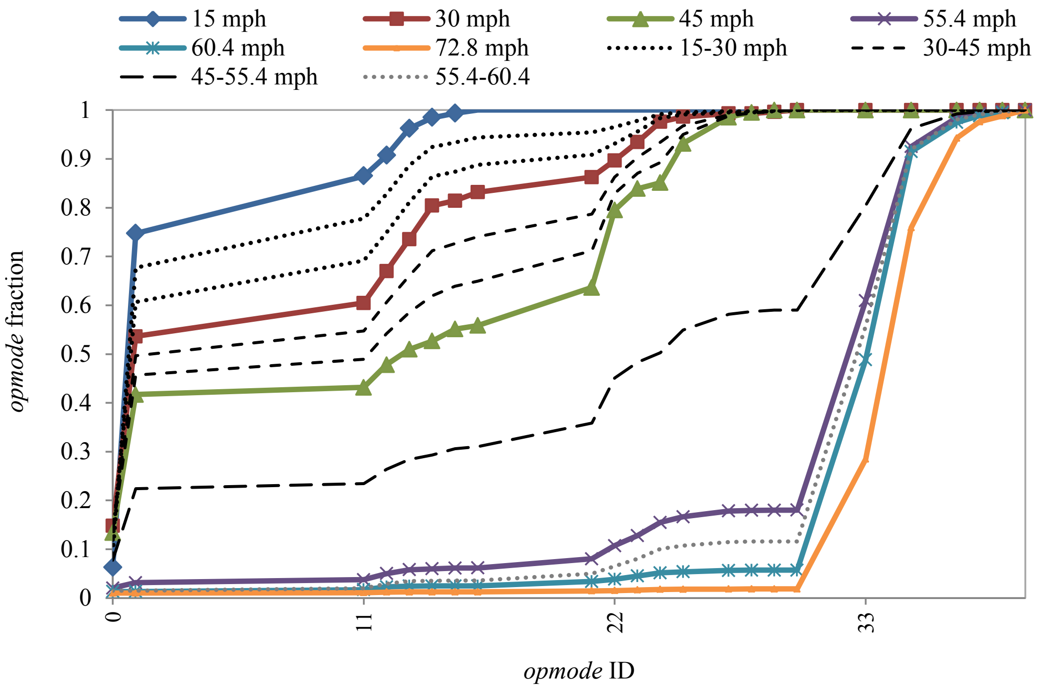


Figure 3-7. Effects of link grade on GHG emissions at different speeds

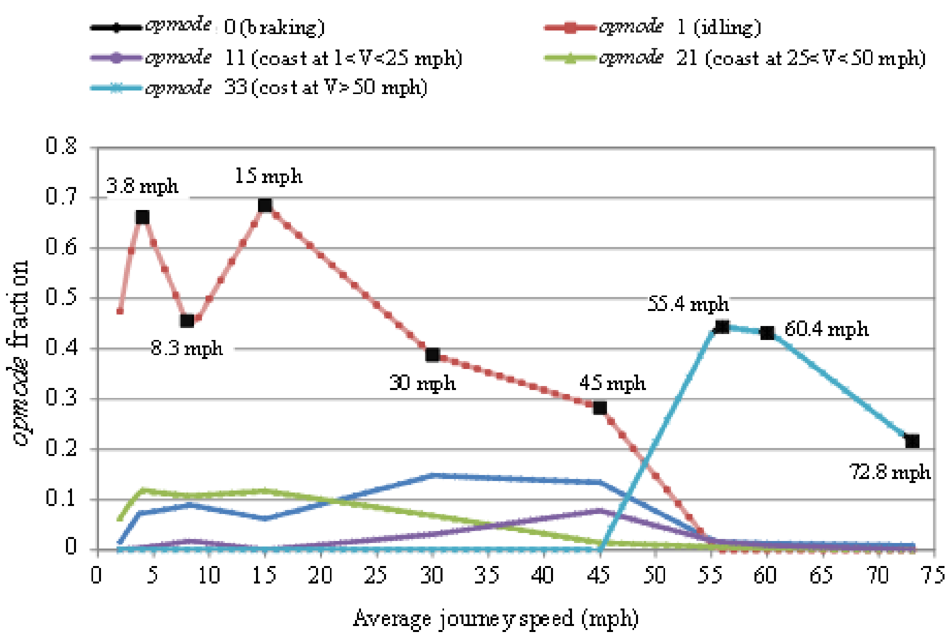
3.5.2 Investigation of MOVES drive cycles and emission rates

To better understand the assumptions behind the estimation of bus emissions in MOVES, we first extracted the MOVES default drive cycles and emission rates. Depending on averaging speed and road type, MOVES uses different drive cycles. Among those cycles, some are for transit buses while others were developed for medium heavy-duty vehicles. In this study, we collected data for the buses operated in "urban unrestricted roads" (i.e. local and major roads excluding highways and ramps). For this road type, MOVES embeds five transit bus specific drive cycles (given as drivescheduleID). The five drive cycles are associated with average speeds of 3.69 mph (drivescheduleID 404), 8.33 mph (drivescheduleID 405), 15 mph (drivescheduleID 401), 30 mph (drivescheduleID 402), and 45 mph (drivescheduleID 403). The first two drive cycles are developed based on actual bus speeds: drivescheduleID 404 is developed using New York (NY) city buses and drivescheduleID 405 using Washington Metro Area Transit Authority (WMATA) buses (US Environment Protection Agency 2014). The drivescheduleID 401 referred as "low speed urban" contains the last 450 seconds of the standard New York Bus drive cycle. The other two drivescheduleIDs, 402 and 403, are collected by Ann Arbor Transit Authority in Ann Arbor (US Environment Protection Agency 2010). It is important to note that the average speeds of 15, 30, and 45 mph do not represent the actual bus average speed, rather they represent the average speed of traffic flow the bus is moving with (US Environment Protection Agency 2010). MOVES also uses three medium duty vehicle drive cycles, drivescheduleID 253, 254 and 254, to estimate emissions for the average speeds of 55.4, 60.4 and 72.8 mph respectively.

These eight "urban unrestricted road" drive cycles are used to generate *opmode* distributions for buses moving at average speeds of 3.7, 8.3, 15, 30, 45, 55.4, 60.4, and 72.8 mph. For other intermediate average speeds, MOVES interpolates *opmode* distributions. **Figure 3-8(a)** illustrates the MOVES embedded cumulative *opmode* distributions. For speeds 15, 30, 45, 55.4, 60.4, and 72.8 mph, the distributions are presented in solid lines while the distributions for intermediate speeds are illustrated as dotted lines. To visualize how MOVES interpolates the *opmode* distributions at different speeds, selected *opmode* fractions are plotted in **Figure 3-8(b)**. Note that since only a small number of *opmodes* is selected, the fractions do not add-up to one. We observe that the fraction of each *opmode* is linearly interpolated between the points for which drive cycles exist.



(a) Cumulative *opmode* distributions embedded in MOVES



(b) *opmode* fractions associated with different average speeds

Figure 3-8. MOVES *opmode* distributions for transit buses associated with different average speeds

3.5.3 Validation of MOVES drive cycles with local data

The drive cycles constructed using the collected GPS data were validated against MOVES drive cycles at different average speeds through the comparison of cumulative *opmode* distributions. **Figure 3-9** illustrates this comparison for regular buses at four average speeds: 3, 4, 6, and 8 mph. These speeds were chosen as MOVES has actual bus drive cycles at 3.7 and 8.3 mph. We observe smaller differences in *opmode* distributions at speeds lower than 15mph compared to the differences at speeds higher than 15mph (**Figure 3-10**). This is probably because MOVES relies on traffic speeds to generate *opmode* distributions in the latter case. We also observe that our local distributions have a lower fraction of the "lower *opmode* IDs" indicating a smaller proportion of time spent idling and in the low speed bins whereas MOVES largely overestimates these proportions. Note that the *opmode* distributions we generated for the average speeds of 3, 4, 6, 8, 15, 20, and 25 mph are based on GPS data for 65, 128, 181, 209, 95, 39, and 25 segments respectively. A closer look at *opmode* 1 (which defines the idling mode) in **Figure 3-11** illustrates the difference between MOVES and local data. When the speed is between 3.8 and 8.3 mph, the difference is smaller compared to the difference observed at higher average speeds.

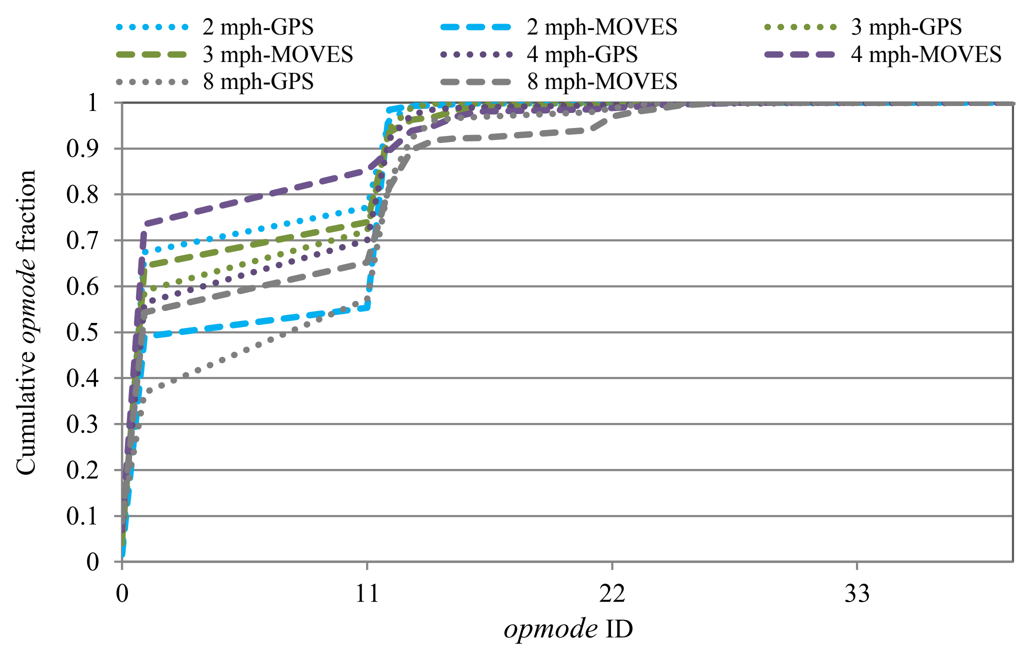


Figure 3-9. Comparison of cumulative *opmode* distributions for regular buses at speeds below 15mph

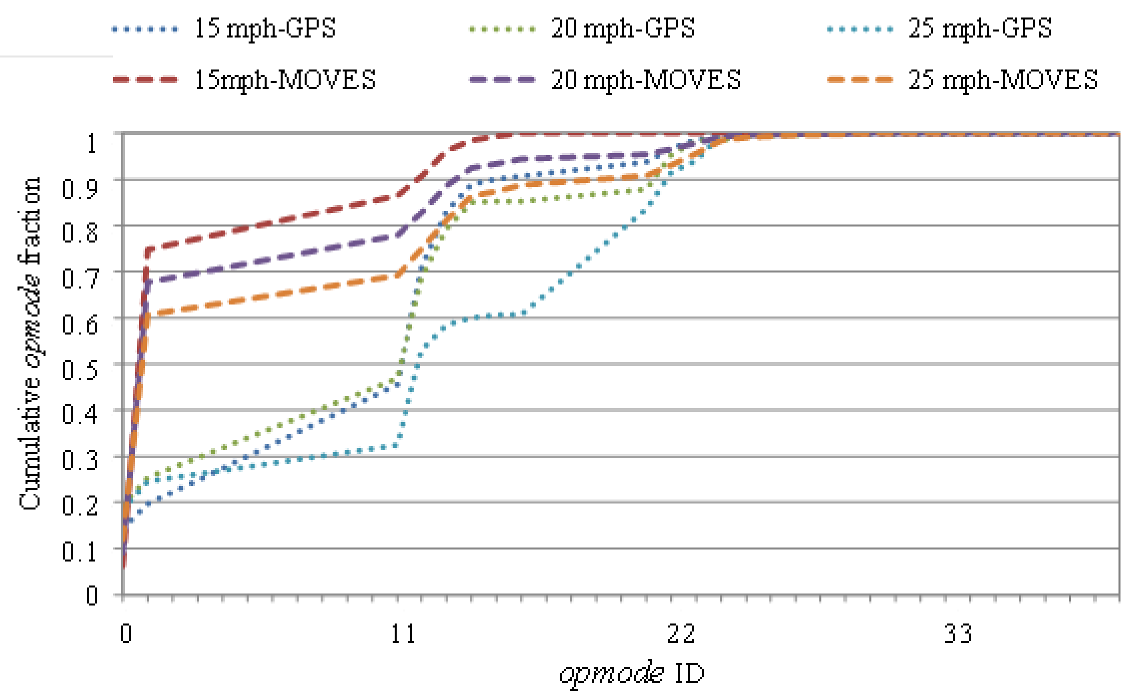


Figure 3-10. Comparison of cumulative *opmode* distributions for regular buses at average speeds higher than 15mph

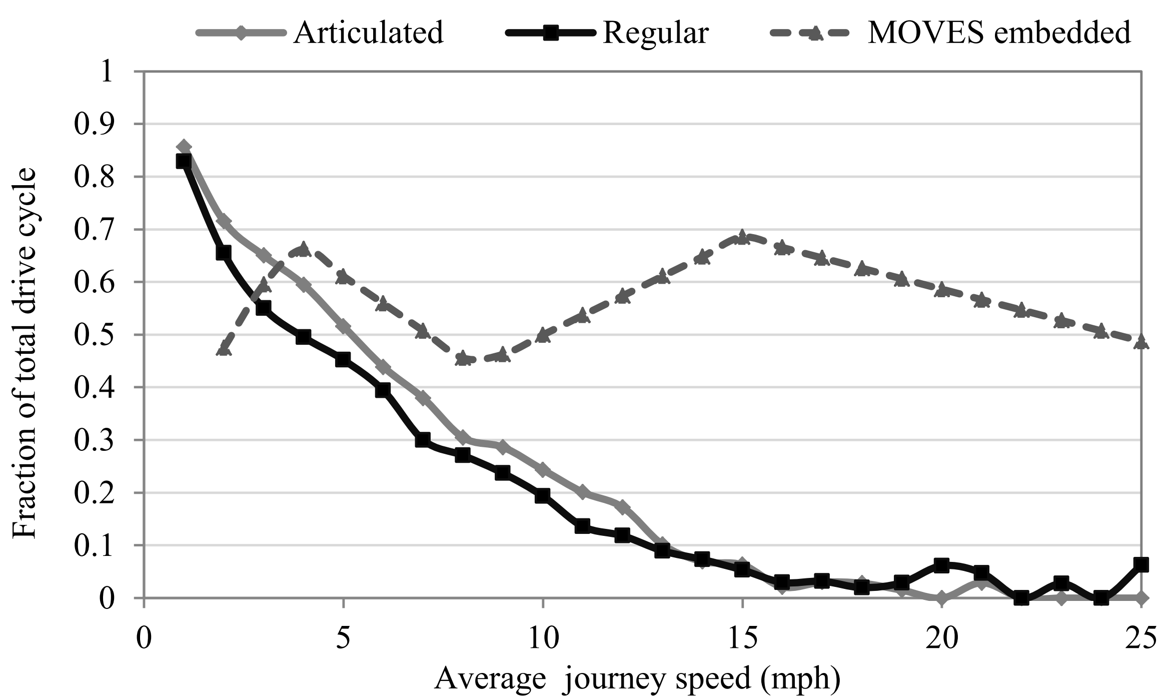
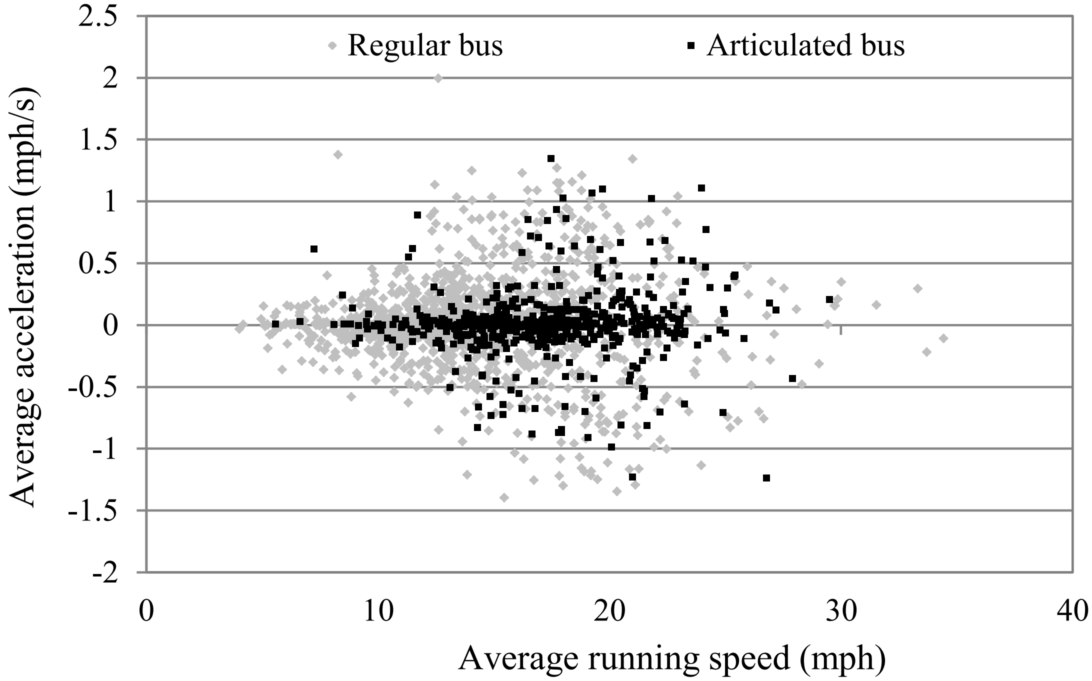
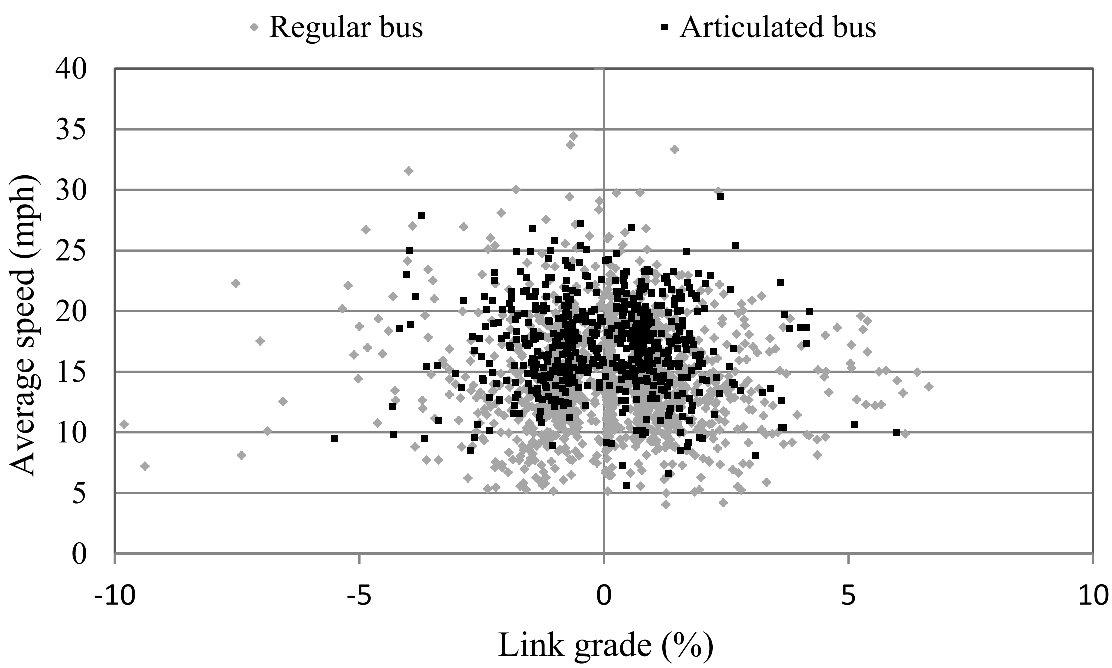


Figure 3-11. Comparison of idling mode fraction as a function of average speed

Regarding the treatment of regular vs. articulated buses, it is important to note that MOVES does not have provisions for differentiating bus types when the average speed method is adopted. It is possible to reflect different bus types (with the same fuel) in MOVES either by: (1) changing the weight of the bus in the MOVES database, or (2) calculating VSPs and *opmodes* externally. However, despite accounting for a different weight in MOVES, different bus types can exhibit different drive cycles; this is a factor that is not yet taken into account in the model. **Figure 3-12(a)** which is developed using our local data shows that articulated buses have a small variation in acceleration rates compared to regular buses at the same average speeds. There exist a statistical significant difference (p=0.001) in the mean absolute acceleration rates, the mean absolute acceleration rate for regular buses is 0.25 mph/s and for articulated is 0.16 mph/s. The interquartile range for the average acceleration is 0.28 and 0.14 mph/s for regular and articulated buses respectively. We observe that at lower running speeds, articulated buses run "more smoothly" with lower acceleration rates. **Figure 3-12(b)** also shows that at higher or lower link grades, the variation in running speed is smaller for articulated buses. The mean average speed between the bus types are also significantly different (p=0.001); whereas the mean average speed for regular and articulated buses are 14.55 and 17.08 mph respectively. The interquartile range for average speed is 5.78 and 4.99 mph for regular and articulated buses. These statistically significant differences in drive cycle characteristics highlight the importance of considering not only bus weight, but also specific drive cycle in emissions estimation.



(a) Avg. acceleration (mph/s) vs running speed (mph)



(b) Avg. speed (mph) vs link grade (%)

Figure 3-12. Comparison of drive cycle characteristics for regular and articulated buses

3.5.4 Effect of drive cycle differences on resulting emissions

Using the instantaneous bus speeds, GHG emissions were estimated at a link level for each route in our campaign; this allowed us to develop a relationship between GHG emissions and average speed. **Figure 3-13** illustrates this relationship for regular and articulated buses separately; the emissions of each link are plotted as a function of its average speed, **Figure 3-13** also illustrates the average speed-based emissions estimated by MOVES. In general, we observe that the average-speed mode in MOVES embedded *opmode* distribution based emissions are significantly different than the emissions estimates using our local *opmode* distribution for regular buses (p=0.04) and articulated buses (p=0.004). The difference in emissions increases with speed because of the high proportion of idling in the MOVES default distributions compared to our GPS data (e.g. 69% more idling time at 15 mph in the MOVES default). When the idling fraction is high, the fractions of other *opmodes* become small. Therefore, the lower emission rate associated with idling (in gr/hr) results in lower emissions (in g/km). We also observe in **Figure 3-13** that at the same average speed, articulated buses significantly (p=0.001) generate higher emissions than regular buses (mean of 2,881g/bus-mile for regular buses vs. mean of 3,332 g/bus-mile for articulated buses).

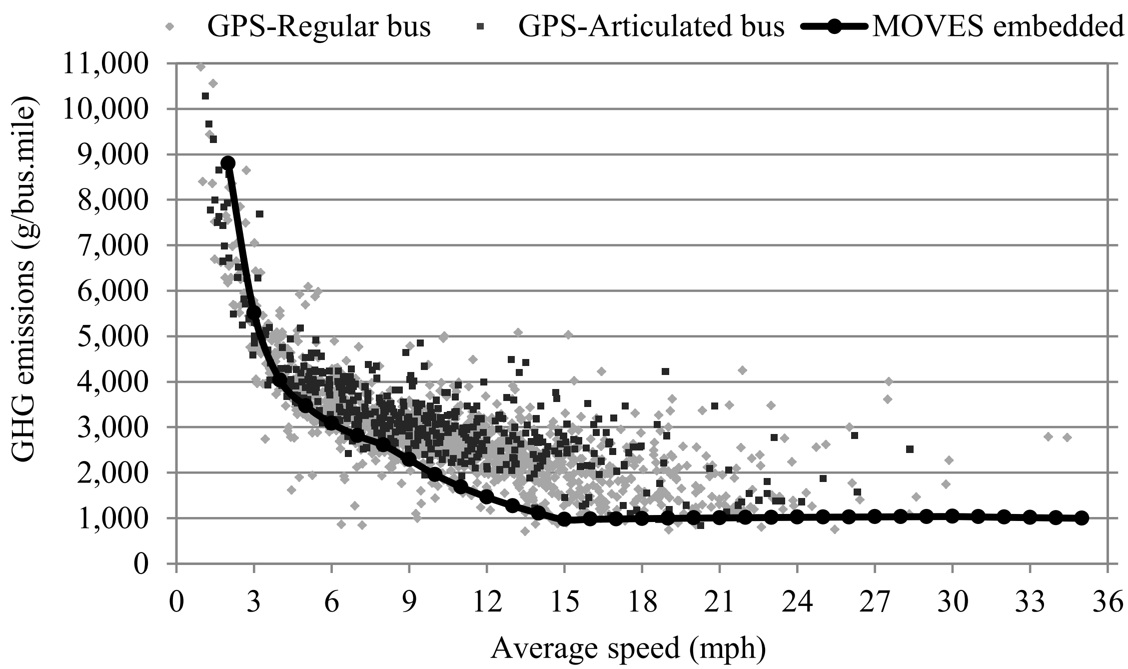
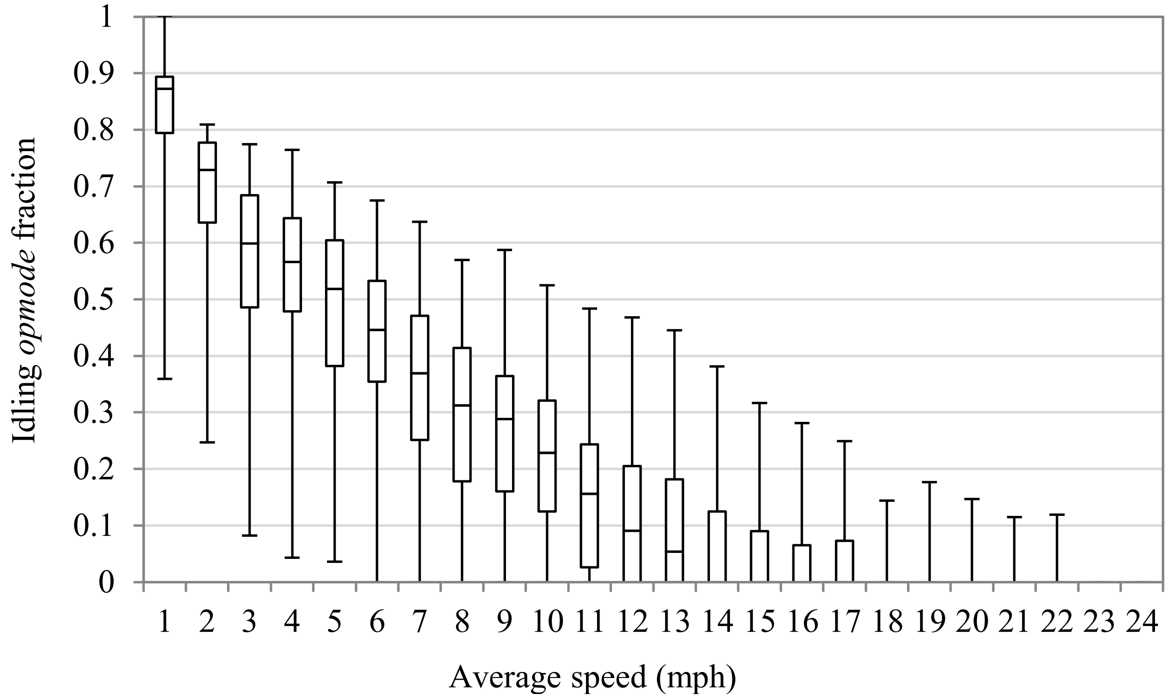


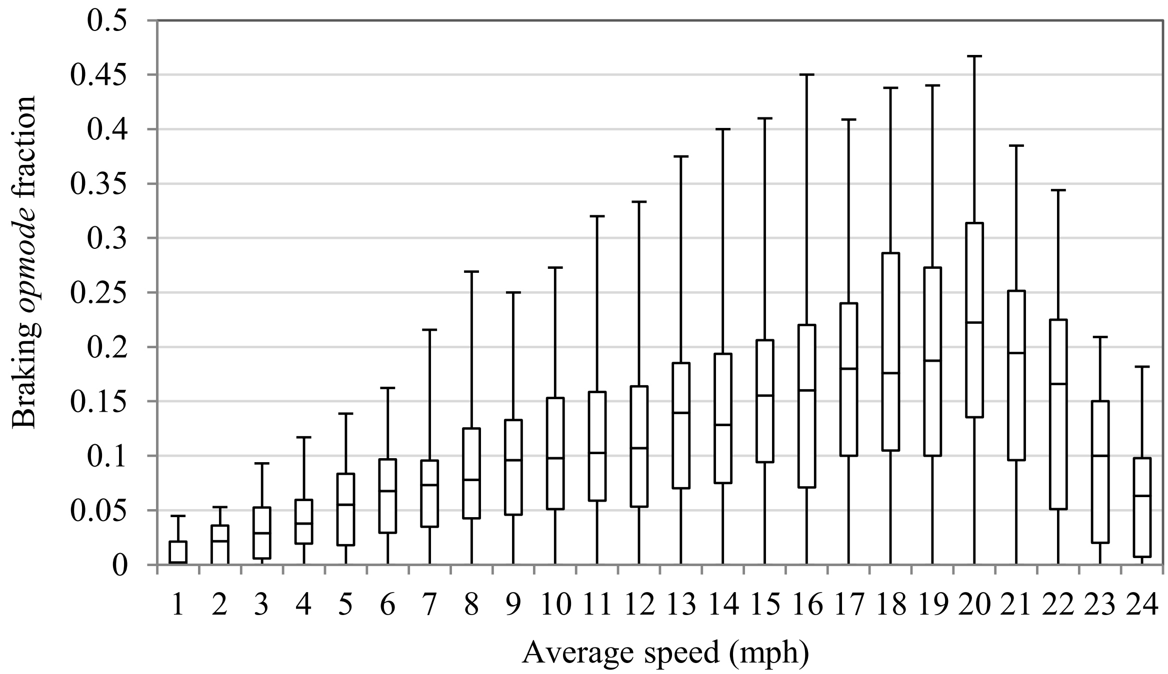
Figure 3-13. Average speed-based GHG emission rates using local GPS data and MOVES embedded drive cycles

3.5.5 Embedding local speed-specific *opmode* distributions into the MOVES database

After the generation of an *opmode* distribution for each observation, the variability of *opmode* fractions across different average speed categories as well as within the same category was observed. **Figure 3-14(a)** shows the variability for the idling fraction. We observe that the amount of idling decreases with increasing average speed. Also at very low speeds, the variability within the same category is very high and it decreases with speed. On the other hand, **Figure 3-14(b)** shows that with the increase in speed, the amount of braking increases until a certain speed (20 mph) and then it starts to decrease. Also the variability within the same category increases with increasing speed and starts to decrease after a certain speed (20 mph).



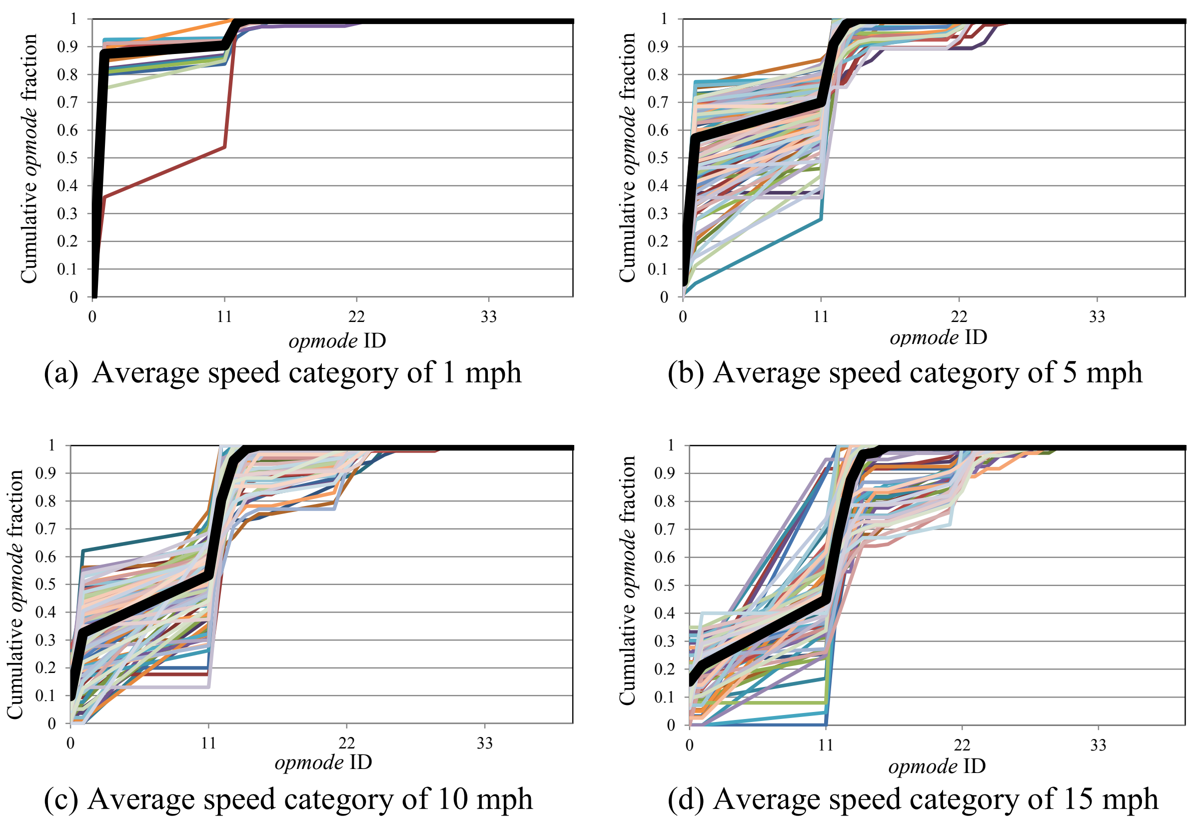
(a) Variability of idling *opmode* fraction at different average speeds



(b) Variability of braking *opmode* fraction at different average speeds

Figure 3-14. Variability of different *opmodes* as a function of average bus speed

After the calculation of a cumulative *opmode* distribution for each link-level observation, a median cumulative *opmode* distribution was identified for each speed category. **Figures 3-15 (a, b, c, d)** show cumulative *opmode* distributions for different speed categories. For each speed category, the *opmode* distributions of different link-level observations are plotted as well as the median cumulative *opmode* distribution (presented in bold). We observe that as the speed increases the variation in cumulative *opmode* distributions increases. The average RMSE for each speed category was calculated and plotted in **Figure 3-16**. It can be observed that the average RMSE increases with average speed which means the variation in cumulative *opmode* distribution within each category increases with speed. The figure also shows the number of link-level observations under each speed category, which were used to calculate median cumulative *opmode* distribution.



(a) Average speed category of 1 mph

(b) Average speed category of 5 mph

(c) Average speed category of 10 mph

(d) Average speed category of 15 mph

Figure 3-15. Variation of cumulative o*pmode* distribution at different average speeds

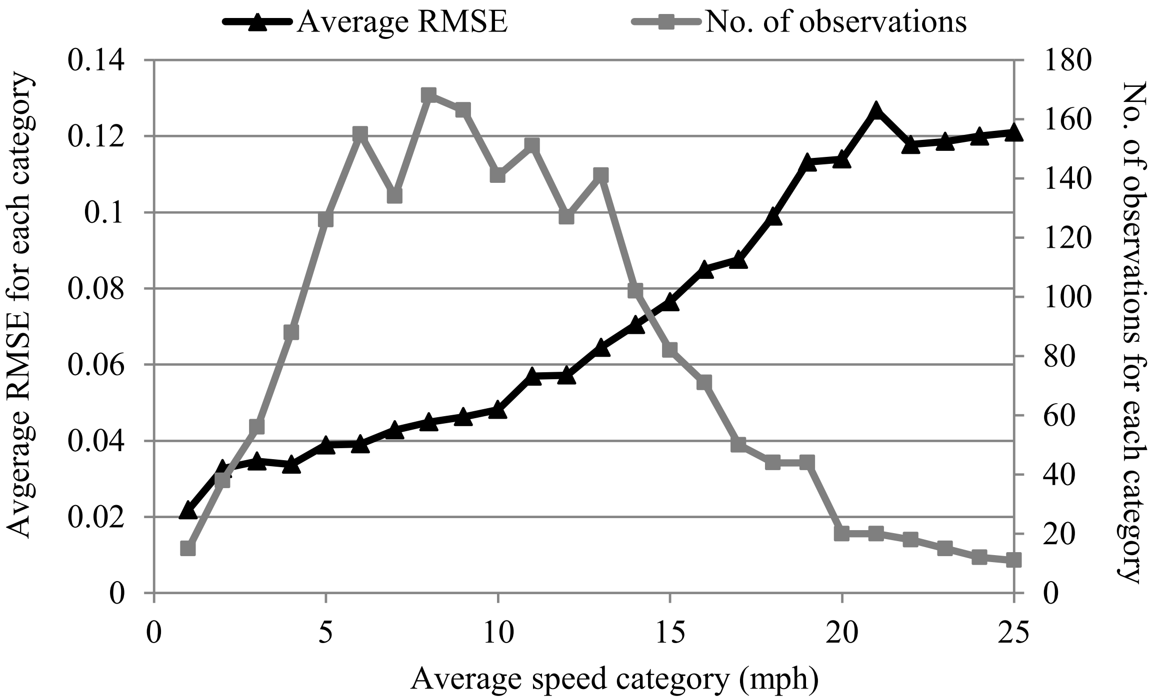
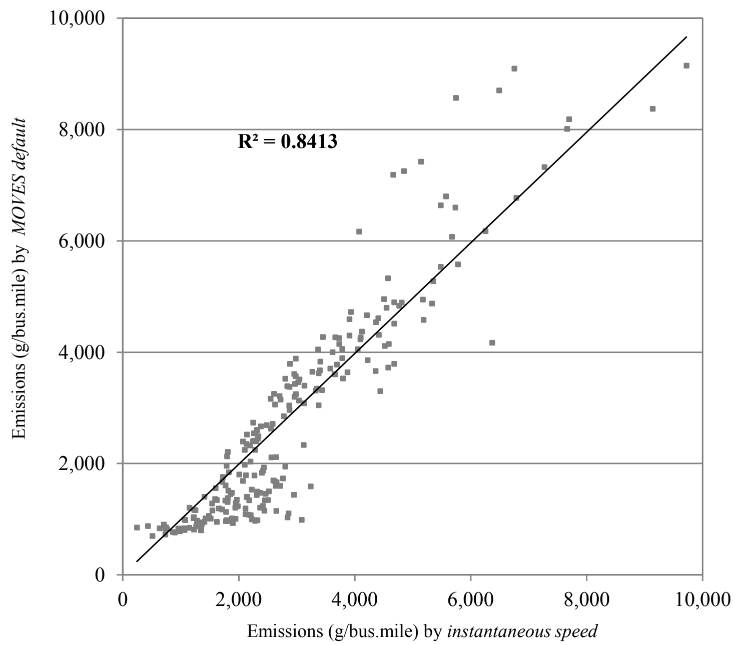


Figure 3-16. Average RMSE of observations at varying average speeds

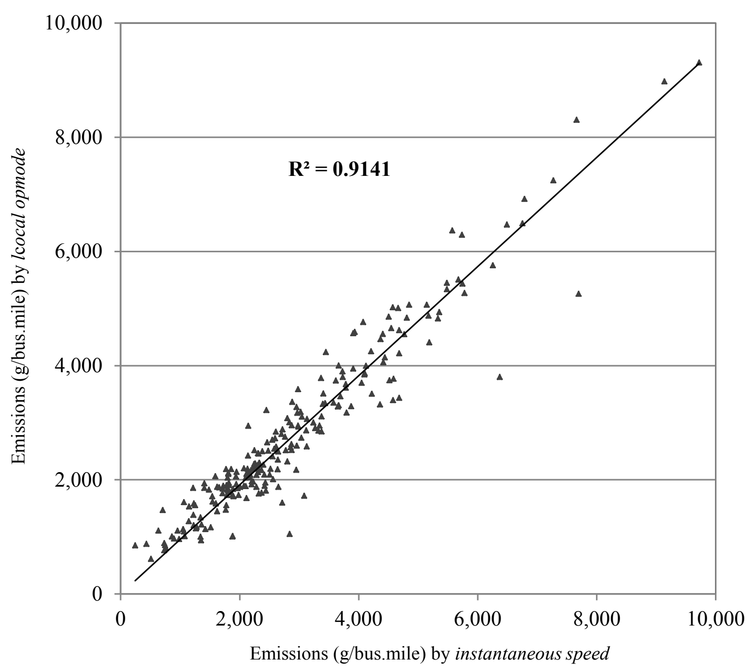
3.5.6 Emissions using embedded drive cycles

After embedding representative drive cycles into the MOVES database, emissions were estimated for a wide range of average speeds and grades. To validate the accuracy of embedded drive cycles, we estimated emissions for the buses running on the Cote des Neiges route (165) which was not included in the original sample. We estimated emissions using the following three approaches: instantaneous speed, MOVES default, and local *opmode*. **Figure 3-17** compares link-level emissions per link estimated by the three approaches. It shows a correlation of 0.91 between local *opmode* and instantaneous speed approaches while a correlation of 0.84 is observed between MOVES default and instantaneous speed. Clearly our local *opmode* estimates are improved than the MOVES default estimates. It can be also observed that at higher emissions the differences are higher when compared to instantaneous speed estimates. Usually higher emissions occur at lower average speeds. Therefore, to observe the effects of speed on the differences between the approaches each link observations are plotted as a function of average speed of the link in **Figure 3-18**. It can be observed that at the lower average speeds MOVES default overestimates emissions and at higher average speeds it underestimates emissions compared to instantaneous speed estimates. On the other hand, in most of the cases local *opmode* estimates are closer to instantaneous speed estimates. Considering all links on average, the absolute difference between instantaneous speed and MOVES default estimates is 554 g/bus.mile (i.e. 23%) whereas it is 309 g/bus.mile (i.e. 13%) between instantaneous speed and local *opmode* estimates. It clearly indicates significant (p=0.001) improvement in emissions estimation by using the local drive cycles replacing default MOVES drive cycles.

To better understand the emissions differences between approaches we categorized the link-level observations into different speed bins. **Table 3-2** illustrates average emissions for six average speed bins containing links at zero grade. We observe that for most of the speed bins the differences between instantaneous speed and local *opmode* are not very large and on an average across all speed bins the absolute mean difference between these approaches is 6.6%. On the other hand, for most of the speed bins, the MOVES default estimates are largely different from the instantaneous speed estimates. For some speed bins the difference could be over 975 g/bus.mile (i.e. 52.5%). Only for the speed bins between 3 and 9 mph the mean estimates are closer to instantaneous speed estimates than other speed bins. We also calculated the absolute emissions difference between approaches for each link and calculated the average for each speed bins which is presented in the last two columns of **Table 3-2**. It shows that local *opmode* estimates are within 12% of the instantaneous speed estimates and in the case of MOVES default it is 32.5%. Again for speed bins between 3 and 9 mph the differences are lower. The reason behind that is MOVES has only two transit bus drive cycles at 3.7 and 8.3 mph average speeds, and when emissions are estimated at and between these two speeds MOVES uses these two speed profiles to generate *opmode* distributions. For speeds above 8.3 mph, MOVES does not include any transit bus specific drive cycle, therefore it uses drive cycles resulting from average traffic flow. It clearly highlights the need for selecting and embedding local drive cycles into the MOVES database to estimate bus emissions using average speeds.



(a) Comparison of estimated emissions between *MOVES default* and *instantaneous speed*



(b) Comparison of estimated emissions between *local opmode* and *instantaneous speed*

Figure 3-17. Comparion of emissions between *MOVES default*, *local opmode*, and *instantaneous speed* approaches

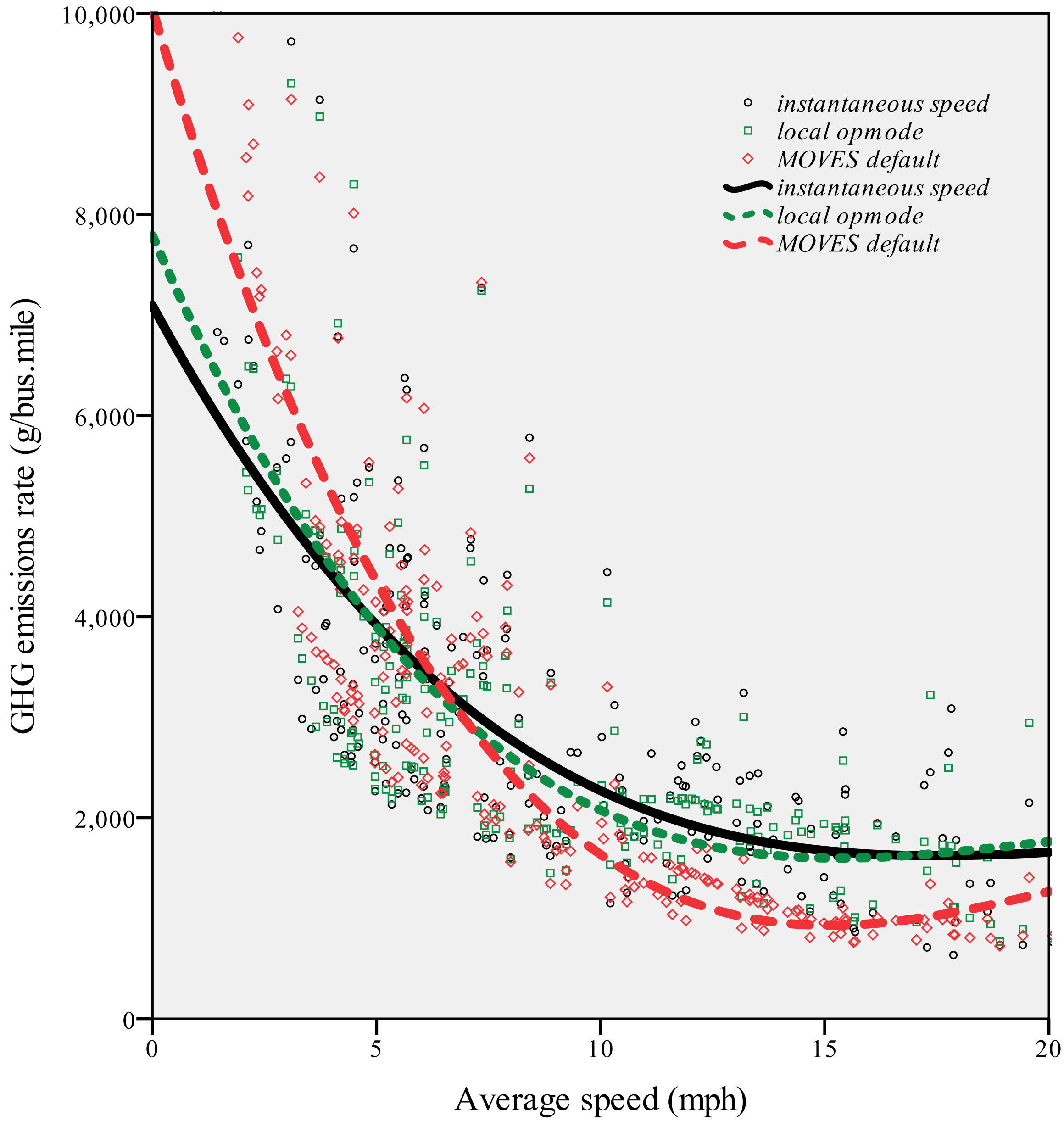


Figure 3-18. GHG emissions estimated in MOVES using three approaches: (a) *instantaneous speed*, (b) *MOVES default*, and (c) *local opmode*

Table 3-2. Mean differences between estimated GHG emissions using three approaches

Avg. speed category (mph)	Approach 1: *instant. speed* (g/bus.mile)	Approach 2: *MOVES default* (g/bus.mile)	Approach 3: *local opmode* (g/bus.mile)	Avg. abs. diff. between appr. 1 & 2 (%)	Avg. abs. diff. between appr. 1 & 3 (%)
1-3	5,720 --	8,570 (49.81%)[1]	6,370 (11.31%)	50.58	20.86
3-6	3,060 --	3,460 (12.89%)	3,160 (2.99%)	13.28	6.25
6-9	2,600 --	2,720 (4.45%)	2,570 (-1.42%)	11.25	9.10
9-12	2,370 --	1,680 (-29.14%)	2,210 (-6.62%)	28.55	9.44
12-15	2,080 --	1,220 (-41.39%)	1,980 (-4.88%)	40.21	12.43
15-18	2,050 --	975 (-52.53%)	1,800 (-12.34%)	51.15	13.30

1 Mean difference (in %) with respect to approach 1 (-ve sign indicates underestimation)

3.6 Conclusion

This study has focused on a validation of the assumptions and embedded drive cycles in the MOVES software package for bus emissions estimation. It also demonstrated a process for selecting local drive cycles that could be embedded into the MOVES database for better emissions estimation using average speeds. Local drive cycles were collected using GPS devices across 3,702 road segments for 96 bus trips on eight bus routes across a variety of transit corridors in Montreal, Canada. GHG emissions were estimated for each link by calculating local drive cycle based *opmode* distributions. Total emissions at route level and per-passenger level illustrated different trends highlighting the importance of ridership data in the evaluation of bus emissions. We observed that MOVES embeds only five transit bus specific drive cycles to generate *opmode* distributions at different average speeds by interpolation. This highlights the need for additional bus data in the MOVES database. In comparing *opmode* distributions, we observed that the MOVES embedded distributions were significantly different from the ones we constructed using the collected GPS data. We estimated emissions using both MOVES embedded *opmode* distributions and the instantaneous speeds we collected. MOVES was found to underestimate emissions because of the presence of high fractions of idling within the default operating modes (such as 69% idling time at 15 mph average speed). We also investigated the drive cycle characteristics of different bus types and observed differences between standard and articulated buses, which are currently unaccounted for by MOVES.

To embed local drive cycles into the MOVES database, we selected representative local drive cycles for speed categories ranging from 1 to 25 mph. The selection process was performed by observing the variability in *opmode* distributions within the same speed category as well as calculating RMSE to select the most representative drive cycles. After embedding the drive cycles in the MOVES database, emissions were estimated for a wide range of speeds and grades. A validation test was conducted for another bus corridor to evaluate the accuracy of the embedded drive cycles. It was observed that when average speed is used to estimate emissions, the MOVES default emissions could be largely different than instantaneous speed emissions and for some speed categories the differences between these two approaches could become over 750 g/bus.mile (approx. 44%). On the other hand, local *opmode* emissions were found to be better estimates and on average they were within 11% of the instantaneous speed estimates. The results reveal that emissions could be largely under/overestimated when the embedded distributions of MOVES are used. Our developed local *opmode* distributions and the representative drive cycles embedded within MOVES could be useful to estimate improved bus emissions when second-by-second bus speeds are unavailable, especially for a regional network.

4 CHAPTER 4: INVESTIGATING THE ISOLATED AND COMBINED EFFECTS OF CONGESTION, ROADWAY GRADE, PASSENGER LOAD, AND ALTERNATIVE FUELS ON TRANSIT BUS EMISSIONS

4.1 Chapter Overview

This study investigates the isolated and combined effects of network congestion, roadway grade, passenger load, and fuel type on transit bus emissions of GHG through a simulation of transit operations and emissions along a busy corridor. We also test the effect of changing random seed on overall corridor emissions. We observe that positive grades have strong effects on emissions. Grade also causes other variables to become important such as passenger load. While an increasing passenger load on the bus increases emissions, we observe that the addition of each passenger influences the per-passenger emissions differently depending on the bus occupancy. When the bus is less crowded each additional passenger can decrease per-passenger emissions by 5% whereas the reduction becomes 1.2% when the bus is crowded. Finally, we observe that the reduction potential of CNG compared to conventional diesel could reach up to 40% depending on speed, grade, and passenger load. CNG benefits increase with increasing congestion, and decrease with increasing grade and passenger load. The results of this study are most relevant to transit planners in the evaluation of potential operational changes with emission reduction potential and in the allocation of alternative fuelled buses along selected transit corridors.

4.2 Introduction

Bus emissions can vary largely depending on their operations, roadway grade, passenger load, age, and fuel type. Few studies have been conducted to investigate the individual and combined effects of different variables affecting emissions. While the accuracy of emission estimates increases with the availability of detailed inputs, the collection of reliable input data is a complex, time and resource intensive exercise. Therefore, a trade-off exists between the desired accuracy in emission estimates and the level of detail in model inputs.

This study investigates the effects of network congestion, roadway grade, passenger load, and fuel type on transit bus emissions. It does so through a structured sensitivity analysis that captures the effects of each variable in isolation and in combination with other variables. The study also evaluates the effects of these factors under real-world operations and via four scenarios with different combinations of grade, passenger load, and fuel type (diesel and compressed natural gas). Our study area is set in Montreal, Canada where transit operations along a busy urban corridor were simulated. Instantaneous bus speeds were used to estimate emissions using the USEPA MOVES model (US Environmental Protection Agency 2010). Emissions are estimated for GHG (in CO_2-equivalent) in two different directions in the morning peak period.

4.3 Materials and Methods

The study corridor is called the Cote-des-Neiges (CDN) corridor; situated in the Cote-des-Neiges/Notre-Dame-de-Grace and Ville-Marie boroughs in Montreal. It runs north-south with Montreal's downtown core located at the south end, making the SB direction more congested in the morning peak. The corridor has one of the highest transit riderships in Montreal; buses running along it serve two metro stations and one commuter train station. The length of the corridor is about 3.4 miles (5.1 km) with various grade changes ranging from +23% to -22% in the northbound (NB) direction and +19% to -28% in the SB direction. This study examines the total trip-level emissions (including running and idling) of the buses that serve route 165 which runs during the day. Along the route there are 35 bus stops in the SB direction and 31 stops in the NB direction. The current bus fleet operating on this route runs on ULSD with 15ppm sulfur content.

The study methodology is divided into four steps: 1) Traffic simulation, 2) Emission modeling, 3) Sensitivity analysis, and 4) Case study. Transit emissions are estimated under a wide combination of network speeds, roadway grades, and passenger load using an instantaneous speed-based approach and taking into account the effect of random seed on emissions. In addition, bus emissions under ULSD and CNG are compared to understand how the emission reduction potential of CNG varies across different combinations of speed, grade, passenger load, and randomness in the traffic simulation.

4.3.1 Traffic simulation

A traffic microsimulation model of bus operations along the CDN corridor was developed using the PTV VISSIM platform (version 5.40) for the morning peak period (7-9 AM). All of the major and minor streets were included; the network consists of 454 links, 70 signal controllers, and 239 routing decisions. Traffic volumes and turning movements were collected at each intersection over three weeks in Spring 2011. Signal timings were also collected for every signalized intersection along the corridor. Road geometry information such as number of lanes, grades, and parking lots were collected from various sources including orthophotographs and autoCAD maps and validated in the field. Finally, the bus schedule for route 165 in the morning peak period and passenger information at each bus stop (boarding and alighting) were obtained from the local transit operator STM. This information was validated against onboard data collection. The numbers of hourly boarding passengers and percentage of alighting passengers at every bus stop were input in order to replicate dwell times.

4.3.2 Emission modeling

Emissions generated during bus operations were estimated using MOVES2010a which is capable of conducting microscale analysis using instantantaneous speed profiles of vehicles including acceleration, deceleration, cruising, and idling. This study focuses on evaluating bus emissions under different roadway characteristics and randomness in traffic simulation. It is therefore crucial to use instantaneous bus speeds and simulate second-by-second emissions along the corridor. We used the 2010 version of the MOVES model in this exercise simply because it was able to run faster than MOVES2014; this was a crucial element since we conducted a very large number of runs for the sensitivity analysis. The results would not have differed had we used MOVES 2014 since the changes that were made to MOVES 2014 did not affect the elements we tested in this chapter. To estimate second-by-second emissions, MOVES requires length, grade, and instantaneous bus speed profile for each link. The link length, grade, and speed profile were obtained from the VISSIM model after each simulation. In addition to link information, MOVES also requires the following inputs: bus age distribution, fuel formulation, and meteorological data. Currently, buses of model years 2009 and 2010 are operated along the corridor. Among those, 58.39% are of model year 2010 and 41.61% are of model year 2009.

Current buses run on ULSD with a sulfur content of 15ppm. Meteorological data were input in the form of hourly temperature (°F) and relative humidity (%), collected from a nearby weather station (less than 1 km distance).

Passenger load on the bus is a contributing factor to total bus emissions and we specifically account for it in this study. In order to do that, we developed a pre-processor that extracts the speed profile of the bus (from the traffic simulation) and the passenger load per link and calculates the VSP and *opmode* category of the bus. The VSP represents the tractive power exerted by a vehicle to move itself and its passengers. It is a function of instantaneous speed, acceleration, vehicle weight, and road grade as shown in equation (1) (US Environment Protection Agency 2010). In MOVES, an *opmode* is determined by following a combination of speed and VSP for each second.

$$\mathrm{VSP} = \left(\frac{\mathrm{A}}{\mathrm{M}}\right) * \mathrm{v} + \left(\frac{\mathrm{B}}{\mathrm{M}}\right) * \mathrm{v}^2 + \left(\frac{\mathrm{C}}{\mathrm{M}}\right) * \mathrm{v}^3 + (\mathrm{a} + \mathrm{gSin\theta}) * \mathrm{v} \quad \text{………..………..……...….} \quad (1)$$

$$\mathrm{A} = (\text{bus weight in metric ton}) * 0.0643$$

$$\mathrm{B} = 0$$

$$\mathrm{C} = (\text{bus weight in metric ton}) * \left(\frac{3.22}{\text{bus weight in kg}} + 5.06 * 10^{-5}\right)$$

where A, B, and C are the rolling, rotating, and drag road load coefficients respectively in the units of (kiloWatt second)/(meter), (kilowatt second^2)/(meter^2), and (kiloWatt second^3)/(meter^3), respectively. The denominator term, 'M', is the fixed mass factor (for transit M=17.1 metric tons), 'g' is the acceleration due to gravity (9.8 meter/ second^2), 'v' is the vehicle speed in meter/second, 'a' is the vehicle acceleration in meter/second^2, and Sinθ is the (fractional) road grade.

In the VSP equation, the A, B, and C terms depend on vehicle weight. As the weight of the bus increases, the values of A, B, and C increase and therefore, the VSP also increases. In other words, as the weight of the bus increases due to additional passengers, the bus needs to generate more tractive power. For each second, we calculate the VSP based on the weight of the bus, speed and acceleration. Then, based on the VSP and speed, the *opmode* is determined for every second of the corresponding drive cycle. The amount of seconds spent in each *opmode* is then calculated and an *opmode* distribution is developed for each link. We input this *opmode* distribution into MOVES to estimate emissions at a link level. When the *opmode* distribution is supplied externally into MOVES, we can specifically account for changes in bus weight rather than adopt the MOVES default weight (16.556 tons) that assumes a constant number of 55 passengers.

4.3.3 Sensitivity analysis

This section describes the design of a sensitivity analysis of transit emissions with respect to traffic load on the network (affecting speed), grade, and passenger load on the bus. All of the results are extracted and analyzed for the more congested southbound direction.

Another element of interest is the effect of random seed in the traffic simulation on the resulting emissions. This is important as different buses experience different traffic situations. For every variable and combination of variables that are tested, six different simulations are conducted under six different random seeds. In each case, running emissions are estimated as well as their mean and coefficient of variation (Standard Deviation/Mean).

Network speed: Speed and number of stops are critical factors as they largely affect bus fuel consumption and emissions (Delgado et al. 2011). Bus operations are simulated at three different levels of traffic loading onto the network. The traffic simulation is run using three different traffic inputs at all boundary links: 1) the base-case traffic obtained during a data collection campaign leading to an average bus journey speed of 9.51mph in the SB direction, 2) 40% of the base-case traffic loading leading to an average bus journey speed of 16.29mph in the SB direction, and 3) 110% of the traffic loading leading to an average bus journey speed of 6.35mph in the SB direction. For each scenario, VISSIM was run six times under six different random seeds resulting in a total of 18 runs.

Grade: Using North American drive-cycles, Khan and Clark (2010) found that the effect of grade changes with operating speed. It is therefore important to consider both speed and grade at the same time to understand the real effect of grade. To observe this, individual grades are simulated, ranging from -7.5% to +7.5% in increments of 2.5% (by changing the grade of every link to the value under study) for each traffic loading scenario. Traffic is simulated six times under six different random seeds which result in a total of 42 runs at each of the three levels of traffic loading. This leads to a total of 126 simulations in order to evaluate the combined effect of speed and grade.

Passenger load: Clark et al. (2007) quantified the impacts of passenger load on emissions and found that buses consume 9% more fuel when running at full weight compared to empty weight. Different values of the passenger load factor (PLF) are considered whereas the PLF is defined as the ratio of total onboard passengers to seating capacity. In this study PLF values ranging from 0 (no passengers) to 2.0 (2 times more passengers than seating capacity) in increments of 0.5 are simulated. We consider the weight of an empty regular bus as 12.69 tons and the seating capacity as 38. Since in MOVES the default bus weight is considered as 16.556 tons corresponding to a PLF of 1.45 (assuming an average passenger weight of 70 kg), this PLF value is also used. As seven values for grade and six values for PLF are evaluated, 42 combinations are run for each traffic loading case. For each combination, MOVES is run six times. In total, 252 runs were conducted to evaluate the combined effect of PLF and grade at a single speed (leading to 756 runs for the three traffic loading conditions).

Figure 4-1 illustrates the sequence of sensitivity tests that we conducted. Each box represents six different model runs (under six random seeds)

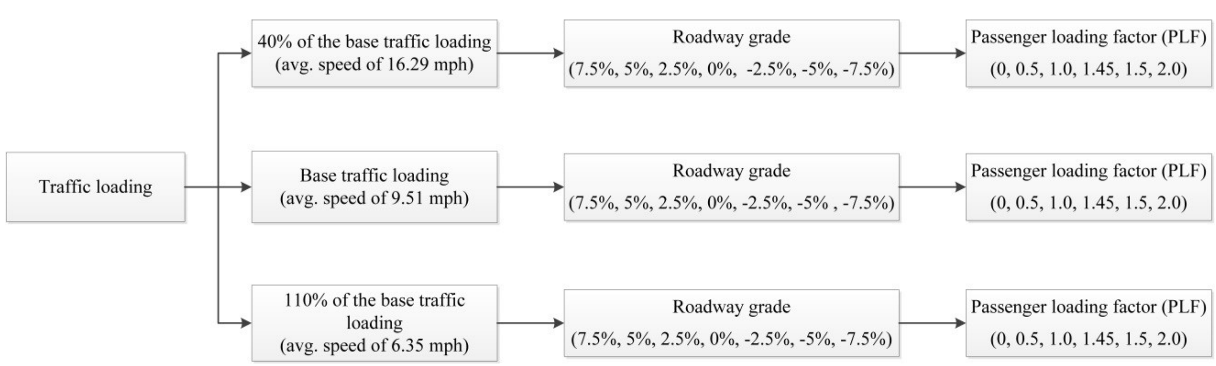


Figure 4-1. Sequence of sensitivity tests

4.3.4 Evaluation of combined effects in real-world transit operations

Transit emissions are influenced by different factors and the previous sensitivity analysis investigates the individual effects of these factors. But in real world conditions, it is not possible to control for combinations of grades, PLF and speed, rather different effects could compound or cancel each other. Therefore, we simulate total emissions along the CDN corridor under real operations and corridor grades that encompass a wide mix of these influencing variables under the following scenarios:

> Scenario 1: Grade and PLF effects are disregarded. This means that every link is considered to have a zero grade and the MOVES default bus weight of 16.556 tons is considered.
>
> Scenario 2: Only PLF is considered, but no grade effect. This means that in the emission estimation process, the actual passenger load is used, but the grade of every link is kept zero.
>
> Scenario 3: Only grade is considered, but no PLF effect. This means that in the emission estimation process, the grade of each link is used, but the passenger ridership information is disregarded. Instead, the default weight of the bus is considered (passenger ridership is still considered in terms of its influence on bus dwell times at stops).
>
> Scenario 4: Both grade and PLF effects are considered.

For each simulation only one bus speed profile (departing after one hour of simulation) is extracted and used to estimate emissions for two different fuels: (1) ULSD and (2) CNG. In this exercise, bus emissions are estimated for the study corridor in both the NB and SB directions. In the morning peak, the SB direction is more congested as commuters travel towards the downtown core.

4.4 Results and Discussion

4.4.1 Validation of base-case speed profiles

Instantaneous speed profiles of buses running along the 435/165 route obtained from the VISSIM model were validated using on-board GPS data collection of a sample of buses in the morning peak period. To account for the variability in traffic, several GPS-based and simulation-based bus speed profiles were collected and compared. Using equation (1), the VSP for each second was calculated outside of MOVES for both the GPS data and instantaneous speeds extracted from the traffic simulation. Then, the *opmode* distributions were compared. To account for the variability in traffic, three on-board GPS drive cycles and three simulated drive cycles (as a result of three different random seeds) were collected. **Figure 4-2** shows the average percentage of time the bus spent in each *opmode* for both GPS and simulated data. We observe that the difference between GPS and simulated data under each *opmode* is not statistically significant (at 99% confidence level). Finally, using these *opmode* distributions, we estimated emissions in MOVES; on average, the difference between the emission estimates based on traffic simulation and GPS data are on the order of 12%.

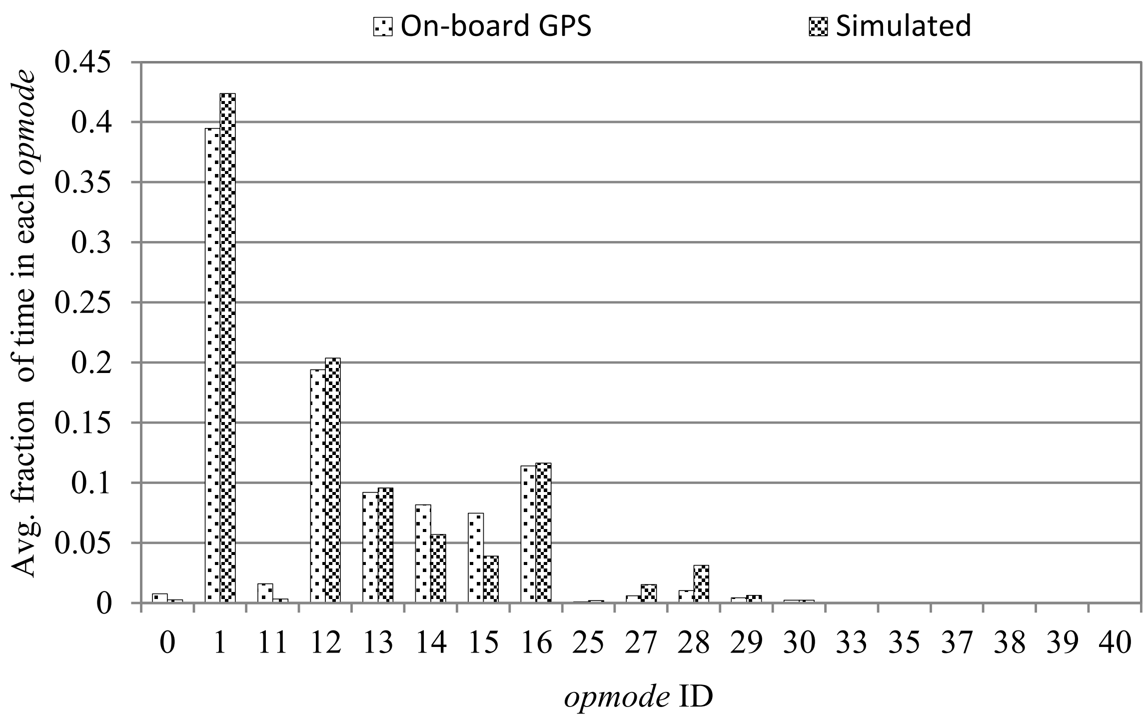


Figure 4-2. Comparison of *opmode* distributions between simulated and observed drive cycles (each bar represents an average of three fractions)

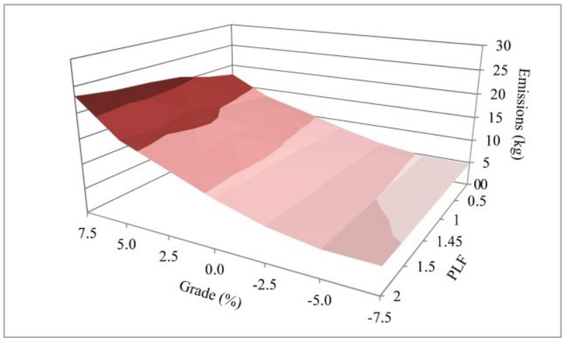
4.4.2 Sensitivity analysis

Results of the full evaluation of isolated and combined effects of speed, grade, and passenger load are presented in a tree structure (**Figure 4-3**). Each box represents an average of total bus emissions in the southbound direction (normalized per bus) resulting from six model runs with varying random seeds. In addition, each average is followed by a coefficient of variation derived from the six iterations. The coefficient of variation is lower at higher journey speeds indicating that random seed effects are more important under congested conditions leading to more variable outcomes.

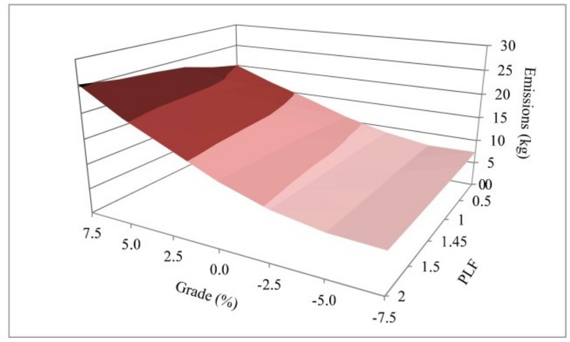
Figure 4-4 presents how grade and PLF affect transit emissions at different speeds. We observe that for the same combination of grade and PLF, a congested network generates higher emissions. It is also clear that at the same speed and PLF, emissions increase largely with grade. On the other hand, for the same speed and grade, PLF tends to increase emissions slightly; the effects of PLF are more important at higher grades. **Figure 4-5** illustrates the effect of grade on emissions estimated at the MOVES default PLF value of 1.45. For each grade, emissions are estimated at three journey speeds. We observe that the effect of grade on emissions is very small when the grade is negative; the dispersion of emissions at negative grades indicates that the effect of increasing negative grades is cancelled out by the randomness in traffic patterns. But when the grade is positive and as the grade increases, emissions increase. This effect is slightly more pronounced at lower network speeds. In addition to the range of grades evaluated in the sensitivity analysis (-7.5 to +7.5%), we estimated emissions at grades ranging from -50% to +50% and observed that when the grade changes from 0% to 50%, emissions increase by 249% and when it changes from 0% to -50%, emissions decrease by 58%. Furthermore, the effect of passenger load was investigated at different grades. **Figure 4-6(a)** illustrates how running emissions increase with the increase in onboard passenger volume at an average speed of 9.51 mph. At -7.5% grade, emissions vary from 7.2 kg to 7.7 kg for PLF values ranging from 0 to 2 translating into a 6.80% increase while at a grade of +7.5%, emissions increase by 26.96% between a PLF of 0 and 2. This indicates that the effect of passenger load is more important at higher grades. To understand the effect of passenger load on dwell emissions at bus stops, dwell emissions were calculated based on passenger ridership (corresponding to the PLF) and added to running emissions so that total emissions (running + dwell emissions) could be estimated. Emission rates were then derived in two cases: (1) not considering dwell emissions, and (2) considering total emissions. **Figure 4-6(b)** illustrates that when the PLF is small, dwell emissions are minimal due to the reduced dwell time for passenger activity (boarding and alighting). As the PLF increases, its effect on bus emissions becomes more important when idling emissions at bus stops are taken into account. To further explore the effect of passenger load, emissions were compared on a bus and passenger basis. **Figure 4-7** illustrates how the addition of every passenger impacts running emissions as a total and on a per passenger basis. When the number of passengers increases from 1 to 76, the bus emission rate increases from 975 g/mile to 1,160 g/mile, an increase of 18.97% (at zero grade and average bus speed of 16.29 mph). But if emissions are considered on a per passenger basis, then an opposite trend is observed. For the same passenger increase from 1 to 76, the emission rate per passenger changes from 975 g/mile.pass to 14 g/mile.pass, a decrease of 98.56%. The reduction in per passenger emissions is high when the bus is less occupied and as the number of onboard passengers exceeds the seating capacity of the bus (PLF>1.0), the benefit of adding passengers starts to decrease. As an illustration, we observe that for the first 19 passengers on the bus (PLF 0.0-0.5), on average, each passenger reduces the per passenger emissions by 4.99% (compared to a 0.39% increase in total emissions). For the next 19 passengers (PLF 0.5 -1.0), each passenger reduces per passenger emissions by 2.53% and for the last 19 passengers (PLF 1.5-2.0), each passenger reduces the per passenger emissions by 1.23%.

Average Trip Speed	Grade	PLF = 0	PLF = 0.5	PLF = 1.0	PLF = 1.45 (default)	PLF = 1.5	PLF = 2.0
6.35 mph	Grade -7.5%	(9,850; 0.086)	(9,927; 0.084)	(10,005; 0.084)	(10,022; 0.083)	(10,092; 0.083)	(10,188; 0.080)
	Grade -5.0%	(9,846; 0.078)	(10,078; 0.075)	(10,262; 0.072)	(10,359; 0.070)	(10,423; 0.071)	(10,571; 0.071)
	Grade -2.5%	(11,152; 0.071)	(11,332; 0.070)	(11,512; 0.06)	(11,575, 0.056)	(11,700; 0.056)	(11,918; 0.055)
	Grade 0%	(13,614; 0.081)	(14,054; 0.072)	(14,630; 0.056)	(14,840, 0.056)	(15,084; 0.053)	(15,496; 0.057)
	Grade +2.5 %	(16,923; 0.058)	(17,655; 0.064)	(18,366; 0.052)	(18,704, 0.039)	(19,028; 0.041)	(19,610; 0.049)
	Grade +5.0 %	(20,040; 0.054)	(20,894; 0.049)	(21,812; 0.051)	(22,257, 0.043)	(23,637; 0.039)	(23,397; 0.046)
	Grade +7.5 %	(22,757; 0.040)	(24,228; 0.054)	(25,433; 0.046)	(26,212, 0.039)	(26,805; 0.032)	(28,006; 0.037)
9.51 mph	Grade -7.5%	(7,237; 0.076)	(7,336; 0.077)	(7,427; 0.077)	(7,487; 0.075)	(7,551; 0.074)	(7,693; 0.074)
	Grade -5.0%	(7,408; 0.082)	(7,602; 0.081)	(7,775; 0.086)	(7,840; 0.083)	(7,932; 0.080)	(8,099; 0.081)
	Grade -2.5%	(8,689; 0.091)	(8,913; 0.088)	(9,185; 0.096)	(9,234, 0.093)	(9,425; 0.095)	(9,692; 0.095)
	Grade 0%	(10,929; 0.064)	(11,312; 0.080)	(11,782; 0.083)	(12,017, 0.078)	(12,263; 0.078)	(12,601; 0.071)
	Grade +2.5 %	(13,985; 0.051)	(14,846; 0.046)	(15,533; 0.057)	(15,777, 0.056)	(16,081; 0.055)	(16,583; 0.048)
	Grade +5.0 %	(16,764; 0.049)	(18,047; 0.037)	(19,005; 0.036)	(19,386, 0.041)	(19,714; 0.042)	(20,511; 0.032)
	Grade +7.5 %	(20,003; 0.036)	(21,328; 0.041)	(23,163; 0.038)	(23,875, 0.042)	(24,374; 0.038)	(25,407; 0.030)
16.29 mph	Grade -7.5%	(4,773; 0.043)	(4,823; 0.044)	(4,885; 0.039)	(4,929; 0.034)	(4,980; 0.035)	(5,093; 0.038)
	Grade -5.0%	(4,702; 0.049)	(4,840; 0.049)	(4,959; 0.048)	(5,013; 0.048)	(5,079; 0.043)	(5,208; 0.047)
	Grade -2.5%	(5,980; 0.101)	(6,147; 0.099)	(6,326; 0.106)	(6,388, 0.103)	(6,488; 0.101)	(6,711; 0.099)
	Grade 0 %	(8,254; 0.052)	(8,491; 0.075)	(8,844; 0.086)	(9,242, 0.063)	(9,192; 0.094)	(9,417; 0.098)
	Grade +2.5%	(10,879; 0.023)	(11,497; 0.041)	(12,056; 0.047)	(13,146, 0.039)	(12,505; 0.044)	(12,923; 0.024)
	Grade +5.0%	(13,265; 0.029)	(14,181; 0.013)	(15,093; 0.025)	(16,973, 0.026)	(15,701; 0.026)	(16,401; 0.022)
	Grade +7.5%	(17,659; 0.014)	(18,963; 0.025)	(20,933; 0.035)	(21,704, 0.039)	(22,182; 0.035)	(23,218; 0.012)

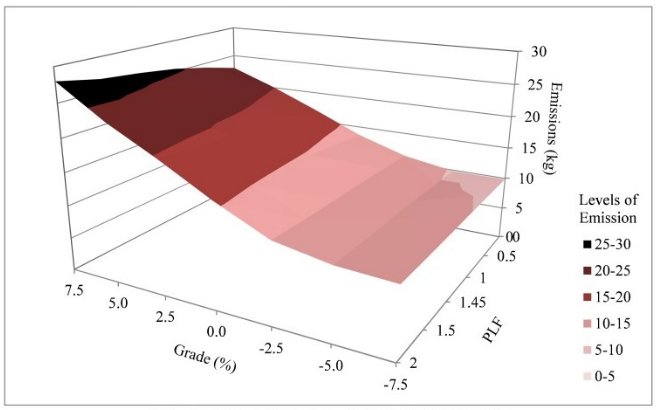
Figure 4-3. Evaluation of isolated and combined effects of speed, grade, and passenger load



A) Average network speed of 16.29 mph



B) Average network speed of 9.51 mph



C) Average network speed of 6.35 mph

Figure 4-4. Effects of road grade and passenger load on GHG emissions under different bus speeds

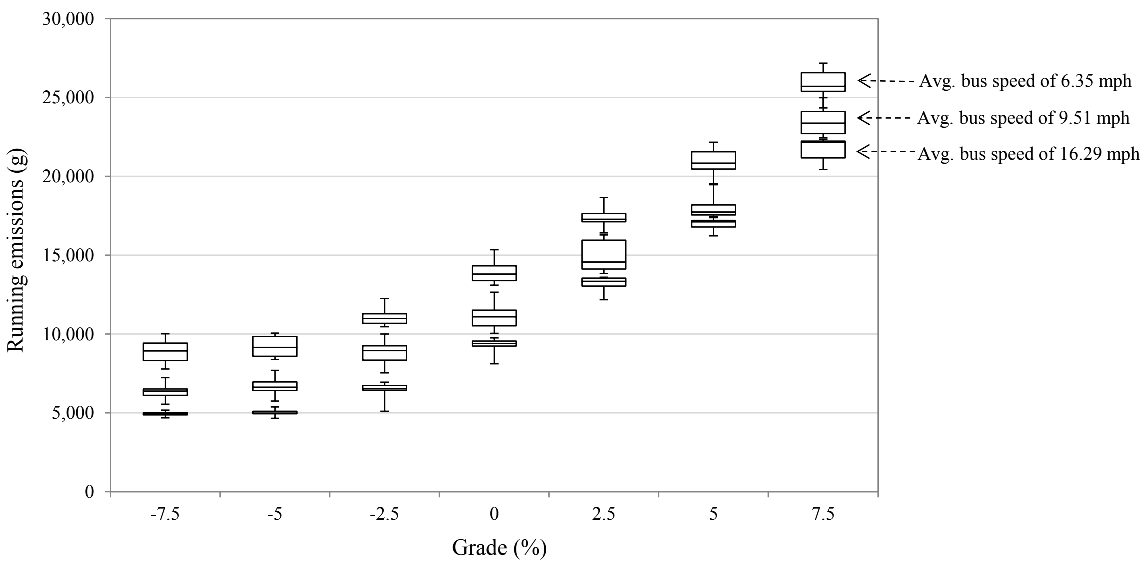
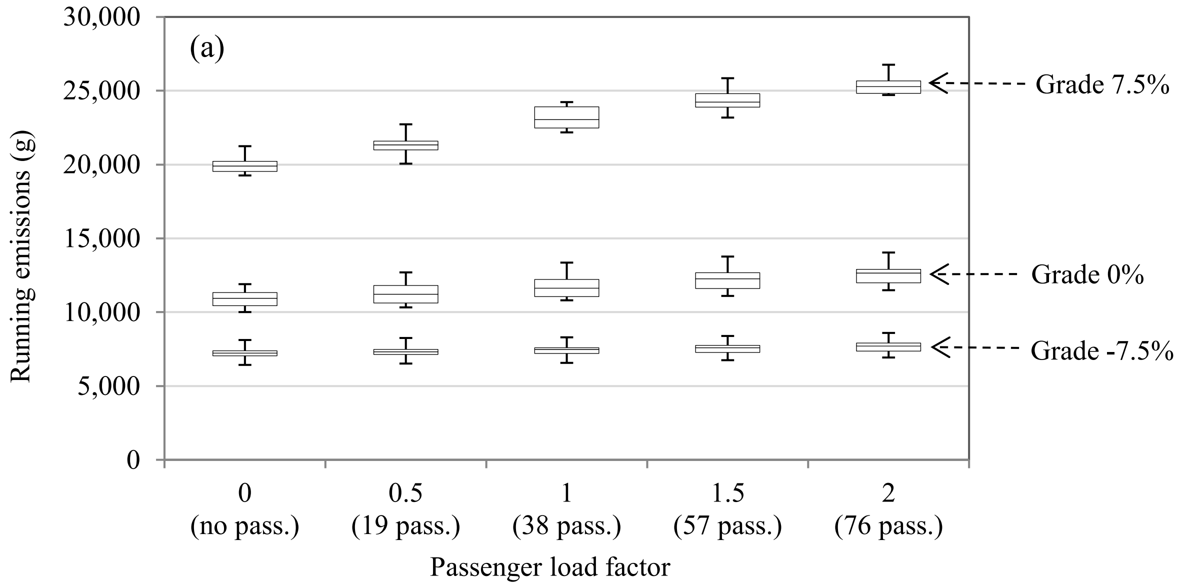
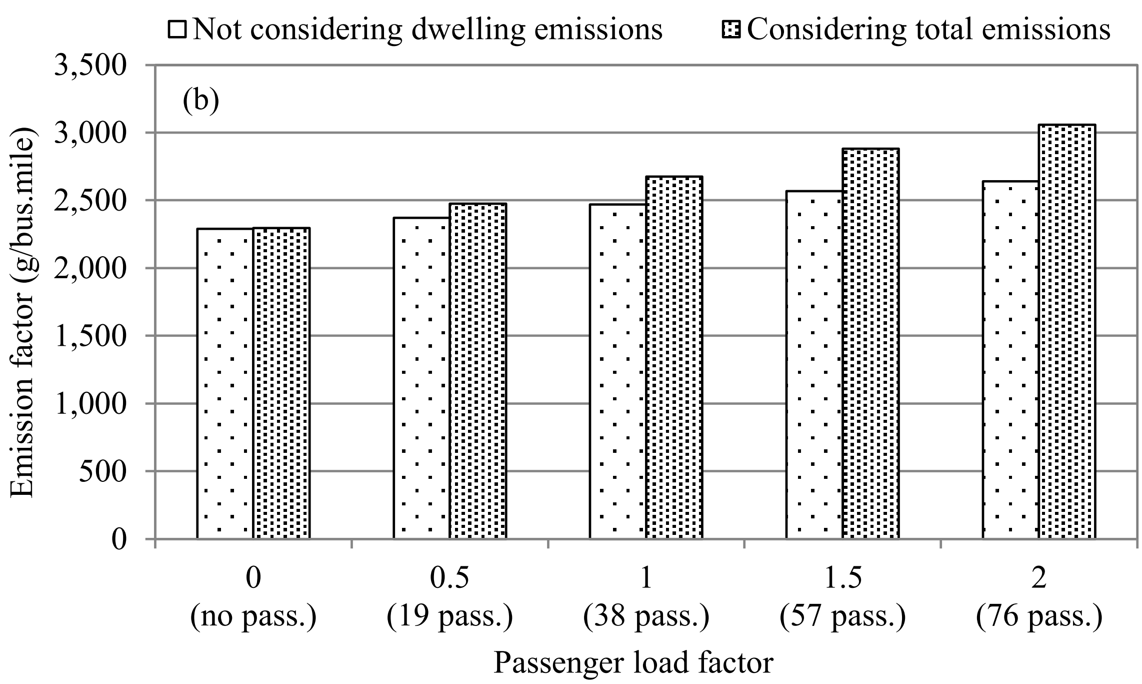


Figure 4-5. Effects of road grade on GHG emissions under different bus speeds at default PLF of 1.45



(a) Under different road grades



(a) At zero grade considering dwell emissions

Figure 4-6. Effects of passenger load on GHG emissions under base traffic with average speed of 9.51 mph

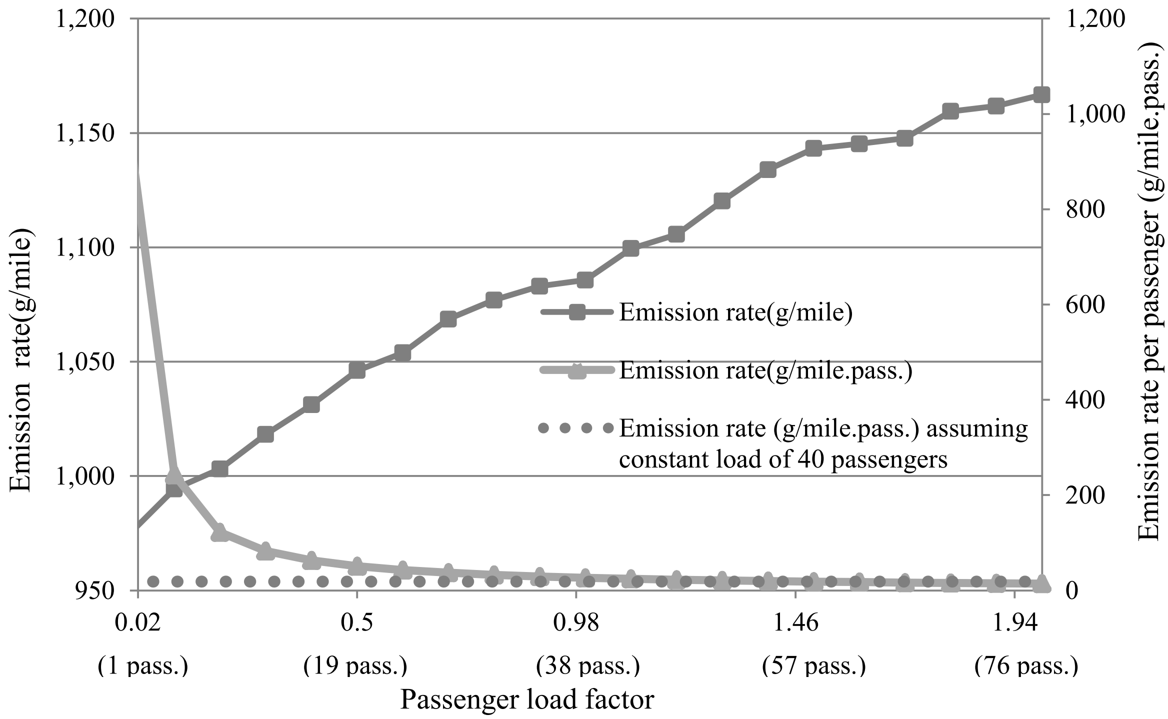


Figure 4-7. Effects of varying passenger load on total and per passenger GHG emissions at zero grade and average speed of 20 mph

4.4.3 Evaluation of combined effects in real-world transit operations

While the previous sensitivity analysis points towards the relative importance of the different variables (and combinations of variables), the motivation for this exercise is to evaluate the 'real' rather than 'structured' combinations of the different effects. We are interested in exploring whether under real-world speed, grade, and PLF combinations (as they occur along the CDN corridor), one or more variables can be disregarded without loss of accuracy in emission estimates. We therefore estimate GHG emissions along the CDN corridor under the four scenarios outlined in Section 4.3.4 while comparing ULSD (current fuel) with CNG.

Emissions were estimated in the SB and NB directions; in each direction, the total emissions normalized per bus are reported. **Figures 4-8** and **4-9** present total emissions under the four scenarios for the two fuel types in the more congested SB (**Figure 4-8**) and less congested NB (**Figure 4-9**) directions. By comparing the 'zero grade and default PLF' scenarios, it is clear that the SB bus generates higher emissions than the NB bus, the effect of neglecting grade leads to a more important underestimation in the SB direction, due to higher congestion. In each scenario, CNG produces lower emissions than ULSD with higher benefits (from switching to CNG) in the congested SB direction.

By comparing **Figures 4-8** and **4-9**, we observe that grade has a larger effect on running emissions. As the SB direction has a higher number of links with positive grades, grade effects are more observed in this direction. On the other hand, the effect of PLF on running emissions is not as large. Considering all links in the SB direction, the average PLF is close to the default MOVES PLF. In the NB direction the average PLF is lower than the default PLF which it does not lead to lower emissions when PLF is considered. This is an outcome of calculating emissions per bus over the entire route because (1) some links have higher and others have lower PLF than the default PLF, and (2) emissions do not only depend on PLF, but also on the bus operating speed.

In addition, the combined effect of grade, PLF, average speed, and fuel type were investigated in both directions. **Figure 4-10** shows the GHG reduction benefit for switching from ULSD to CNG (a positive sign indicates CNG has lower emissions while a negative sign indicates that CNG has higher emissions) as a function of network speed, grade, and passenger load. **Figure 4-10(a)** shows how the reduction benefit varies with link average speed. We observe that when the network is congested, CNG performs better than diesel. In this case, drive cycles mainly consist of 'braking' with a higher number of 'stop and go' events; emissions rates for CNG in such events are much lower than those for ULSD. **Figure 4-10(b)** shows how the grade can affect the GHG reduction benefits of CNG. We observe that at lower grades the benefits are higher and as the grade increases the benefits decrease. As CNG benefits also depend on the bus speed, the average speed was also indicated in the figure (larger size of points indicates higher average speed). We observe that for a particular grade the effect of slope is not fixed; rather it varies depending on the speed of the bus. At zero grade, the benefit is higher for congested links but at higher positive or negative grades, the reduction potential is dependent on the combination of speed and grade. This observation is in-line with the findings of the sensitivity analysis. Finally, **Figure 4-10(c)** shows that with the increase in PLF, the GHG reduction potential of CNG decreases. In fact, as the bus weight increases (due to increasing passenger load), the CNG emission rate increases faster than that of ULSD. Also for the same PLF, benefits are higher for congested links.

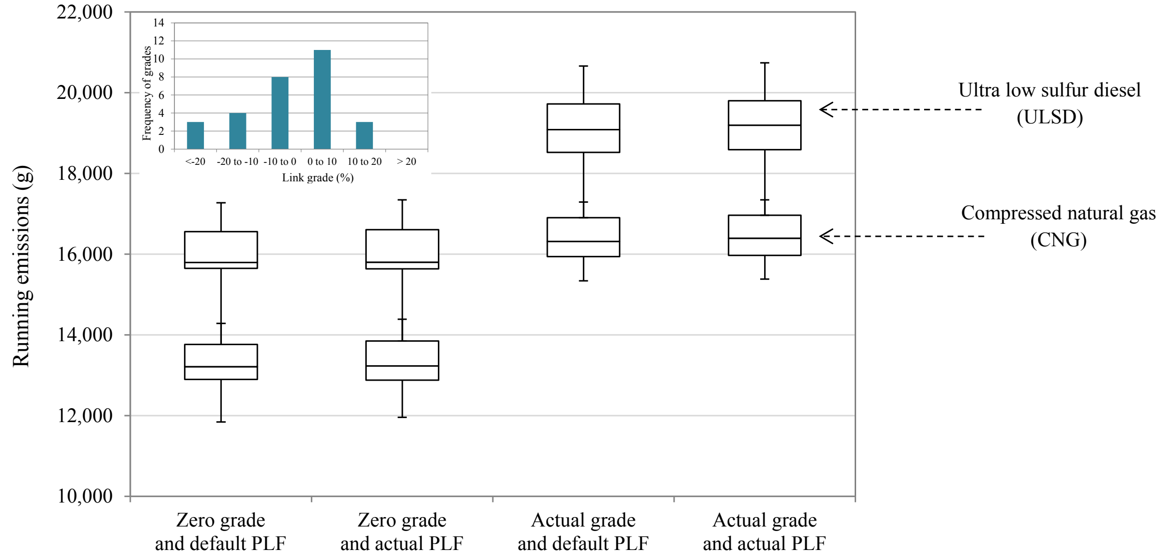


Figure 4-8. Bus GHG emissions under four scenarios in the SB direction

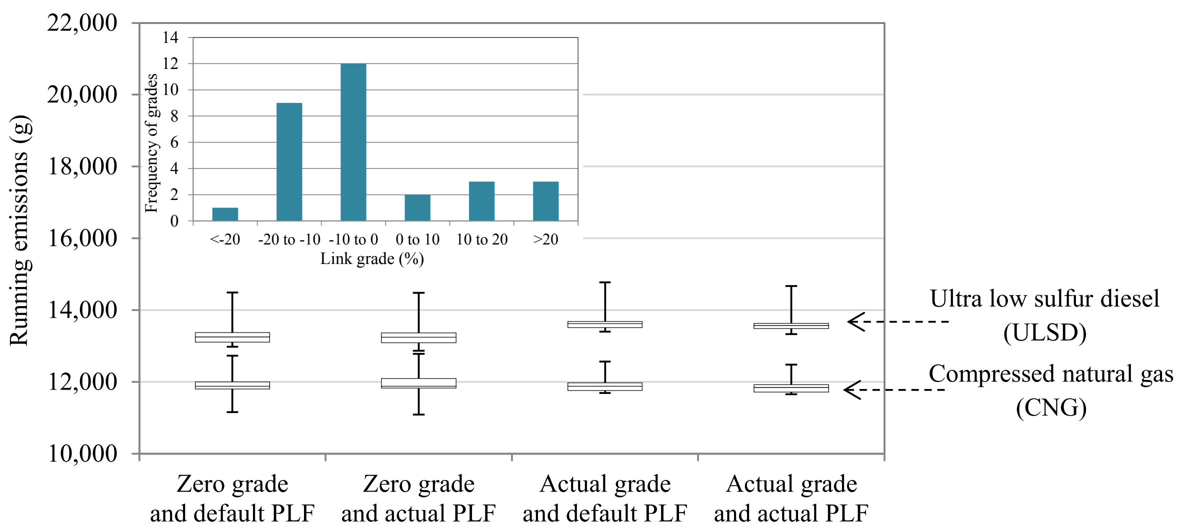
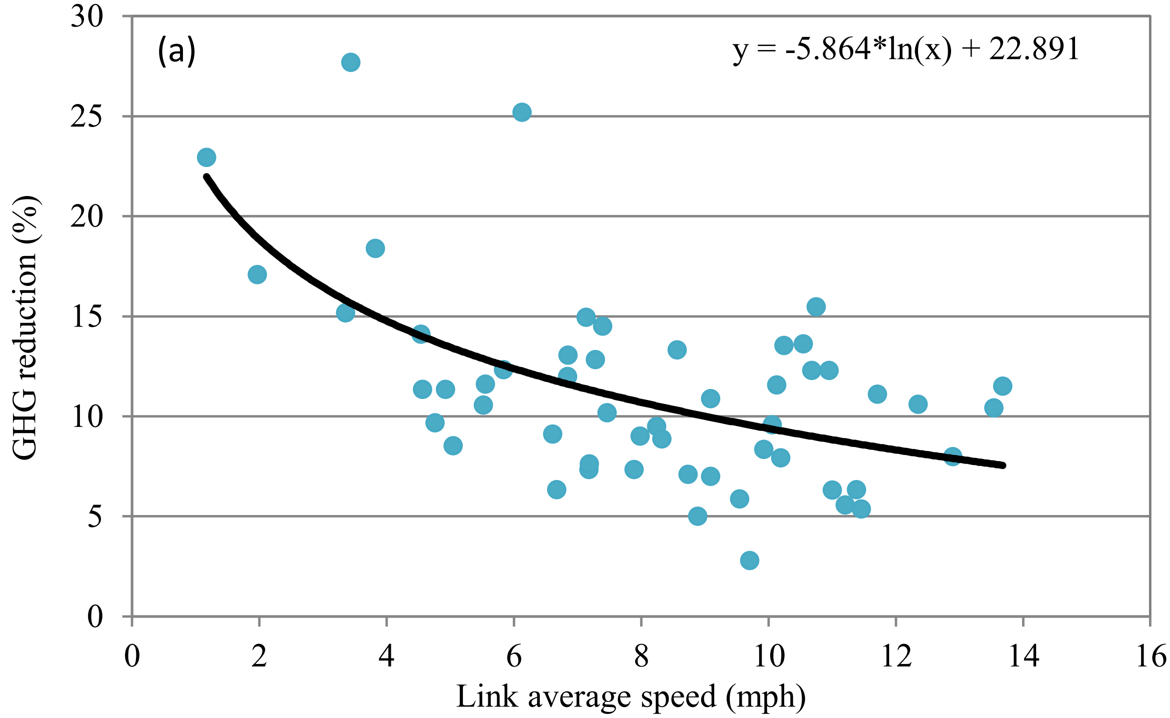
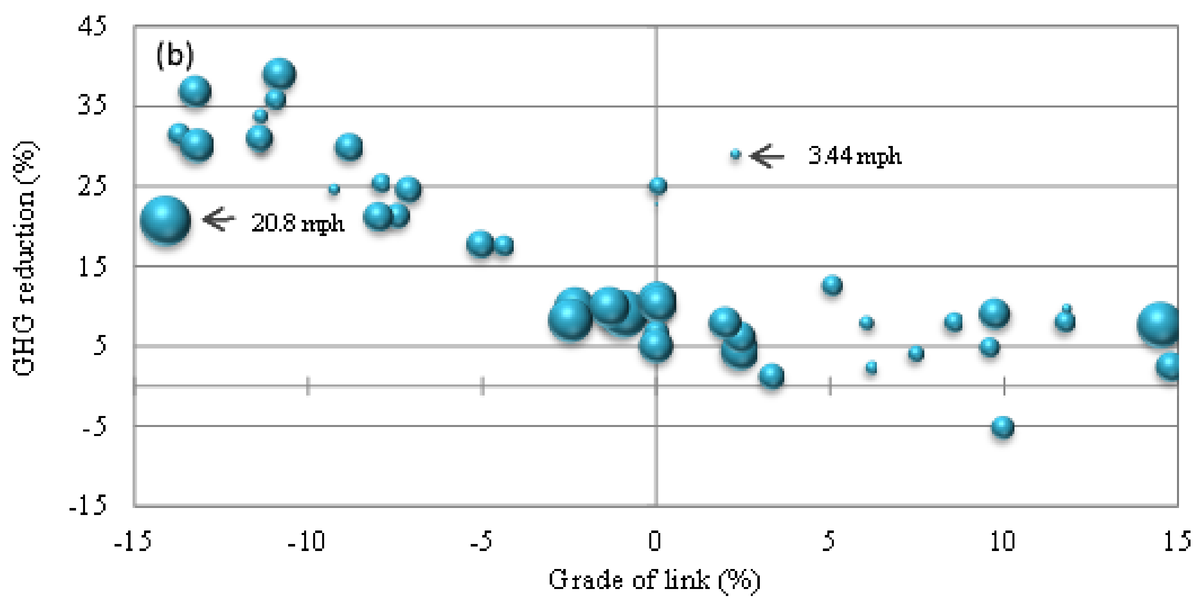


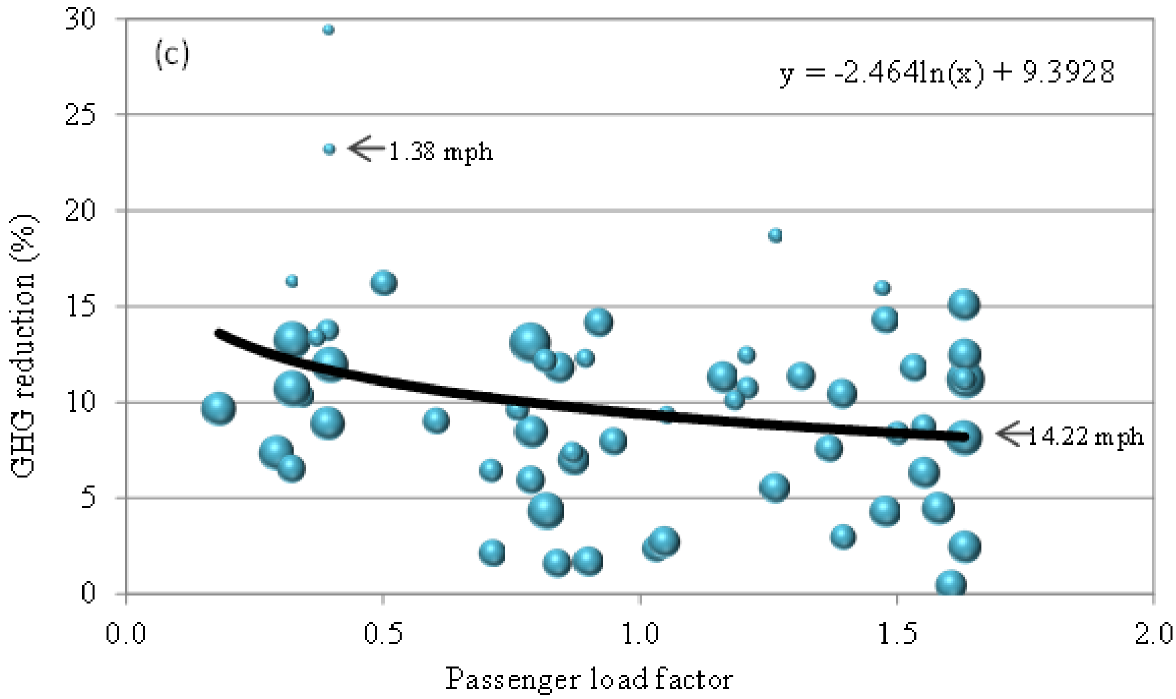
Figure 4-9. Bus GHG emissions under four scenarios in the NB direction



(a) Effect of link average speed at zero grade and PLF 1.45



(b) Effect of link grade at PLF 1.45 (size of the dot follows link average speed, larger dots indicate higher speeds)



(c) Effect of passenger load factor at zero grade (size of the dot follows link average speed, larger dots indicate higher speeds)

Figure 4-10. Effect of speed, grade, and passenger load factor on the GHG reduction potential of CNG compared to ULSD (a positive sign indicates CNG has lower emissions while a negative sign indicates that CNG has higher emissions)

4.5 Conclusion

This study investigates the isolated and combined effects of roadway grade, passenger load, network congestion level, and fuel type on transit bus emissions. First, the isolated and combined effects of the different variables were analyzed through a structured sensitivity analysis. Next, the effects of disregarding grade and PLF were assessed under realistically occurring combinations of these variables. In both exercises, the Cote-des-Neiges corridor in Montreal, Canada was chosen because it features a wide variation in traffic, grades and passenger activity across its different links. In both the sensitivity analysis and case-study, every model result represents an average of six different model runs (under six different random seeds).

Our investigation allowed us to derive a number of conclusions which are useful under two main applications: 1) when corridor-level emission estimations are conducted by transit providers in order to evaluate total and per passenger emissions, and 2) in the selection of corridors when a number of new and alternative-fuelled buses are to be deployed. Our most intuitive finding relates to the effect of speed; indeed, buses generate higher emissions in congested networks due to lower speeds, higher frequency of acceleration and deceleration events, and higher dwell times at stops. The effects of grade are different at different network speeds and positive grades have a higher effect on emissions than negative grades. Moreover, the effect of negative grade is cancelled out by the randomness in traffic patterns. The consideration of passenger load also affects bus emissions but the influence of load is not as strong as it is for grade. Load effects are more important under high positive grades and if dwell emissions are considered along with running emissions, the effect becomes larger. The consideration of passenger load is important when emissions are estimated on a per passenger basis. When the number of passengers exceeds the seating capacity of the bus, additional passengers no longer contribute noticeably reducing per passenger emissions. In comparing CNG and ULSD, we observe that the benefit of using CNG increases with an increase in network level congestion. Also, the CNG benefit decreases with an increase in grade and passenger load.

5 CHAPTER 5: REDUCING TRANSIT BUS EMISSIONS: ALTERNATIVE FUELS OR TRAFFIC OPERATIONS?

5.1 Chapter Overview

In this study, we simulated the operations and GHG emissions of transit buses along a busy corridor and quantified the effects of two different fuels (conventional diesel and compressed natural gas) as well as a set of driving conditions on emissions. Results indicate that CNG reduces GHG emissions by 8-12% compared to conventional diesel, this reduction could increase to 16% with high levels of traffic congestion. However, the benefits of switching from conventional diesel to CNG are less apparent when the road network is uncongested. We also investigated the effects of bus operations on emissions by applying several strategies such as TSP, queue jumper lanes, and relocation of bus stops. Results show that in congested conditions, TSP alone can reduce GHG emissions by 14% and when combined with improved technology; a reduction of 23% is achieved. The reduction benefits are even more apparent when other transit operational improvements are combined with TSP. Finally a sensitivity analysis was performed to investigate the effect of operational improvements on emissions under varying levels of network congestion. We observe that under “extreme congestion”, the benefits of TSP decrease.

5.2 Introduction

This study aims to quantify transit bus emissions under varying traffic operations as well as explore the effect of alternative technology. It evaluates whether significant emission reductions can be achieved through operational improvements alone as well as the potential of alternative technology under varying traffic conditions. Our research is set in Montreal, Canada where bus operations along a busy transit corridor are simulated in the NB and SB directions. Instantaneous bus speed profiles are then used to simulate emissions using USEPA’s MOVES fit with local input data describing the vehicle fleet and ambient conditions (US Environmental Protection Agency 2010). We evaluate the effects of several transit improvement scenarios including TSP, bus stop relocation, and queue jumper lane. We also simulate emissions for two different fuels: conventional diesel (currently used) as well as CNG. Finally, the combination of different fuels and transit operating conditions are compared and evaluated under various congestion levels. Emissions are estimated for GHG (in $CO_{2\text{-eq}}$) and fine particulate matter ($PM_{2.5}$).

5.3 Description of the Study Corridor

The study corridor is called the Cote-des-Neiges (CDN) corridor situated in the Cote-des-Neiges/Notre-Dame-de-Grace and Ville-Marie boroughs in Montreal. It runs North-South with respect to the downtown (located south of the corridor). The length of the corridor is about 3.4 miles (5.1 km) with various grades ranging from -17% to +8%. The corridor has a high frequency of buses (4-5 minutes) during peak periods compared to other routes and it has one of the highest transit riderships in Montreal making it a candidate for infrastructure or operational improvements by the transit operator. It has significant differences in traffic flow between the NB and SB directions as well as between morning and afternoon peak periods. As such, the high passenger ridership, frequent bus service, and distinct directional traffic flow make it an ideal corridor for scenario analysis using a traffic simulation model. Moreover, our study corridor has a total of 64 links with different levels of traffic congestion and grade. Combining both directions, we observe a significant variability in link congestion levels with average speeds ranging between 1.11 mph and 17.74 mph.

Three buses operate along the corridor (1) route 165 that runs during the day, (2) route 369 that follows a night schedule and (3) route 435 that operates only during peak periods on weekdays. In 2009, route 435 was the third most heavily used bus route with an average weekday ridership of 33,425 (Société de transport de Montréal 2009). The purpose of route 435 is to supplement route 165 during peak periods in order to provide sufficient service along the corridor. Both bus routes run concurrently; however, route 435 buses replace the majority of route 165 buses during peak periods. Eleven other bus routes cross through the corridor.

This study examines the operations and exhaust emissions of the buses that serve route 435/165. Along the route there are 31 bus stops in the NB direction and 35 stops in the SB direction. The current bus fleet runs on conventional diesel with low sulfur content. Recently, articulated buses were introduced to increase passenger capacity. At present, 80% of the 435/165 buses are articulated and the remaining are standard buses (Société de Transport de Montréal 2011). In this specific study, we have estimated the emissions of regular buses only since our main focus is on quantifying the impacts of alternative fuels and transit service improvements rather than comparing emissions between different bus types.

5.4 Materials and Methods

The study methodology is divided into four steps: 1) Traffic simulation, 2) Validation of traffic simulation output, 3) Emission modeling, and 4) Scenario analysis. Base case transit emissions are estimated using an instantaneous-speed approach and compared with emissions obtained under one technology scenario (CNG) and a set of operational scenarios (including TSP, queue jumper lanes, bus stop location). We also evaluate the effect of congestion level on strategy performance.

5.4.1 Traffic simulation

Traffic models entail a representation of the transportation system including road network, vehicles, traffic signals and pedestrians (Pursula 1999). These models are capable of representing vehicle interactions, turning behavior and impacts of traffic on the network; but the level of detail depends on the scale of analysis. Macro-scale models usually cover large networks and consider traffic flow as a continuous entity employing hydrodynamic and gas kinetics theory frameworks of analysis (Helbing et al. 2009). Mesoscopic models consider aggregated sets of vehicles employing speed-density relationships coupled with queuing theory concepts. On the other hand, micro-scale models simulate individual vehicles at a fine resolution considering second-by-second speeds, accelerations, lane-changing behaviors, and yielding decisions (Burghout et al. 2005; Burghout and Wahlstedt 2007).

Microsimulation of bus transit flow along the CDN corridor was conducted for the morning peak period (7-9 AM) using the PTV VISSIM platform (version 5.40). All major and minor crossing streets (51 in total) are also included in the simulation. The network consists of 454 links, 70 signal controllers, and 239 routing decisions. Traffic volumes were collected at three instances over three weeks during the spring 2011. All signals are currently fixed along the corridor, signal timings were collected for every signalized intersection. Turning movements (left, through and right turn) at each intersection were observed for 10 minutes and the proportion of directional traffic was calculated. This process was also repeated over three days. Road geometry information such as number of lanes, slope, and parking lots were collected from various sources including orthophotos and AutoCAD maps and validated in the field in order to best represent the road configuration of the CDN corridor. Finally, the bus schedule for route 435/165 in the morning peak period and passenger information at each stop (boarding and alighting) were obtained from the local transit operator STM. This information was validated by on-board GPS data collection in the morning peak period (conducted over one week in the Spring 2011). The numbers of hourly boarding passengers and percentage of alighting passengers at each bus stop were input in order to replicate dwell times per stop. The simulated network is presented in **Figure 5-1**.

Figure 5-1. The network in the traffic simulation model (links are shown in grey, signal heads in red, bus stops in green, and southbound bus route in yellow)

5.4.2 Validation of traffic simulation model output

Instantaneous speed profiles of buses running along the 435/165 route obtained from the VISSIM model were validated using on-board GPS data collection of a sample of buses in the morning peak period both in the NB and SB directions. Several GPS-based and simulation-based bus speed profiles were collected and compared to take into account the variability in drive-cycles. This data collection campaign lasted for one week in the Spring of 2011. The validation was performed by comparing *opmode* distributions. The reason behind choosing *opmode* distribution is because MOVES estimates second-by-second emissions based on the *opmode* of each second. This means that even if two drive-cycles are not exactly identical, they may lead to the same amount of emissions if they have similar *opmode* distributions. This no longer imposes on the traffic simulation model to exactly mimic second-by-second conditions but rather to follow similar *opmodes*.

Each *opmode* is associated with an emission rate (gm/hr) as a function of a number of variables (e.g. vehicle type, model year, meteorology, fuel). Using the corresponding rate, the emissions for that particular second are estimated. In MOVES, an *opmode* is determined by following a combination of speed and VSP for each second. The VSP represents the tractive power exerted by a vehicle to move itself and its passengers. It is a function of instantaneous speed, acceleration, vehicle weight, and road grade as shown in equation (1) (US Environment Protection Agency 2010). Roughly, a low *opmode* indicates a low speed and a low VSP while a high *opmode* indicates a high speed and VSP.

$$\mathrm{VSP} = \left(\frac{A}{M}\right) * v + \left(\frac{B}{M}\right) * v^2 + \left(\frac{C}{M}\right) * v^3 + (a + g\mathrm{Sin}\theta) * v \quad \ldots\ldots (1)$$

$$A = (\text{bus weight in metric ton}) * 0.0643$$

$$B = 0$$

$$C = (\text{bus weight in metric ton}) * \left(\frac{3.22}{\text{bus weight in kg}} + 5.06 * 10^{-5}\right)$$

where A, B, and C are the rolling, rotating, and drag road load coefficients respectively in the units of (kiloWatt second)/(meter), (kilowatt second^2)/(meter^2), and (kiloWatt second^3)/(meter^3), respectively. The denominator term, 'M', is the fixed mass factor (for transit M=17.1 metric tons), 'g' is the acceleration due to gravity (9.8 meter/ second^2), 'v' is the vehicle speed in meter/second, ‘a’ is the vehicle acceleration in meter/second^2, and Sinθ is the (fractional) road grade.

Based on the collected on-board GPS data the VSP was calculated (outside of MOVES). In a second step, the amount of time buses spend in each *opmode* over the entire route was calculated. Then, a cumulative *opmode* distribution was developed over the entire route. This cumulative distribution function was compared with the cumulative distribution function obtained with simulated buses in VISSIM; also derived in the same way.

5.4.3 Emission modeling

Emissions generated during bus operations were estimated using MOVES2010a that can estimate emissions at macro and meso scale using average speeds, and micro-scale using instantaneous speeds. Our study focuses on evaluating bus transit emissions along a busy corridor; it is therefore crucial to use instantaneous bus speeds and simulate sec-by-sec emissions along the corridor in order to fully capture the effect of changes in operational speeds due to TSP or other strategies. We used MOVES2010a here because it had a faster runtime, the results would not have changed if we had used MOVES2014 since we only used MOVES to estimate second by second emissions.

In order to simulate emissions, MOVES requires instantaneous speeds for each segment along the route. Therefore the speed profiles of all buses running in the morning peak period were allocated to individual segments corresponding to the individual links in the traffic simulation (defined from one bus stop to another). This also allowed us to capture the effect of grade by inputting the grade of each link as an attribute. In the NB direction, 30 links (corresponding to 31 bus stops) were defined while in the SB direction, 34 links were defined. Following the definition of each link, bus speed profiles simulated in VISSIM were disaggregated per link.

In addition to link information, MOVES also requires the following inputs: bus age distribution, fuel formulation, and meteorological data. The age distribution of the buses operating on the 435/165 route were obtained from the STM. Currently, buses of model years 2009 and 2010 are operated along the corridor. Among those, 58.39% are of model year 2010 and 41.61% are of 2009. Current buses run on ULSD with a sulfur content of 15ppm. Meteorological data were input in the form of hourly temperature (°F) and relative humidity (%), collected from a nearby weather station (less than 1 km away from the corridor).

The MOVES model was used to estimate the total amount of GHG (in $CO_{2\text{-eq}}$) and $PM_{2.5}$ on a segment level along the entire route (using all the buses that run along the corridor in the morning peak period). Emissions were estimated separately for the NB and SB directions (as they exhibit different traffic flow characteristics) as well as for both running and idling. Results are presented on a link and bus basis as well as on a route and bus basis. Two measures of emissions were estimated: Total emissions (g/bus) as well as emissions per vehicle mile (g/bus.mile).

5.4.4 Scenario analysis

Following the base case traffic and emission simulations, one technology scenario was simulated. It entails the replacement of the current ULSD with CNG. The adopted CNG formulation includes: specific energy of 45 MJ/kg, carbon content coefficient of 0.0161 KgC/MMBtu, zero values for sulfur, ethanol, aromatic, olefin and benzene content.

In addition, five different operational scenarios were implemented in VISSIM and emissions were simulated under each case. In each scenario, we compared emissions for ULSD and for CNG in order to identify the additional impact of an alternative technology under various bus operations. The operational scenarios are described herein.

Scenario 1 – TSP: TSP was implemented in VISSIM using ring barrier controller (RBC) signal control system. To detect transit vehicles, two types of detectors were applied. The first type of detector called *check-in detector*, detects the arriving bus and sends a signal to the controller. For near-side detectors, the detectors were placed on the bus stop with 'departure signal' functionality that sends a request to the signal controller based on the pre-calculated required dwell time at the stop. The required dwell time at the stop is calculated based on the passenger alighting and boarding information of that particular bus stop. Based on the information, the signal controller turns the signal green so that the bus can proceed forward without experiencing extra idling at the bus stop. The second type of detector called *check-out* *detector* was placed immediately downstream of the stop line at the intersection. The *Check-in detector* initiates the TSP action until the bus passes the *check-out detector* which indicates the end of the TSP event. Each TSP event is applied using two strategies: (1) *green extension* and (2) *early green*. The former extends the green phase so that the bus can pass through the intersection. When a bus passes the *check-in detector,* it sends a request to the signal controller and the controller calculates whether the current remaining green time is adequate for the bus to pass the intersection or not. If not, then the amount of *green extension* (15 seconds) is added to the current green phase. After the *green extension*, if the bus still cannot cross an intersection, the TSP request remains active and it initiates an *early green* strategy. This strategy shortens the length of green for the non-priority phase (i.e. truncate the red phase of the priority phase) to the minimum green time. The minimum green time for the non-priority phases was set at 50% of their initial fixed green time.

Scenario 2 - relocation of bus-stops without TSP: It is well known that vehicles emit higher pollutants and experience more engine damage while idling compared to running (Idle Free BC 2013; Office of Transportation and Air Quality 2008; US Federal Highway Administration 2011). Due to the prevalence of near-side bus stops in the study area, passengers have to wait at intersections and are potentially exposed to higher air pollutant concentrations. Therefore, in this scenario the bus stops are moved to mid-block. As most of the intersections are closely spaced, moving bus-stops from intersection to mid-block would not significantly increase walking distance for the transit passengers. It should be noted that relocating bus stops to mid-block has concern with passenger's safety depending on the situation.

Scenario 3 - relocation of bus-stop with TSP: Near-side bus stops were relocated to mid-block and TSP was applied at each signalized intersection.

Scenario 4 - queue jumper lane without TSP: As queue jumper lanes can ensure smooth traffic flow at the intersection, they could reduce overall emissions as well. In this scenario, queue jumper lanes were introduced at each intersection without relocating bus-stops.

Scenario 5 - queue jumper lane, relocation of bus-stop and TSP strategy: This scenario combines all the previous improvements under one scenario. Near-side bus stops are moved to mid-block and queue jumper lanes are introduced with TSP. A transit specific signal-phase is installed on the jumper lane so that at the start of the green phase, the transit vehicle can move before other vehicles. Jumper lanes are also given priority over general traffic so that the bus can easily enter general traffic flow.

In order to capture the effect of traffic congestion on the performance of each of the five scenarios in a systematic manner, we ran the traffic and emission simulations at four different levels of traffic loading onto the network (resulting in different congestion levels) as well as the base-case traffic conditions. The results of this sensitivity analysis are presented only for the SB direction; emissions were estimated only for GHGs. In order to vary network speed while continuing to simulate bus operations, we varied traffic inputs at all boundary links according to the following conditions:

1) Base-case traffic (i.e. 100% traffic loading) with a total journey time of 3,002 seconds in the SB direction

2) 10% of the base-case traffic load with a total journey time of 1,707 seconds in the SB direction

3) 50% of the base-case traffic load with a total journey time of 1,820 seconds in the SB direction

4) 80% of the base-case traffic load with a total journey time of 1,925 seconds in the SB direction

5) 110% of the base-case traffic load with a total journey time of 3,611 seconds in the SB direction.

5.5 Results and Discussion

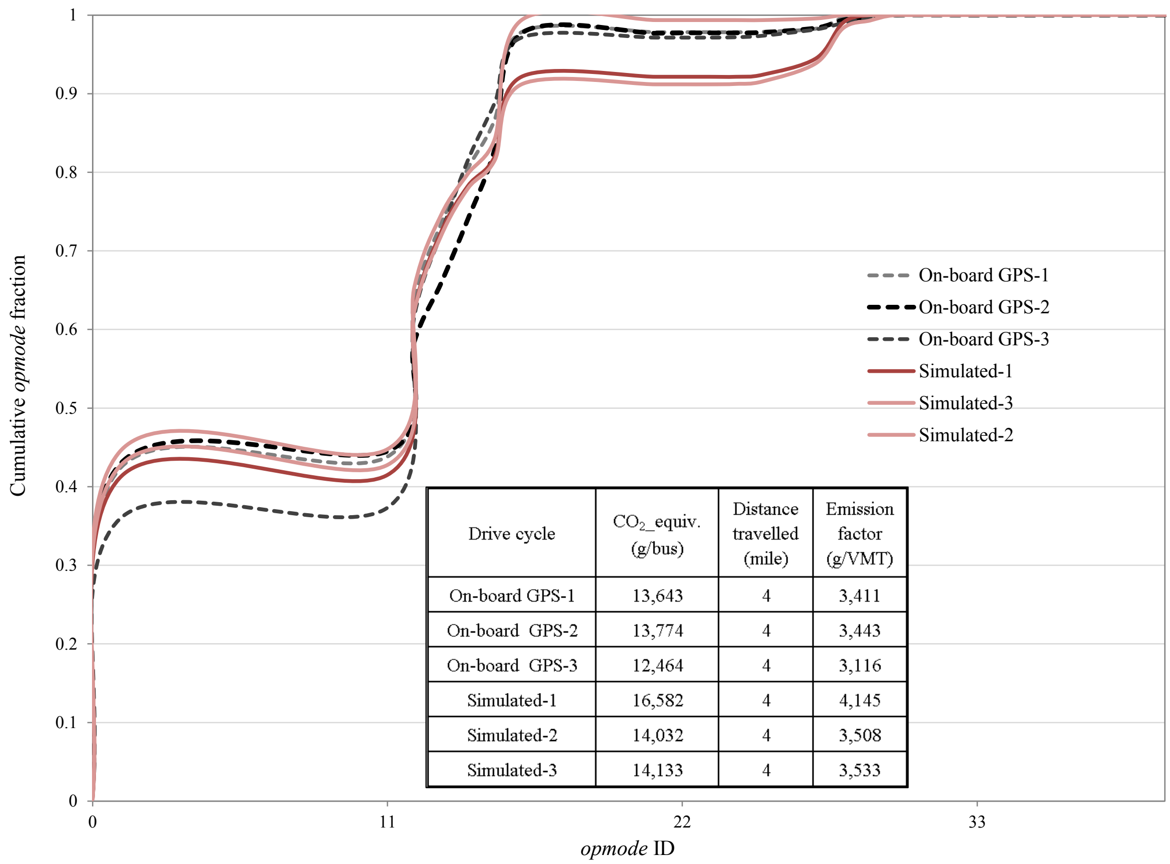
5.5.1 Characterization and validation of base-case bus speed profiles

Speed profiles for both SB and NB directions were extracted from VISSIM and analyzed. A summary of the links and base case bus speed profiles is given in **Table 5-1**. It can be seen that the SB approach (towards downtown) has longer travel times than the NB approach (away from downtown). This is expected as in the morning peak period, most commuters travel towards the downtown core. The effect of congestion can also be observed in the speed profile of the buses. Almost 50% of time the SB buses have speeds less than 1 mph, whereas in the NB direction 22.7% of the speeds are in that range.

Table 5-1. Summary of base case simulated bus speed profiles

Variables	SB	NB
Length (mile)	4.74	4.09
Number of bus stops	34	30
Length of longest link (mile)	0.3	0.3
Length of shortest link (mile)	0.0775	0.05
Travel time per bus (min)	50.03	30.10
Average journey speed per bus (mph)	5.68	8.15
Maximum speed (mph)	28.83	27.43
Average time spent per bus (sec) during journey	2,579	1,228
Between 0- 1 mph	1,296	279
Between 2-5 mph	301	147
Between 6-15 mph	517	336
Between 15-25 mph	369	437
>25 mph	96	29

Figure 5-2 illustrates the cumulative *opmode* distributions for three GPS traces and 3 VISSIM simulations under different random seeds. A strong and significant correlation is observed between measured and simulated data. Finally, emissions were estimated for each case and it was found that on average, the difference between the emission estimates based on traffic simulation and GPS data are on the order of 12%.



Drive cycle	CO_2_equiv. (g/bus)	Distance travelled (mile)	Emission factor (g/VMT)
On-board GPS-1	13,643	4	3,411
On-board GPS-2	13,774	4	3,443
On-board GPS-3	12,464	4	3,116
Simulated-1	16,582	4	4,145
Simulated-2	14,032	4	3,508
Simulated-3	14,133	4	3,533

Figure 5-2. Comparison of *opmode* distributions between simulated and GPS drive cycles (southbound direction)

5.5.2 Bus emissions under base-case operations

Using the simulated bus speed profiles, we estimated emissions under base-case operations for both fuels: ULSD and CNG. To better understand these emissions, we divided them into running emissions which do not include emissions occurring at bus stops (but do include emissions occurring during idling in traffic) and dwell emissions which include those occurring only during boarding and alighting of passengers at bus stops.

The results for running emissions (not including idling at bus stops) in each direction (NB and SB) normalized by bus and by the length of roadway are presented in **Table 5-2**. The table shows that the emissions for both $CO_{2\text{-eq.}}$ and $PM_{2.5}$ are higher in the SB approach than the NB approach which is expected since the SB approach is more congested. The results for dwell emissions (per bus) at bus stops are presented in **Table 5-3.** The table also shows that the amount of dwell emissions in the SB direction is higher than in the NB direction which is expected due to the higher number of commuters going towards downtown. To better understand the difference between NB and SB emission levels, CO_{2eq} emissions for diesel fuel were plotted on a link (in g/bus.mile) and stop (in g/bus) level in both directions. These two figures also provide a clear picture of the corridor-wide emission levels. **Figure 5-3** presents the link-by-link emissions in the NB direction while **Figure 5-4** illustrates emissions in the SB direction. Comparing the two figures, it is clear that links in the SB direction experience higher emissions than NB links. In the SB approach, buses produce significantly higher emissions as they enter the downtown area located in the lower right quadrant of the map. They also spend longer time at downtown bus stops thus generating higher dwell-time emissions.

Table 5-2. Running emissions for different fuels (g/bus.mile)

	SB			NB		
	Diesel	CNG	Reduction (%)	Diesel	CNG	Reduction (%)
$CO_{2\text{-eq.}}$	3,500	3,090	11.75	2,840	2,610	8.03
$PM_{2.5}$	0.046	0.007	84.79	0.036	0.004	88.68

Table 5-3. Dwell emissions at bus stops for different fuels (g/bus)

	SB			NB		
	Diesel	CNG	Reduction (%)	Diesel	CNG	Reduction (%)
CO_2-eq	1,720	1,360	21.00	668	528	21.00
$PM_{2.5}$	0.035	0.005	86.28	0.014	0.002	86.28

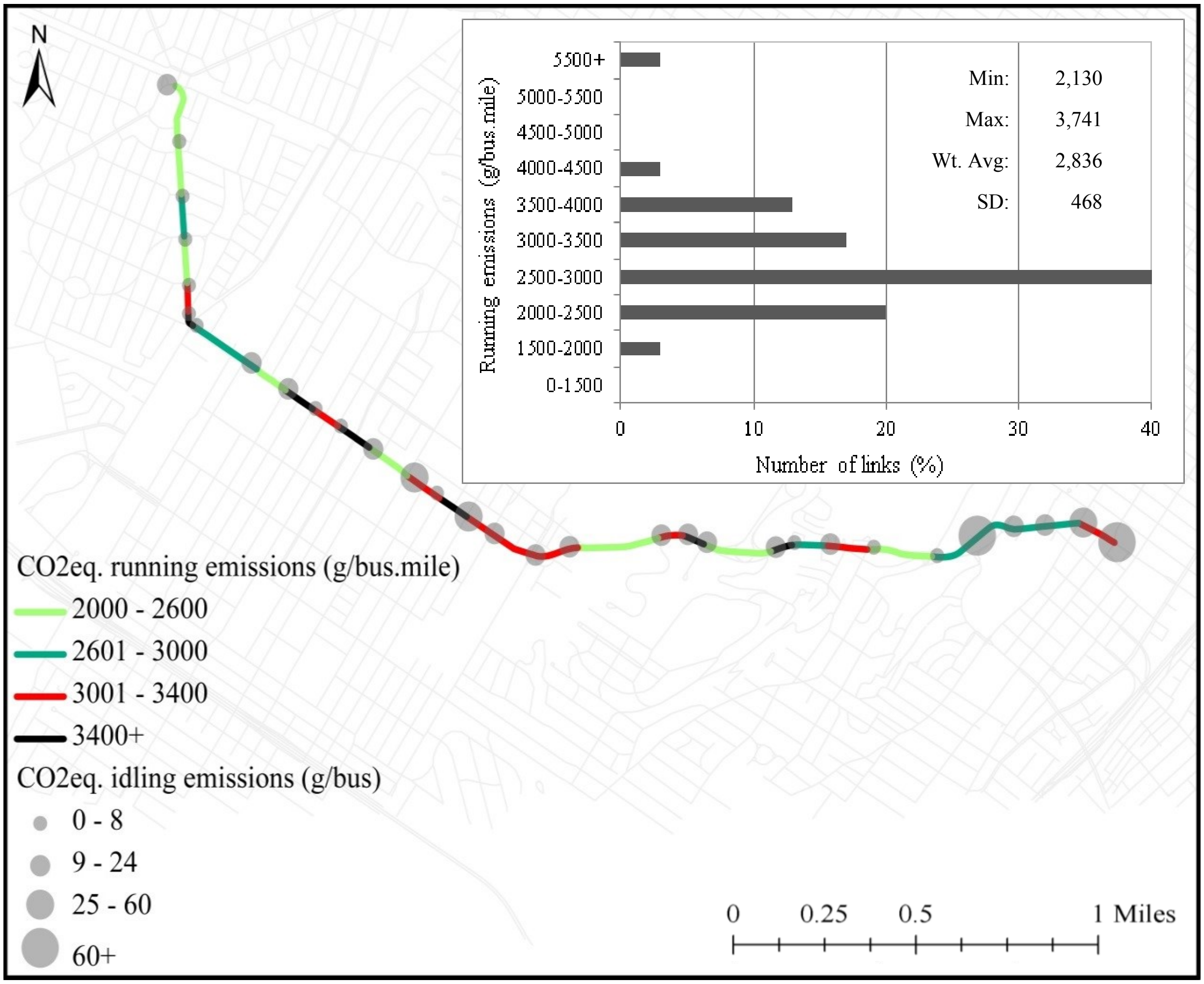


Figure 5-3. Running (g/bus.mile) and idling (g/bus) CO_2-eq emissions of NB diesel buses

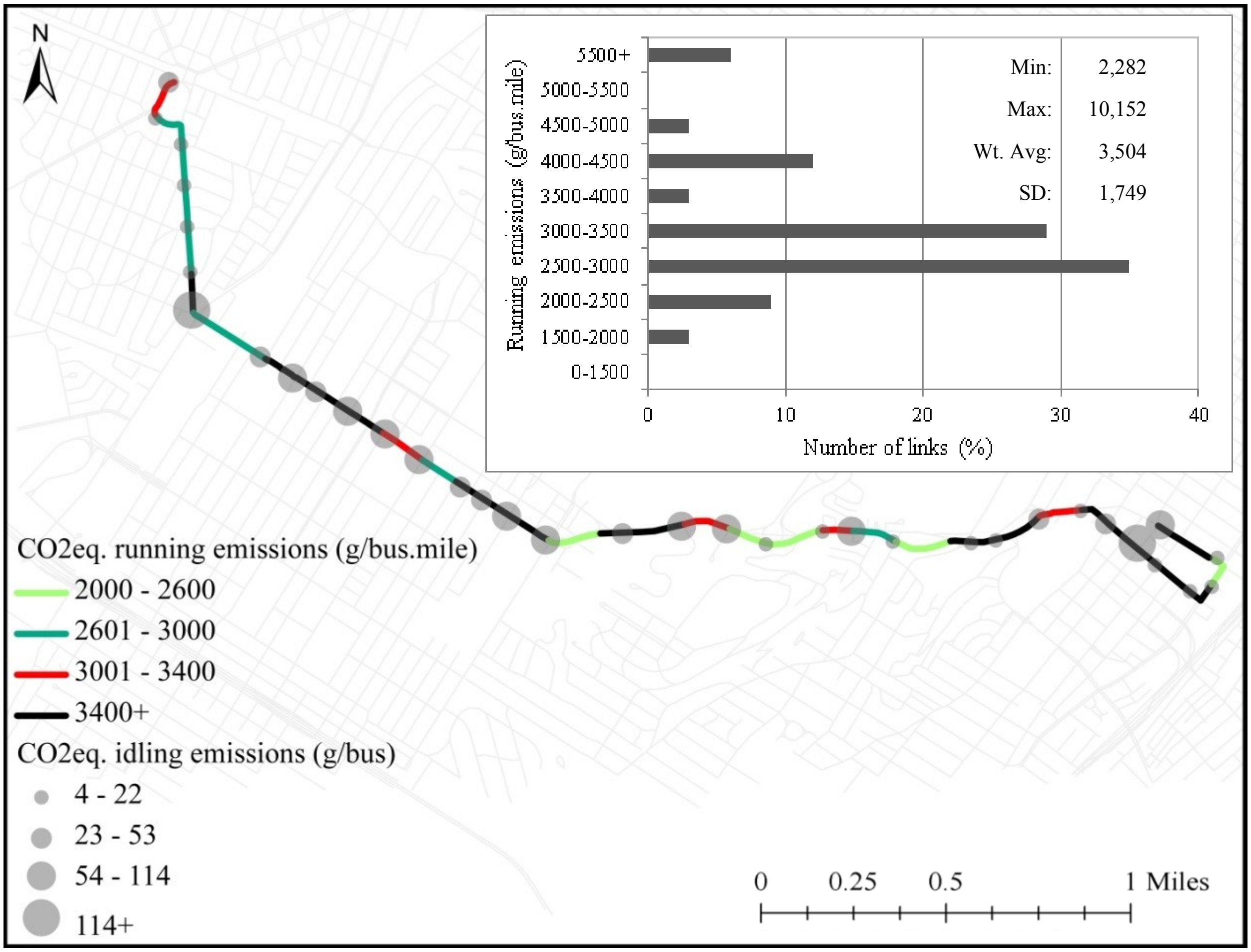
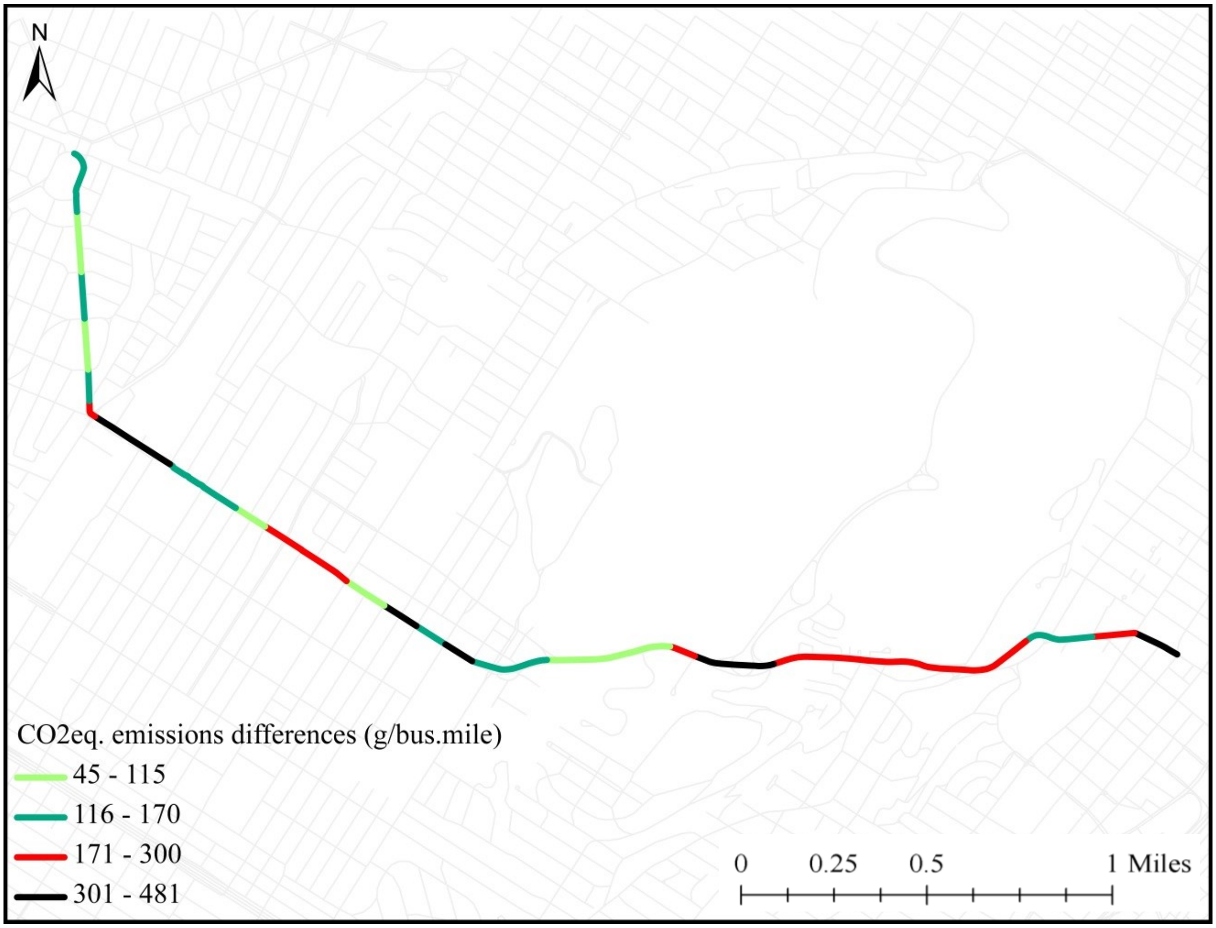


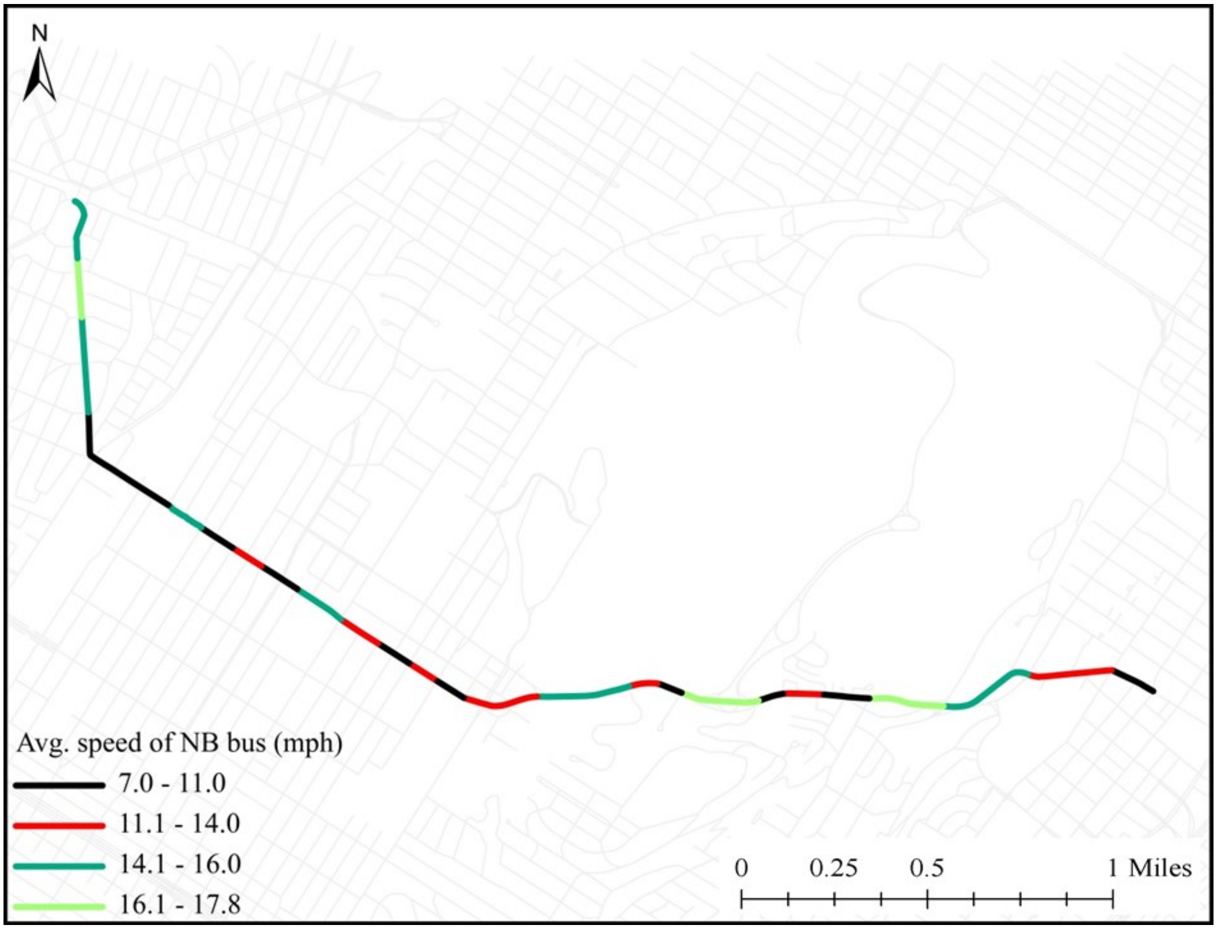
Figure 5-4. Running (g/bus.mile) and idling (g/bus) CO_2-eq emissions of SB diesel buses

Beyond the difference between NB and SB bus emissions, **Tables 5-2** and **5-3** also illustrate the emission reductions obtained when switching from the current ULSD to CNG. **Table 5-2** shows that CNG has the potential to reduce $CO_{2\text{-eq}}$ emissions by 8 to 12 percent. The reduction is higher in the more congested SB direction indicating that the benefits of switching to CNG are more significant as congestion levels rise. To better illustrate this point, we plotted the differences in emissions between diesel and CNG on a link-level in the NB direction standardized by roadway length and number of buses. **Figure 5-5(a)** illustrates link-level differences in emissions while **Figure 5-5(b)** presents the average bus speed per link in the NB direction, indicating that the difference in emissions is higher (i.e. higher reductions due to CNG) where the average travel speed is lower. **Table 5-3**, which illustrates dwell emissions also shows that CNG can reduce $CO_{2\text{-eq}}$ dwell emissions by 21% and $PM_{2.5}$ dwell emissions by 86.28%.

These idling emissions reductions are greater than the reductions observed for running emissions, again pointing to the fact that CNG outperforms diesel in congested situations.



(a) Changes in $CO_{2\text{-eq.}}$ emissions (g/bus.mile) in the NB direction



(b) Average Travel Speed of the NB Buses

Figure 5-5. The GHG reduction benefit of CNG and average speeds in the NB direction

5.5.3 Evaluating the effects of operational scenarios on emissions

The total emissions for each of the five scenarios presented in the "Scenario Analysis" section were estimated in the case of diesel and CNG under base-case traffic loading. Results for $CO_{2\text{-eq}}$ emissions are illustrated in **Table 5-4** which summarizes three variables: 1) emissions in each direction in g/bus.mile, 2) percent reduction in emissions compared to the base case scenario with diesel, and 3) travel time per bus in each direction (in minutes) excluding the contribution of dwell times at stops.

We observe that Scenario 1 that entails TSP at each intersection reduces $CO_{2\text{-eq}}$ emissions by 13.49% in the SB direction and 5.91% in the NB direction. This implies that TSP is more effective in the congested direction compared to the uncongested direction. In fact, in the SB direction, TSP alone provides higher emission reductions than switching to CNG technology (13.49% for TSP vs. 11.75% for CNG). The implementation of CNG in addition to TSP further reduces emissions to 22.66% in the SB direction and 14% in the NB direction.

In Scenario 2, relocating bus stops to mid-block reduces base-case emissions by 8.92% in the SB direction, a smaller reduction compared to TSP. However, this strategy does not lead to emission reductions in the NB direction (a slight increase of 0.47%). A similar phenomenon is observed in the case of $PM_{2.5}$. In fact, in congested situations, buses need more time to reach the bus stop. In addition, if the bus stop is upstream of the intersection and the signal is in the red phase, the bus has to wait longer at the intersection after passengers board the bus. Because of these extra stopping events, buses produce more emissions. Relocating bus stops to mid-block would eliminate the need for reaching near-side bus stops when the signal is green and offer easy maneuver to stop at the mid-block bus stop. Thus, by reducing the variation in speeds, emissions are reduced under congested directions. On the other hand, in the northbound direction, the level of congestion is lower; therefore it is easy to reach the near-side bus stop. By stopping once, the bus could serve to load passengers while waiting at the intersection. But when the bus-stop is moved to mid-block the bus needs to stop once at the intersection and another time to load passengers. This leads to additional emissions.

In Scenario 3, the relocation of bus stops in addition to TSP reduces emissions by 12.6% in the SB direction and 2.09% in the NB direction. Compared to scenario 2, the introduction of

TSP can improve the overall performance of bus stop relocation; however, TSP alone remains a more appropriate measure with higher emission reductions.

Queue jumper lanes in Scenario 4 achieve important reductions in the SB direction (14.73%) however they only achieve minimal reductions in the less congested NB direction (1.17%). As queue jumper lanes are exclusive separate lanes for transit buses near an intersection, buses can easily bypass the queue of traffic producing fewer emissions in the congested direction. But in the less congested direction, the introduction of a queue jumper lane does not add extra benefits.

Finally, in Scenario 5 the combination of TSP, queue jumper lanes and bus-stop relocation seems to achieve the highest emission reductions in the SB direction (17.61%) as all of these three strategies have the ability to reduce emissions. But in the NB direction, the combination yields smaller reductions (3.64%) because bus-stop relocation and queue jumper lanes are not very effective in this direction. All scenarios illustrate that the introduction of CNG in combination with operational changes further improves $CO_{2\text{-eq}}$ emission reductions.

Note that each of the five scenarios reduces travel time compared to the base case scenario but it is important to note that the $CO_{2\text{-eq}}$ emission reductions do not linearly follow travel times reductions. For example, Scenario 3 reduces emissions by 12.6% in the NB direction and travel time by 40.6% whereas Scenario 4 reduces emissions by 14.73% and travel time by 36.55%. This shows that travel time savings are not easily translated into emissions savings thus highlighting the importance of accounting for instantaneous speeds.

Table 5-4. Comparison of $CO_{2\text{-eq.}}$ emissions (g/bus.mile) under different operational scenarios and fuels

Scenario No.	Scenario Description	CO_{2eq} (g/bus.mile) for Diesel		CO_{2eq} (g/bus.mile) for CNG	
		SB	**NB**	**SB**	**NB**
	Base	3,500 -- (42.98min)	2,840 -- (20.47min)	3,092 (-11.75%) (42.98min)	2,610 (-8.03%) (20.47min)
1	Introduction of TSP	3,030 (-13.49%)[1]** (29.37min)[2]	2,670 (-5.91%) (18.5min)	2,709 (-22.66%) (29.37min)	2,440 (-14.00%) (18.5min)
2	Relocating bus-stops to mid-block	3,190 (-8.92%) (31.53min)	2,850 (+0.47%) (20.81min)	2,869 (-18.12%) (31.53min)	2,640 (-6.94%) (20.81min)
3	Introducing TSP and mid-block bus-stop relocation	3,060 (-12.60%)* (25.53min)	2,780 (-2.09%) (19.13min)	2,770 (-20.93%) (25.53min)	2,550 (-10.12%) (19.13min)
4	Introducing queue jumper lane	2,990 (-14.73%)** (27.27min)	2,800 (-1.17%) (19.15min)	2,692 (-23.17%) (27.27min)	2,540 (-10.33%) (19.15min)
5	Introducing TSP, queue jumper lane and relocating bus-stops to	2,890 (-17.61%) (24.46min)	2,730 (-3.64%) (18.7min)	2,654 (-24.26%) (24.46min)	2,500 (-11.70%) (18.7min)

1 Percent reduction in emissions compared to base case (positive sign indicates an increase in emissions)
2 Travel time

The effects of CNG and operational changes on $PM_{2.5}$ emissions are presented in **Table 5-5.** We observe that there are no trade-offs between CNG and operational changes in terms of $PM_{2.5}$ emission reductions as was the case for $CO_{2\text{-eq}}$. The reduction benefit for CNG is very large and ranges from 85% to 93%, whereas it ranges from 0% to 18% in the case of operational changes. The reason behind this behavior is that CNG emits very few particulates compared to diesel and hence the switch to CNG will induce reductions in particulate emissions that are by far higher than reductions obtained by any operational scenarios.

Table 5-5. Comparison of $PM_{2.5}$ emissions (g/bus.mile) under different operational scenarios and fuels

Scenario No.	Scenario Description	$PM_{2.5}$ (g/bus.mile) for Diesel		$PM_{2.5}$ (g/bus.mile) for CNG	
		SB	NB	SB	NB
	Base	0.046 -- (42.98min)	0.036 -- (20.47min)	0.007 (-84.79%) (42.98min)	0.004 (-88.68%) (20.47min)
1	Introduction of TSP	0.039 (-16%)[1] (29.37min)[2]	0.033 (-8.76%) (18.5min)	0.004 (-92.40%) (29.37min)	0.006 (-90.12%) (18.5min)
2	Relocating bus-stops to mid-block	0.042 (-9.89%) (31.53min)	0.036 0.00% (20.81min)	0.004 (-92.40%) (31.53min)	0.004 (-88.68%) (20.81min)
3	Introducing TSP and mid-block bus-stop relocation	0.039 (-16.25%) (25.53min)	0.035 (-0.73%) (19.13min)	0.004 (-92.40%) (25.53min)	0.004 (-88.68%) (19.13min)
4	Introducing queue jumper lane	0.038 (-17.56%) (27.27min)	0.035 (-1.40%) (19.15min)	0.003 (-92.48%) (27.27min)	0.004 (-88.77%) (19.15min)
5	Introducing TSP, queue jumper lane and relocating bus-stops to mid-block	0.038 (-18.36%) (24.46min)	0.035 (-2.06%) (18.7min)	0.003 (-92.69%) (24.46min)	0.004 (-88.77%) (18.7min)

1 Percent reduction in emissions compared to base case
2 Travel time

5.5.4 Investigating the effect of congestion level on operational strategies

Each of the five operational scenarios was simulated under different traffic loadings (110%, 80%, 50%, and 10%) as well as base-case traffic (100% loading) in order to investigate the effect of congestion on operational strategies. The results for the SB direction and for GHGs are presented in **Figure 5-6**.

Regarding TSP, we observe that the GHG reduction benefit increases with the increase in traffic loading. Under high traffic loading, without TSP, buses take longer to cross a signalized intersection. But as the traffic loading reaches 110%, the benefit of TSP decreases. Indeed, when the network is highly congested (this happens at 110% traffic loading), the calculated travel time by the TSP controller is very far from the actual travel time, and hence the benefit of TSP decreases (but a reduction is still observed compared to the no-TSP scenario).

With queue jumper lanes, the reduction in emissions increases with increasing traffic loading, and becomes highest at 110% loading. Since queue jumper lanes are exclusive separate lanes for transit buses near an intersection, buses can easily bypass the congestion producing lower emissions under high traffic loading.

We observe with bus stop relocation to mid-block that bus emissions slightly increase with lower traffic loading and then start to decrease with increasing traffic loading. We already mentioned that in congested situations, buses need more time to reach the bus stop. In addition, if the bus stop is upstream of the intersection and the signal is in the red phase, the bus has to wait longer at the intersection after passengers board the bus. Relocating bus stops to mid-block would eliminate the need for reaching near-side bus stops when the signal is green and offer easy maneuver to stop at the mid-block bus stop. In uncongested conditions, mid-block bus stops cause buses to stop twice (at the intersection and at the stop) hence increasing emissions.

Together, queue jumper lanes and bus stop relocation are more effective in congested conditions. We have verified that by looking at the bus speed cycle and found that when the network is at low traffic loading, the total travel time does not change much whereas significant travel time reductions are observed at high loading conditions. On the other hand, TSP is effective for both congested and uncongested networks. When TSP is combined with other measures such as bus stop relocation and queue jumper lanes, the reduction benefits are small in uncongested conditions because other strategies are not very effective in these situations.

When comparing the effect of CNG in the base-case scenario with emission reductions under all other scenarios with diesel fuel, it is interesting to note that CNG is always more beneficial in uncongested conditions compared to operational improvements. On the other hand, in congested situations (100% and 110% loading) individual operational strategies achieve better GHG reductions than switching to CNG and maintaining base-case operations.

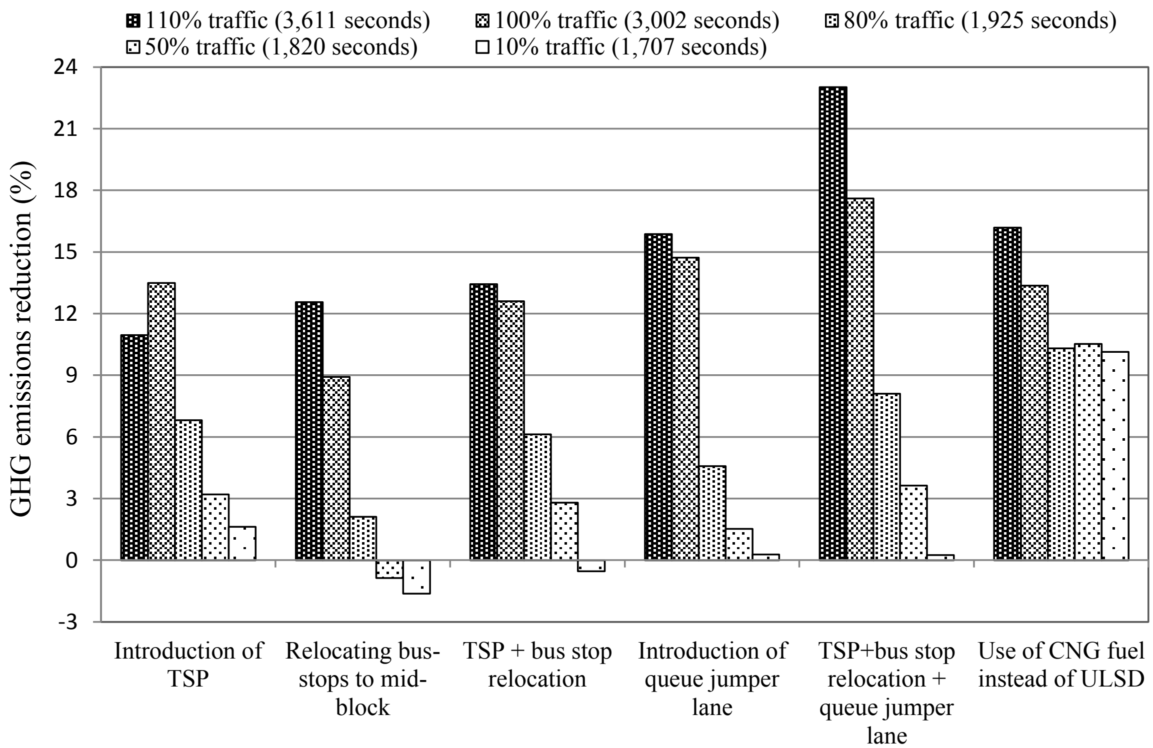


Figure 5-6. Effect of congestion level on reductions in GHG emissions (compared to base-case operations with diesel fuel) under different operational scenarios

5.6 Conclusion

Our study aimed to quantify transit bus emissions under varying traffic operations as well as to explore the effect of an alternative technology. We evaluated whether significant emission reductions could be achieved through operational improvements alone as well as the potential of alternative technology under varying traffic conditions. Using five operational scenarios (including a combination of TSP, queue jumper lanes, and bus stop relocation) and one alternative technology (CNG), we simulated the operations and emissions of buses along a busy transit corridor in Montreal, Quebec. The chosen corridor presents an interesting case-study since it exhibits different traffic volumes and drive-cycles in the two directions in the morning peak period: a busy SB direction going towards the downtown core and a less congested NB direction going away from downtown.

The results show that switching from diesel to CNG under current bus operations reduces emissions of $CO_{2\text{-eq.}}$ by 8% in the less congested NB direction and by 12% in the congested SB direction. As congestion levels rise, the benefit of switching to CNG becomes more apparent. The GHG reduction benefits of all operational improvements also increase with increasing congestion. When the network is less congested, queue jumper lanes and bus-stop relocation are not significant. On the other hand, TSP alone has the ability to reduce emissions significantly for both conditions, congested and uncongested. All scenarios illustrate that the introduction of CNG in combination with operational changes further improves emission reductions. However, in the case high congestion, operational changes such as TSP and queue jumper lanes can achieve better GHG reductions than switching to CNG and maintaining base-case operations. This indicates that lowering transit bus GHG emissions in a busy corridor does not necessarily entail switching to an alternative fuel as lower-cost alternatives such as TSP can be equally or even more successful. On the other hand, the $PM_{2.5}$ reduction benefit for CNG is very large and ranges from 85% to 93%, whereas it ranges from 0% to 18% in the case of operational changes. Hence, the emission reduction strategy selection depends on the type of pollutants, corridor characteristics, congestion level, and available budget. These results could be useful to transit planners in the selection of appropriate GHG reduction strategies as well as in the selection of corridors when a number of new and alternative-fuelled buses are to be deployed.

6 CHAPTER 6: A SIMULATION OF TRANSIT BUS EMISSIONS ALONG AN URBAN CORRIDOR: EVALUATING CHANGES UNDER VARIOUS SERVICE IMPROVEMENT STRATEGIES

6.1 Chapter Overview

This study investigates the impacts of transit improvement strategies on bus emissions along a busy corridor in Montreal, Canada. The local transit provider, Société de Transport de Montréal, has implemented a number of strategies which include the use of smart cards, limited-stop (express bus) service, and reserved bus lanes along this corridor. Using data collected on-board for instantaneous speeds and stop-level ridership, we estimated bus emissions of greenhouse gases and other pollutants at three levels: road segment, bus-stop, and per passenger. A regression of segment-level emissions against a number of explanatory variables reveals that reserved bus lanes and express bus service reduce emissions significantly. On the other hand, smart card use reduces idling emissions compared to other fare payment methods. Our findings are of most relevance for transit planners who are seeking to implement different strategies to reduce emissions and improve transit performance.

6.2 Introduction

Worldwide concerns for rising GHG emissions in metropolitan areas are often at the forefront of political campaigns and public debates. The transportation sector is one of the largest contributors with about 23% of GHG emissions (Li et al. 2010). In large metropolitan areas, public transit is considered as an alternative to the private vehicle with a significantly lower carbon footprint. Transit agencies are adopting several improvement strategies to enhance the service and increase its competitiveness. The most widely adopted strategies include implementation of limited-stop (express bus) service, reserved bus lanes, smart cards, queue jumper lanes, and high capacity articulated buses. Several studies have found that express bus service, and reserved bus lanes can decrease bus running times (Kimpel et al. 2005; Surprenant-Legault and El-Geneidy 2011; Tétreault and El-Geneidy 2010), whereas the introduction of smart cards and articulated buses can potentially increase running times (Diab and El-Geneidy 2013; El-Geneidy and Surprenant-Legault 2010; El-Geneidy and Vijayakumar 2011).

To the best of our knowledge, most of the existing literature has investigated the individual impacts of bus service improvements, and only a few studies assessed the combined effects of various strategies on transit bus emissions (Alam and Hatzopoulou 2014; Dion et al. 2004; Hemily and King 2008). In this paper we investigate the isolated and combined effects of a range of transit service improvements on the emissions of GHGs and other pollutants along a busy transit corridor in Montreal, Canada. This is done by collecting second-by-second bus speed data and passenger ridership. The resulting segment-level, stop-level, and passenger-level emissions are analyzed in order to capture the effects of the implemented strategies.

6.3 Description of the Study Corridor

Boulevard Saint Michel is a busy transit corridor located in the east side of Montreal, Canada. It runs north-south over a 5.8 mile length with Montreal's downtown located on the west side of the corridor (**Figure 6-1**). The corridor crosses five boroughs of the City of Montreal and connects two metro stations. Bus service is provided by the local transit provider, STM. Two types of bus service concurrently run along the corridor: regular route 67 (R67) and express route 467 (R467). The majority of the Saint Michel corridor consists of three lanes in each direction with no median separating traffic. Route 67 has an average stop spacing of 241m and 255m in the SB and NB directions respectively, whereas the stop spacing for route 467 is 611m and 623m in the SB and NB directions, respectively.

A slightly shorter sub-segment of the corridor extending between Boulevard Saint Joseph and Rue Fleury is subject to our analysis. It encompasses 28 signalized intersections all of which are equipped with TSP system. When a TSP-equipped bus is detected, the signal either provides a green extension or a red truncation (Société de Transport de Montréal 2011). STM implemented a series of service improvements along the corridor. In April 2008, STM replaced traditional flash passes with a smart card fare collection system called 'OPUS'. In March 2009, STM implemented a limited-stop bus service, also known as express service 467, running parallel to the regular 67 route. The express service serves only 40% of the regular bus stops and runs on weekdays (from 6 AM to 7 PM). Later in August 2009, reserved bus lanes were operated during peak periods. The reserved lane becomes effective in the SB direction during the morning peak period (6.30 AM to 9.00 AM) and in the NB direction in the afternoon peak (2.30 PM to 6.30 PM). In February 2010, articulated buses were introduced along Route 467. Finally, in September 2011, the STM introduced articulated buses incrementally along Route 67, offering more space and seating capacity on buses.

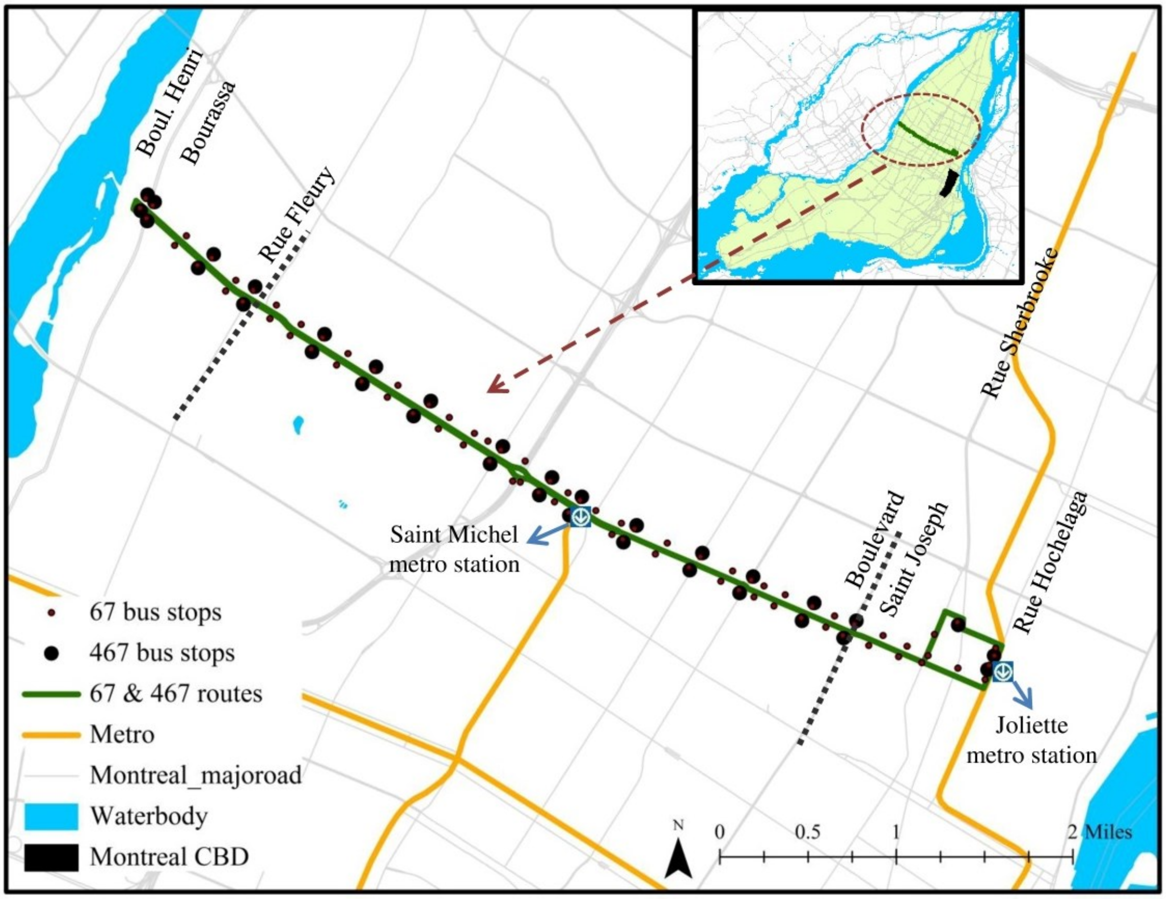


Figure 6-1. Saint Michel corridor

In this study the effects of bus service improvements such as smart card, express bus service, and reserved bus lanes are quantified in terms of the resulting bus emissions. Bus emissions are estimated at the segment level where each segment is defined as the journey between the start of the trip and the arrival at the 'Saint Michel' metro station. It was found that the bus ridership at the metro stop changes drastically with a higher number of passengers alighting and boarding at the stop. In the NB direction, two segments are defined spanning 1.75

miles (2.8 km) and 2.93 miles (4.67 km). On the other hand, in the SB direction, two segments are defined spanning 2.93 miles (4.67 km) and 1.75 miles (2.8 km).

6.4 Methodology

The study methodology is divided into three sections: 1) Data collection (bus speed, passenger ridership, and dwell characteristics), 2) Emission modeling, and 3) Statistical analysis. A comparison of emissions across strategies s performed in order to evaluate the effects of service improvements. A regression of total (including running and dwell) and dwell emissions against a number of operational variables is conducted to unveil the associations between various strategies affecting service and bus exhaust emissions. The overall methodology of the study is presented in **Figure 6-2**.

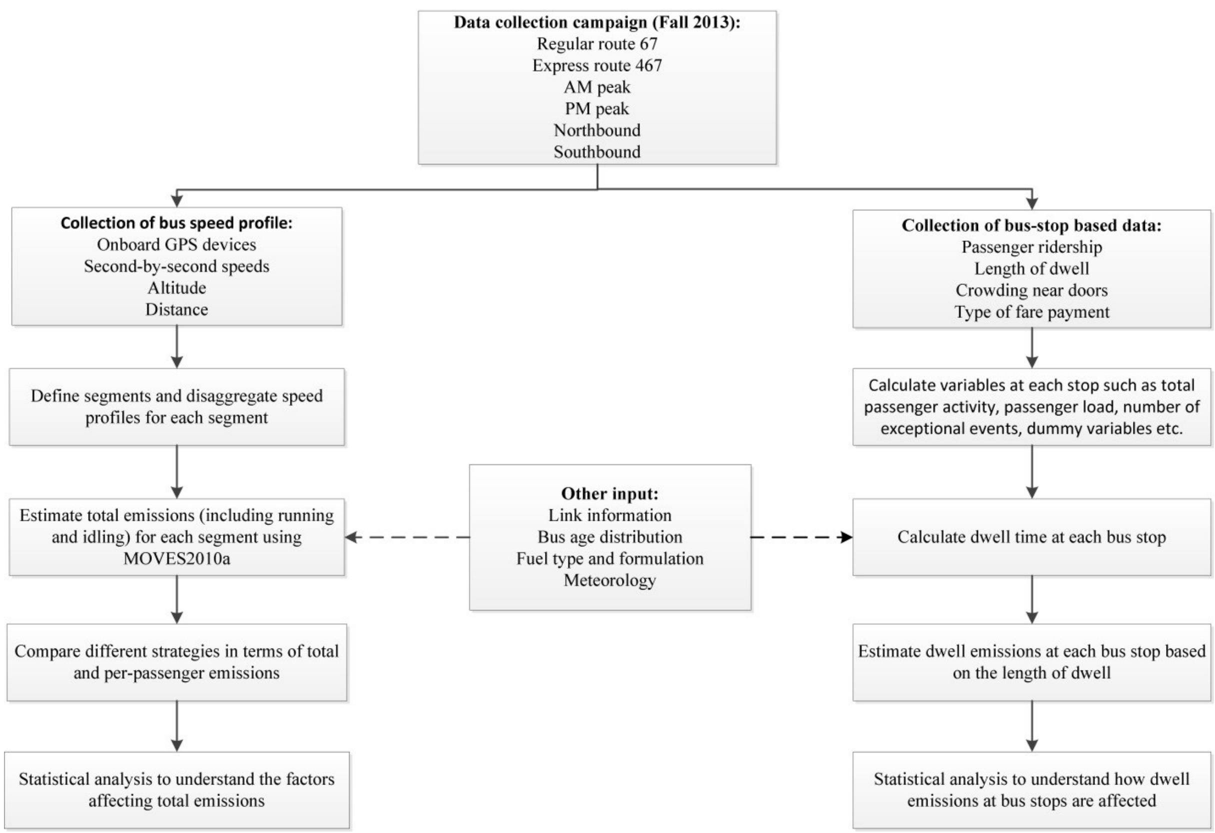


Figure 6-2. Overall methodology of the study

6.4.1 Collection of bus data

A data collection campaign was designed and executed over the span of two weeks in October 2013. Data from a total of 96 trips were collected for both routes (regular and express). A trip is defined from the beginning to the end of one route in a single direction (NB and SB). For each route, 24 trips were covered in the morning and afternoon peaks totaling 48 trips, spread equally over the two directions. In this research, we focus on articulated bus emissions only as regular buses are operated occasionally due to STM ongoing plan to shift all buses running on Montreal's heavily used corridors to articulated by 2020 (Riga 2012). Data were collected by research assistants riding the buses with three research assistants present in each bus. Each research assistant was located near one bus door. The instantaneous speeds of the buses were collected using global positioning system (GPS) devices. Data from two separate GPS devices were collected in each bus for quality control. The allocation of research assistants and GPS units to trips/buses were randomized.

Stop level data were collected using a tally sheet and stopwatch. At each bus door, a research assistant recorded the number of individuals boarding and alighting and the idling time at each stop. In addition, the fare payment associated which each boarding was recorded, payment types include: smart card 'OPUS', magnetic swipe, cash, and no fare. The smart card has an electronic chip embedded into the card and the passengers have to attach the card to a chip reader to be validated. The duration for the validation usually varies between 1 to 3 seconds. On the other hand, the magnetic swipe card is a paper-based ticket which has a magnetic strip along one side of the ticket. Passengers have to swipe the card through a reader and this process often varies from 2 to 4 seconds. Finally, cash users have to place the fare (either by cash or coins) into a farebox. The length of this process varies largely from one person to another. The total idling time at each bus stop was recorded from door opening to door closing. This idling time was recorded at each door for two stages: (1) the required dwell time for passengers boarding and alighting, and (2) any excess time that was not associated with boarding and alighting defined as *exceptional dwell* such as a stop due to a red signal or a conversation with a passenger. In addition, the number of individuals standing near the door (defined as *crowding*) after the bus departure from the stop was also recorded at each door.

A data cleaning process was conducted by removing incomplete trips associated with recording errors such as missing GPS signals. Data cleaning was also conducted at the stop level. Data were excluded if (1) dwell time was reported even though no passenger activity occurred at a bus stop, (2) when recordings were flagged by research assistants as possibly erroneous (e.g. due to GPS malfunction or inability to count passengers), (3) the recorded dwell time was zero even though passenger activity occurred, and (4) if the dwell time at a single stop was recorded as exceeding 200 seconds. Finally, the trip-level second-by-second speed profiles were split into two based on the location of the metro stop. Data for a total of 192 segments (96 trips divided into two) were collected. Following the data cleaning process, a total of 132 segment level and 1,556 stop level observations remained for analysis.

6.4.2 Emission modeling

Emissions generated during bus operations were estimated using MOVES2010a, developed by the United States Environmental Protection Agency (USEPA). In this study bus emissions were estimated using second-by-second speeds collected with the GPS devices. Emissions were estimated for GHGs (in CO_2-equivalent), fine particulate matter ($PM_{2.5}$), CO, and NO_x at the (1) segment level (including running and idling) and (2) stop-level (only idling).

To estimate emissions, MOVES requires additional inputs such as link length and grade; fuel type and formulation; vehicle type; vehicle model year; and meteorology including temperature (°F) and relative humidity (%). The link length for each segment is calculated from Google Map and validated using geographic information systems (GIS) and onboard-GPS data. All current buses are articulated buses and run on ULSD with a sulfur content of 15ppm. Meteorological data were input in the form of hourly temperature (°F) and relative humidity (%). Meteorology data were collected from Environment Canada and it was found to be fairly stable during the duration of the data collection. Therefore average values of 50.3*F temperature and 74% relative humidity were used.

When MOVES estimates emissions, it does not differentiate the type of bus (regular or articulated); it also assumes a constant bus weight of 16.556 tons. However, articulated buses are heavier than regular buses and they require more tractive power to operate the vehicle. In this study, we have explicitly considered the effect of bus weight estimating emissions. Articulated buses operating along the route have an empty weight of 18.86 tons (with a seating capacity of 47 and total capacity of 112). We also consider an average passenger weight of 70 kg. Bus weight (including passenger load) was used to estimate the VSP and *opmode* category. The VSP represents the tractive power exerted by a vehicle to move itself and its passengers. It is a function of instantaneous speed, acceleration, vehicle weight, and road grade as shown in equation (1) (US Environment Protection Agency 2010).

$$\mathrm{VSP} = \left(\frac{\mathrm{A}}{\mathrm{M}}\right) * \mathrm{v} + \left(\frac{\mathrm{B}}{\mathrm{M}}\right) * \mathrm{v}^2 + \left(\frac{\mathrm{C}}{\mathrm{M}}\right) * \mathrm{v}^3 + (\mathrm{a} + \mathrm{gSin\theta}) * \mathrm{v} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\mathrm{A} = (\text{bus weight in metric ton}) * 0.0643$$

$$\mathrm{B} = 0$$

$$\mathrm{C} = (\text{bus weight in metric ton}) * \left(\frac{3.22}{\text{bus weight in kg}} + 5.06 * 10^{-5}\right)$$

where A, B, and C are the rolling, rotating, and drag road load coefficients respectively in the units of (kiloWatt second)/(meter), (kilowatt second^2)/(meter^2), and (kiloWatt second^3)/(meter^3), respectively. The denominator term, 'M', is the fixed mass factor (for heavy vehicle such as transit, M=17.1 tons), 'g' is the acceleration due to gravity (9.8 meter/ second^2), 'v' is the vehicle speed in meter/second, 'a' is the vehicle acceleration in meter/second2, and Sinθ is the (fractional) road grade.

The terms, A, B, and C, are weight dependent. As the segments in the study corridor are relatively flat, we considered a grade of zero. Using equation (1), the VSP was calculated for each second during the trip. In MOVES, an *opmode* is determined by following a combination of speed and VSP for each second. Therefore, based on the VSP and speed, the *opmode* was determined for every second of the corresponding drive cycle. In the next step, for each segment travelled the amount of seconds spent in each *opmode* was calculated and an *opmode* distribution was developed. The *opmode* distribution provides the amount of time that the vehicle has spent under different *opmode* categories. This *opmode* distribution was input into MOVES to estimate emissions at a segment level. In MOVES, each *opmode* has a particular emission rate (gm/hr) that is dependent on a number of variables such as fuel type, meteorology, and vehicle age.

6.4.3 Statistical analysis

In order to capture the effects of various service improvement strategies and bus attributes on emissions, a linear regression is estimated. The analysis is intended to capture how emissions vary at the segment level as well as at the stop level. The list of variables tested is presented in **Table 6-1** along with the mean and standard deviation of each variable.

6.5 Results

6.5.1 Descriptive analysis of onboard data collected

The data collection effort was conducted for both routes, both peak periods, and both directions. **Figure 6-3** presents the bus travel time for the combinations of direction and time of day. We observe that the NB-pm and SB-am combinations have higher travel time which is in-line with morning and afternoon commuting patterns. Reserved lanes are operated for these two combinations of direction and time of day; nevertheless, the average bus speed remains around 7.7 mph. We also observe that the SB-pm combination (without reserved lane) has a higher travel time as non-commuters often travel towards the downtown in the afternoon peak period to engage in various activities. This figure also shows that the express bus route R467 has consistently lower travel time. With reserved lanes, the travel time for the express bus decreases by a larger amount (compared to the case without the reserved lane) compared to the effect of the reserved lane on travel time of the regular bus suggesting that the reserved lanes along this corridor are more effective for express buses.

Figure 6-4 illustrates the average number of onboard passengers. We observe that when reserved lanes are used under congested conditions, more commuters are found on the express bus (R467), presumably because of the faster travel time. On the other hand, when the reserved lane is not in effect, more commuters are found on the regular bus (R67) despite its higher travel time. A possible reason could be that non-commuting passengers prefer regular service because it serves more stops.

Table 6-1. Description of variables tested in the statistical analysis

Variable Name	Description	Mean	Std. Deviation
	Segment level total emissions (running + idling)		
GHG Emissions Rate (g/bus.mile)	Total GHG emissions in grams generated by one bus for travelling one mile during a segment travel	2,214.46	475.21
$PM_{2.5}$ Emissions Rate (mmg/bus.mile)	Total $PM_{2.5}$ emissions in milligrams generated by one bus for travelling one mile during a segment travel	29.46	4.65
Total Passenger Activity (PAX)	The total number of passengers boarding and alighting during a segment travel	97.05	50.37
PAX Square	Square of the PAX value during a segment travel	11,935.59	12,864.18
R467	A dummy variable that equals 1 if the trip was made on route 467	0.59	0.49
Reserved Bus Lane	Dummy variable which equals 1 if the observed trip used the reserved bus lanes. When it is equal to 1, this means the trip was made between 6:30 AM and 9:00 AM in the southbound direction or between 2:30 PM and 6:30 PM in northbound	0.44	0.5
Southbound	Dummy variable which equals 1 if the trip was made in the southbound direction	0.57	0.5
AM Peak	A dummy variable which equals 1 if the trip was made in the morning peak period (6:30 AM- 9:30 AM)	0.46	0.5
PM Peak	A dummy variable which equals 1 if the trip was made in the afternoon peak period (3:30 PM- 6:30 PM)	0.54	0.5
Segment Level Crowding	Total number of passengers standing near the door during the whole segment	22.35	27.42
	Bus stop level idling emissions		
Total Idling GHG Emissions	Total amount of GHG emissions for idling at each bus stop	117.33	110.93
Smart Card User	Number of boarding passengers paying fare by smart card	4.64	6.44
Magnetic Swipe Card User	Number of boarding passengers paying fare by magnetic swipe card	0.16	0.79
Cash User	Number of boarding passengers paying fare by cash	0.15	0.45
No Fare User	Number of boarding passenger paying no fare	0.15	0.48
Door 1 Alight	Total number of passengers alighting through door 1	1.57	2.04
Door 2 Alight	Total number of passengers alighting through door 2	1.9	3.06
Door 3 Alight	Total number of passengers alighting through door 3	1.63	3.15
Stop Level PAX Square	Square term of the PAX value at a bus stop where PAX is calculated as the sum of total passengers boarding and alighting at a stop	239.68	735.04
Bus Stop Level Crowding	Total number of passengers standing near the door when the bus arrives at the stop	2.53	4.09

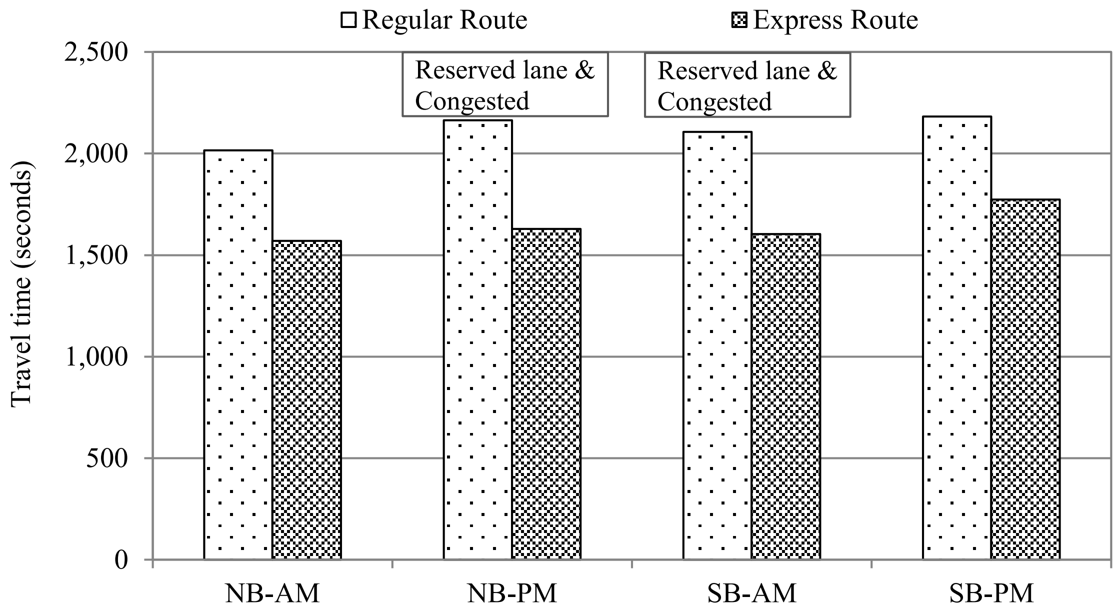


Figure 6-3. Travel time along different directions and time periods for regular (R67) and express (R467) buses

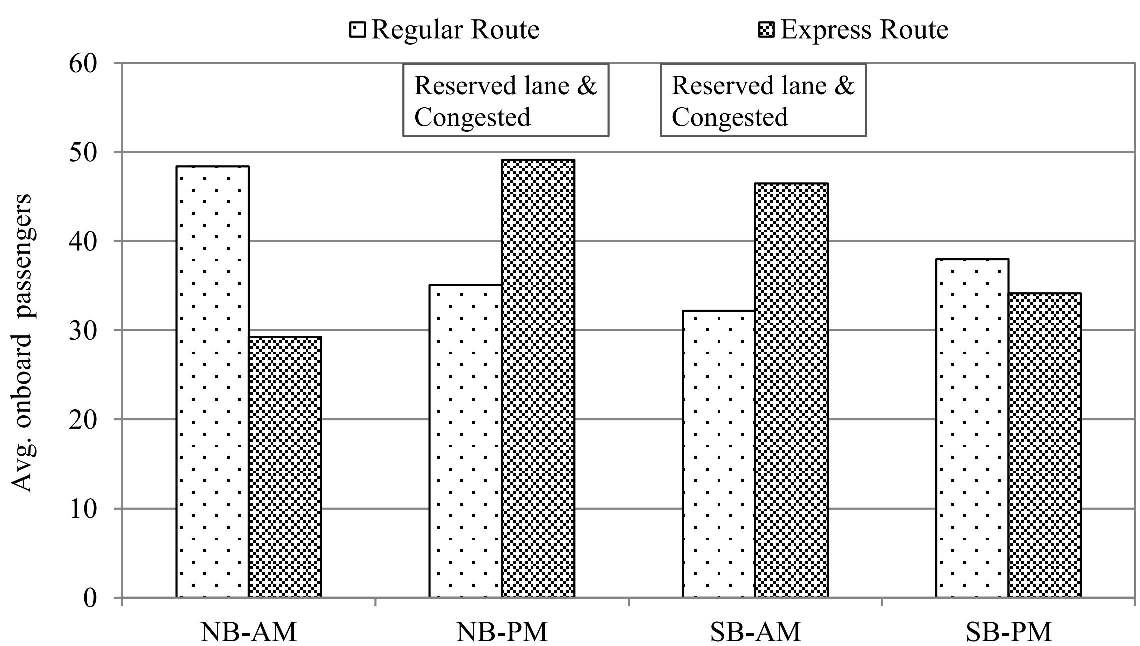


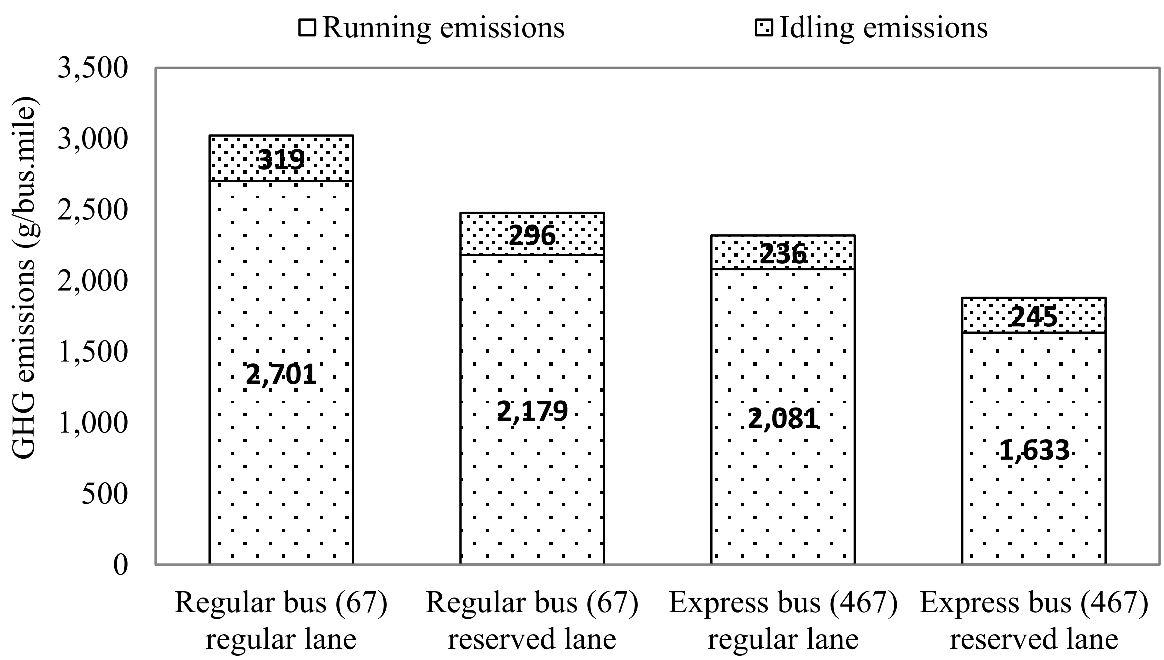
Figure 6-4. Average number of onboard passengers along different directions and time periods for regular (R67) and express (R467) buses

6.5.2 Descriptive analysis of estimated emissions

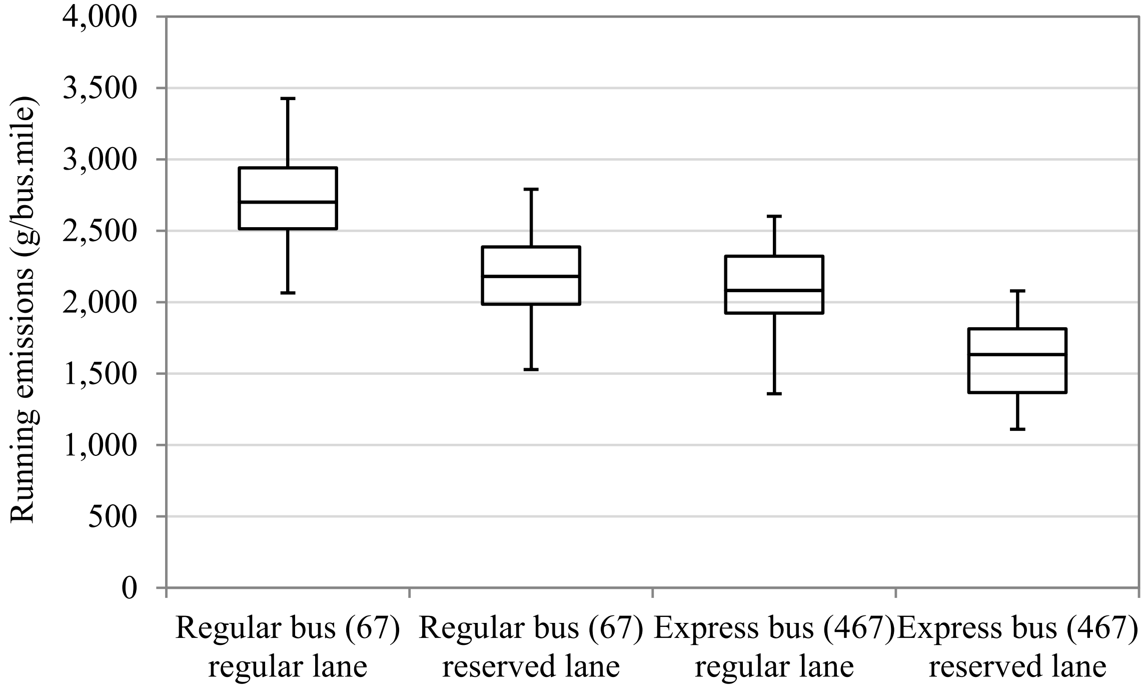
Total emissions per segment (including running and idling) were estimated for each bus trip. Segment-level emissions were also compared across different combinations of route and reserved lane facility. **Figure 6-5(a)** illustrates average segment-level GHG emissions (in g/bus.mile) while the bus is running and idling. We observe that running emissions are highest when buses operate in regular service without a reserved lane. When buses are operated on the express route and use reserved lanes, running emissions are lowest. In terms of idling emissions, we observe that regular buses without reserved lane generate the highest emissions and express buses without reserved lanes generate the lowest. Also note that even with the same number of onboard passengers at a segment level, regular buses have more idling emissions because of more frequent stops. It is also interesting to see that express buses generate higher idling emissions when reserved lanes are in effect because of the higher passenger ridership during these times. Also note that the benefit of express buses can be potentially increased by decreasing their idling emissions associated with waiting behind a regular bus at a bus stop. **Figure 6-5(b)** illustrates the variability in total emissions over the entire dataset. For the regular route, we observe a large variability in trip-level emissions because of the higher number of bus stops. The variability is lowest for express service and reserved lane. This happens because the service improvements not only reduce travel time but presumably also yield a stable, smooth flow having less 'stop and go' events. It is also interesting to see that the changes in travel time (i.e. average speed) do not necessarily translate into linear changes in emissions highlighting the importance of using second-by-second bus speeds in emission estimation (**Table 6-2**).

In addition, per passenger GHG emissions were calculated by dividing the total emissions per segment (including running and idling) by the average number of onboard passengers and summarized as an emission rate in g/pass.bus.mile (**Figure 6-6).** We observe that per passenger emissions are highest on the regular bus without a reserved lane while the regular bus with reserved lane and express bus without reserved lane come close. The reason for this small difference is attributed to passenger ridership. Even though regular buses without the reserved lane produce higher emissions, they also have the highest ridership which reduces per passenger emissions. On the other hand, for the next two combinations, service improvements (i.e. express bus and reserved lane) reduce total emissions but lower ridership does not help reduce per passenger emissions largely. By looking at the spread in per passenger emissions, we observe that there are cases where the bus produces more emissions per passenger than a private auto with a driver and a passenger (assuming 125 g/passenger.mile for a typical 2011 car with 2 individuals). Finally, express buses in a reserved lane have the lowest per passenger emissions. The variability in emissions is also smaller for express buses on reserved lanes indicating that they have more stable passenger ridership, probably because of high proportion of commuters to downtown.

In addition to GHG, we also estimated emissions for $PM_{2.5}$, CO, and NO_x. **Figure 6-7** illustrates the percentage reduction for each pollutant by comparing each bus-lane combination with the emissions of the regular bus without a reserved lane (base case). We observe that the express buses and reserved lanes are also effective at reducing these pollutants.



(a) Mean running and idling GHG emissions under different combinations of bus route and lane facility



(b) Variability in running GHG emissions under different combinations of bus route and lane facility

Figure 6-5. GHG emissions under different combinations of bus route and lane facility

Table 6-2. Percent reductions in average travel time and average GHG emission reduction under various service improvements (compared to the case of the regular bus without a reserved lane)

Combinations	Avg. travel time reduction (%)	Avg. GHG emission reduction (%)
Regular bus (67) & reserved lane	2.13	18.01
Express bus (467) & regular lane	20.39	23.29
Express bus (467) & reserved lane	23.04	37.84

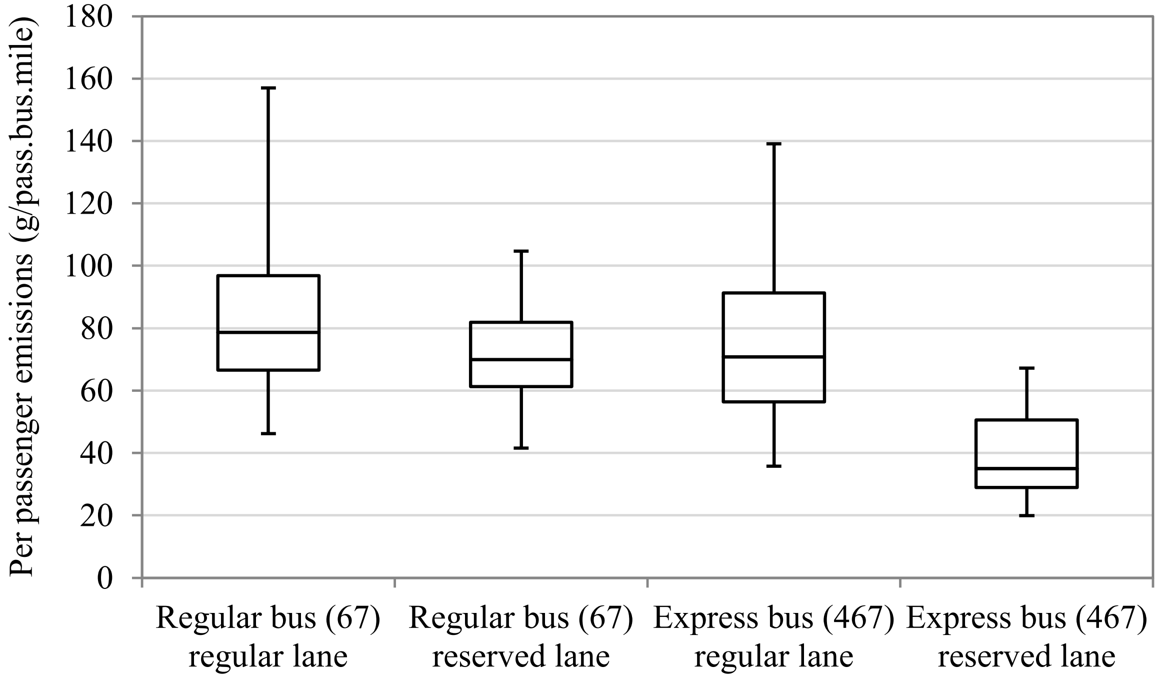


Figure 6-6. Per passenger GHG emissions variation under different combinations of bus route and lane facility

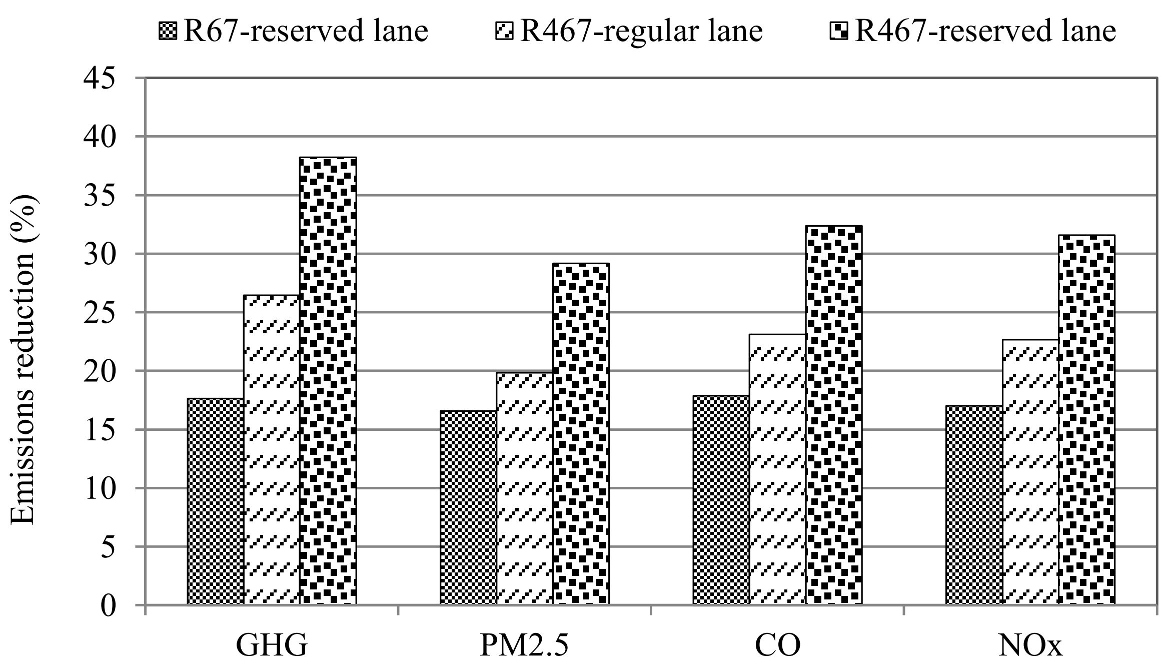


Figure 6-7. Percent reductions in GHG and air pollutants under various service improvements (compared to the case of the regular bus without a reserved lane)

6.5.3 Statistical analysis

A linear regression of segment-level total emissions (including running and idling) and stop-level idling emissions was conducted for routes 67 and 467 against a set of potential explanatory variables described in Section 6.4.3. The segment level emissions regression was performed for GHG emissions (in grams) and $PM_{2.5}$ emissions (in milligrams) and the regression results are summarized in **Table 6-3** and **Table 6-4**; where information from 132 segments is used to estimate the model. **Table 6-5** presents the results for GHG idling emissions.

Table 6-3 shows that the largest positive impact on emissions is associated with the introduction of *Reserved Bus Lanes* that can reduce GHG emissions by 441g per mile of bus travel. The express bus service, *R467,* has the second largest negative coefficient decreasing GHG emissions by 431g/mile. Regarding the control variables, *Passenger Activity (PAX)* has a positive sign indicating that as the number of passengers boarding and alighting increases, total emissions increase. This increase is mainly associated with longer idling time. But the square term of *PAX* has a negative sign indicating that the relationship between total emissions and *PAX* is not linear; after a certain number of passengers, total emissions start to decrease. This decrease is associated with two potential factors: (1) the relationship between dwell time and the number of boarding/alighting passengers is not linear, as the number of passengers increases, the time required for each passenger to board/alight decreases (El-Geneidy and Vijayakumar 2011); and (2) the average bus speed increases as drivers tend to drive faster when the bus has a higher number of passengers onboard (El-Geneidy and Surprenant-Legault 2010).

Finally, time of day and direction of travel were also observed to significantly affect bus emissions. If the bus runs SB, total emissions are 101g/mile less than the NB trips; this is due to the traffic conditions and geometric configuration of the corridor. It was also observed that trips made during the *PM peak* period have emissions higher by 263g/mile compared to the *AM peak* period. Similar effects can be observed for $PM_{2.5}$ as shown in **Table 6-4**.

Table 6-5 illustrates the effect of different variables on idling emissions at bus stops. Each *Smart Card User* increases GHG emissions by 7.5g. Each *Magnetic Card User* and *Cash User* increases emissions by 9.2g and 13.7g respectively. These two fare payment processes take longer processing time compared to the smart card (Kittelson & Associates et al. 2003). Each *No*

Fare User increases emissions by 13.2g. Even though these users do not pay a fare (e.g. children or infants) they often take time to board the bus. The level of emissions generated for each alighting passenger depends on the door location. Alighting through the first door (*door 1*) generates almost 1.5 to 2 times higher emissions compared to alighting via the 2nd and 3rd doors. We also observe that c*rowding* is associated with a reduction in idling emissions meaning that as the number of standing people near the door increases, emissions start to decrease because of faster alighting. *PAX Square* was also found to be negative indicating that when the passenger activity is very high then the effect of each additional passenger on idling emissions starts to decrease. After controlling for the other variables, we observe that the express bus (*R467) and Reserved Lane* do not significantly affect idling emissions at bus stops.

Table 6-3. Regression results for GHG emissions (g/bus.mile)

	Coefficient	Std. Error	t
Constant	2111.84***	143.420	14.723
R467	-430.60***	60.711	-7.093
Reserved lane	-441.14***	60.191	-7.329
PM Peak	263.04***	58.461	4.499
Southbound	100.96*	61.003	1.655
Total Passenger Activity (PAX)	5.41**	2.262	2.389
PAX Square	-0.02*	0.009	-1.954
$R^2 = 0.561$ N=132			
*** Significant at 99% ** Significant at 95% * Significant at 90%			

Table 6-4. Regression results for $PM_{2.5}$ emissions (mg/bus.mile)

	Coefficient	Std. Error	t
Constant	28.19***	1.049	26.871
R467	-4.27***	.444	-9.626
Reserved lane	-4.44***	.440	-10.084
PM	4.04***	.428	9.444
Southbound	1.25***	.446	2.809
Total Passenger Activity (PAX)	.04***	.017	2.271
PAX Square	$-6.97*10^{-5}$	.000	-1.085
$R^2 = 0.755$ N=132			
*** Significant at 99% ** Significant at 95% * Significant at 90%			

Table 6-5. Regression results for GHG idling emissions (g) at bus stop

	Coefficient	Std. Error	t
Constant	15.510***	1.748	8.873
Smart Card User	6.518***	0.185	35.315
Magnetic Swipe Card User	9.240***	0.963	9.591
Cash User	13.686***	1.662	8.234
No Fare User	13.169***	1.584	8.316
Door1 Alight	2.617***	0.462	5.664
Door2 Alight	1.740***	0.373	4.664
Door3 Alight	1.395***	0.366	3.815
Bus Stop Level Crowding	-.345*	0.186	-1.854
PAX Square	-.015***	0.002	-6.776
Southbound	2.603*	1.482	1.757
PM Peak	0.327	1.484	0.22
R467	-1.123	1.663	-0.675
Reserved lane	0.941	1.468	0.641
R^2 = 0.779 N= 1,556 stop level observations			
*** Significant at 99% ** Significant at 95% * Significant at 90%			

6.6 Conclusion

This study investigates the impacts of various service improvement strategies on transit bus emissions along the Saint Michel corridor in Montreal, Canada. To estimate emissions, second-by-second bus speeds as well as stop level passenger information were collected. GHG and air pollutant emissions were estimated at a segment level for total emissions (including running and idling) as well as at stop level for idling emissions. The resulting segment-level and passenger-level emissions were compared across different strategies. A regression analysis was conducted in order to quantify the effects of service improvements on segment level total and stop level idling emissions. We observe that the highest reduction in emissions comes from the implementation of reserved bus lanes and express bus service. Together, both strategies could reduce GHG emissions by 40% compared to the scenario with regular bus and no reserved lanes. We also observe that the smart card leads to lower idling emissions compared to magnetic swipe cards and cash. Also passengers should be encouraged not to alight through the front door.

It is important to note that along the corridor, reserved lanes are curb-side located in the rightmost lane. However, they are not continuous throughout the corridor but rather end 50m upstream of each intersection thus allowing a passage to the right turning vehicles for their safe maneuvers. In Montreal, a ‘no right turn on red’ policy is always in effect for passenger cars and therefore buses have to idle behind passenger cars waiting to take a right turn. In this context, the introduction of queue jumper lanes near intersections is recommended since they would allow buses to bypass the waiting cars thus reducing congestion at intersections

7 CHAPTER 7: CONCLUSION

7.1 Summary of Chapters

This dissertation addressed critical gaps in the current literature on transit bus emissions. We first discussed the contribution of vehicle emissions to the total GHG emissions in Canada. Later, by focusing on the importance of reducing private vehicle dependency and shifting towards transit buses, we introduced the negative health effects of diesel bus exhaust and the need to overcome the current challenges in transit bus emission estimation. The preceding chapters have addressed the following research questions:

1) How do state-of-art emission inventory models estimate transit bus emissions? And what is the effect of incorporating local drive cycles as opposed to embedded default distributions?

2) How can traditional emission modelling techniques be improved without resorting to micro-simulation tools, especially when transit bus emissions are estimated for large urban areas?

3) What are the factors that can significantly affect transit bus emissions and what are their individual and combined effects along busy corridors?

4) What is the potential of alternative fuels and transit service improvements in the reduction of transit bus emissions?

Chapter 3 compared the embedded distributions of the most common emission inventory model in North America, USEPA's MOVES, in a local context. MOVES can estimate emissions at three levels of aggregation namely: macro, meso, and micro level. When macro and meso scale analyses are performed for transit buses, MOVES uses average speeds of the buses in parallel with speed specific *opmode* distributions developed using the data collected by instrumented vehicles in US cities (Sierra Research Inc. 2009). Using such non-local default distributions could under/overestimate emissions compared to a local context. Therefore, we collected second-by-second bus speeds using GPS devices and stop-level passenger ridership data for eight bus routes for a total of 3,702 road segments covering 606.18 miles (970 km) of roads across a variety of transit routes (downtown and suburban/highway) and bus types (standard, articulated, old, and new). For each segment, *opmode* distributions and emissions were estimated using both MOVES2014 embedded data and local second-by-second data. We observed that MOVES has only two transit bus drive cycles at 3.7 and 8.3 mph. To estimate emissions for other average speeds (running on local and arterial roads), MOVES uses either average traffic flow or medium duty vehicle drive cycles. When compared with local data, we observed that MOVES assumed different driving characteristics (i.e. percentage of idling, braking etc.) and when average speed is used to estimate emissions, MOVES generates significantly different emissions estimates using its default distributions. The results clearly suggested the need for collecting local speed data and developing local *opmode* distributions that could be embedded into the MOVES database to estimate improved average speed based emissions.

Chapter 3 also used the same second-by-second speed and passenger ridership data to estimate emissions in MOVES2014. We generated an *opmode* distribution for each link level observation based on the associated drive cycle and grouped the *opmode* distributions into different average speed categories. Then, for each average speed category, a representative drive cycle was selected by calculating the root mean square error of individual link observations. A total of 25 representative drive cycles were selected for average speeds ranging from 1 to 25 mph. These 25 drive cycles specific to average speeds were then input into the MOVES2014 database. It forced MOVES to use the local drive cycles to generate *opmode* distributions and to estimate emissions instead of using its embedded drive cycles. A validation study was conducted on another corridor of Montreal which suggested that *MOVES default* estimates were largely under or overestimated compared to *instantaneous speed* estimates. On average, the difference between these two approaches was 554 g/bus.mile (i.e. 23%) and for some speed bins the difference was as large as 975 g/bus.mile (i.e. 53%). On the other hand, the embedded local drive cycles could estimate emissions within 13% of *instantaneous speed* estimates. A correlation of 0.91 was observed at link level observations between *local opmode* and *instantaneous speed* estimates. In addition to embedding local drive cycles into the MOVES database, we also observed the temporal and spatial variation of emissions across different time periods, directions, land uses, passenger demand, and transit service facilities. We observed that emissions could largely vary across network speed, roadway grade, and passenger ridership.

Chapter 4 investigated the individual and combined effects of different factors through a simulation of transit bus operations in a busy corridor, Cote-des-Neiges, in the City of Montreal. It was observed that bus emissions are strongly affected by the average speeds of buses. Emissions are higher at lower speeds and as the average speed increases, emissions become lower. Grade is another factor that can largely affect bus emissions, especially at higher positive grades. With an increase in positive grade, emissions increase exponentially, reaching very high levels when buses run on high grades at lower speeds. On the other hand, at negative grades emissions do not change much with the change in grade. It was observed that at negative grades, the effect of grade can be cancelled by the randomness in traffic patterns. The effect of passenger ridership was also found to be important. While higher passenger load on the bus increased emissions, we observed that the addition of each passenger influences the per-passenger emissions differently depending on the bus occupancy. When the bus is less crowded, each additional passenger can decrease the per-passenger emissions by 5% whereas the reduction becomes 1.2% when the bus is crowded. We demonstrated that in order to reduce per-passenger emissions, it is not necessary to over-crowd the bus. In fact per-passenger emissions do not decrease much after a certain number of onboard passengers. We also investigated the emission reduction potential of CNG under various conditions. It was observed that the reduction potential of CNG compared to conventional diesel could reach up to 40% depending on speed, grade, and passenger load. CNG benefits increase with increasing congestion, and decrease with increasing grade and passenger load.

Chapter 5 investigated the potential of alternative fuels and transit operational improvement strategies to reduce emissions by simulating transit buses on the busy Cote-des-Neiges corridor of Montreal. Emissions were estimated for both directions of travel to capture the effects of speeds, grades, and traffic variability. It was found that CNG can reduce GHG emissions by 8-12% compared to conventional ultra low sulfur diesel and this reduction could increase to 16% with high levels of traffic congestion. However, the benefits of switching from conventional diesel to CNG were less apparent when the road network is uncongested. We also investigated the effects of implementing transit signal priority, introducing queue jumper lane, and relocating of bus stops on bus emissions. Results show that in congested conditions, TSP alone could reduce GHG emissions by 14% and when combined with alternative fuels; a reduction of 23% was achieved. The reduction benefits were even more apparent when other transit operational improvements were combined with TSP. Finally a sensitivity analysis was performed to investigate the effect of operational improvements on emissions under varying levels of network congestion. We observed that under “extreme congestion”, the benefits of TSP decreased and of queue jumper lanes increased.

Chapter 6 investigated the impacts of transit service improvements on bus emissions along a busy corridor, Saint Michel, in the City of Montreal. The local transit provider, Société de Transport de Montréal, had implemented a number of strategies including the use of smart cards, limited-stop express bus service, and reserved bus lanes along this corridor over several years. Using GPS devices, trip level instantaneous speeds and stop level passenger ridership were collected for a total of 96 trips for both regular (route 67) and express (route 467) bus routes. For each route, data were collected for 24 trips in the morning peak and 24 trips in the afternoon peak totaling 48 trips, spread equally over the two directions. Emissions were estimated for three levels: road segment, bus-stop, and per passenger. It was observed that regular buses running on regular lanes generated the highest emissions whereas express buses running on reserved bus lanes generated the lowest. Express buses on reserved lanes could reduce GHG emissions by 38%compared to regular buses on regular lanes. Emissions were also observed to vary largely depending on the service type, passenger ridership, and time period of the day. The variation in emissions was observed less for reserved lane compared to regular lane service. A linear regression at segment-level was performed against a number of explanatory variables to observe the effects of each variable on bus emissions. It was observed that reductions of 441 g/mile and 431 g/mile could be achieved for the implementation of reserved bus lanes and express bus service respectively. We also observed that the smart card led to lower idling emissions compared to magnetic swipe card and cash fare payments.

7.2 Research Contributions

The research aimed to address the gaps in the current knowledge on transit bus emissions. The main contributions of the dissertation can be categorized into four components. First, in

Chapter 3 we compared the output of the most common emission inventory model in North America, MOVES, with locally-derived data. MOVES is a data driven model, most of its data are collected in US cities. When MOVES is used to estimate emissions in Canada, careful considerations should be made when data are input into the model, especially drive cycles. As the embedded drive cycles of MOVES are not local, it is important to validate emissions in a local context. To date, few studies have validated MOVES for passenger vehicles, but no study has been performed to validate MOVES for transit buses comparing individual operating modes, distributions of operating modes, and emissions at different speeds and grades. This study discusses embedded data and the process of estimating bus emissions in MOVES. This study demonstrated the limitations of the current MOVES2014 model. It also demonstrated the extent to which emissions could be different when MOVES uses its embedded distributions to estimate emissions using average speeds. This validation study would be useful for transportation planners when emissions are estimated using average speeds, especially at a regional scale. The results of the study also highlight the need for more research to refine average speed based emission estimates.

Second, in **Chapter 3** this dissertation introduced a process to embed local driving characteristics into the MOVES database to improve bus emissions. The process described to select representative drive cycles could be very useful when emissions are estimated for a large area, such as for the region where average speeds are used to estimate emissions using bus schedule or regional transportation planning model output. The steps involved in the process can be replicated for other transit networks as well as for other vehicle types.

Third, in **Chapter 4** we examined the individual and combined effects of different factors on bus emissions while most of the existing studies have focused on individual factors only. While transit buses are considered environmentally friendly, the per passenger emissions analysis provided another dimension by showing how transit buses could become more polluting than passenger cars. We also analyzed total and per-passenger emissions showing network-wide variability under different transit improvement scenarios. The results could be very useful to transit planners before introducing new routes or evaluating existing routes considering per passenger emissions.

In **Chapters 5,** we found-out that operational improvements could out-perform alternative technologies in terms of emission reduction potential. This finding is crucial for transit agencies looking to renew part of their fleet as well as to install operating improvements. Finally in **Chapter 6** we identified the types of service improvements that are associated with the highest reduction potential. These results are useful to transit planners and policy makers in the selection of appropriate GHG reduction strategies as well as in the selection of corridors when a selected number of new and alternative-fuelled buses are to be deployed.

7.3 Recommendations for Future Research

While this dissertation explored important gaps in the current literature on transit bus emissions, there are many issues that need to be addressed. The following are the recommendations that could become areas of future research:

(1) This dissertation validated MOVES for transit buses running on 'urban unrestricted roads' which are mainly local and arterial roads. The validation study can be extended for other cases such as transit buses running on highways and collectors, school buses, intercity buses, and especially passenger vehicles. As more than 60% of GHG emissions are generated by passenger vehicles, validation of MOVES could certainly help in estimating emissions accurately and in prioritizing emission reduction policies. The effort could eventually lead to the development of local operating mode distributions and better estimation of emissions. It would also allow customizing MOVES in the Canadian/local context.

(2) Statistical relationships could be developed between transit emissions and various determinants (e.g. average speed, road geometry, type of service, bus type, average ridership). This can be achieved by collecting instantaneous bus speeds on many different types of links and estimating emissions. Later, a link level regression model can be developed that can estimate emissions using average speeds and other roadway and trip characteristics without relying on instantaneous bus speeds. Such a regression model can be integrated to the transportation planning model from where the input of

the regression model will come. It would also allow estimating and comparing emissions due to region-wide transit oriented developments.

(3) MOVES is a data-driven model and the emission database is developed using US vehicles. But emissions could be different in the Canadian context as it varies largely depending on many factors. Moreover, the present MOVES database does not offer estimating transit bus emissions for a wide range of bus types and alternative fuels. Therefore, emission measurement campaigns for transit buses need be conducted in Canada using on-board emission measurement devices. The emission measurement campaign could be conducted for different types of buses including regular and articulated transit buses, school buses, intercity buses, and alternative fuelled buses. The measured emissions could enhance the MOVES database and would allow customizing MOVES in the Canadian context. It would also facilitate validating MOVES outputs for different vehicles and fuel types as well as validating the accuracy of any proposed and existing emission measurement techniques. This campaign can be expanded for other vehicle types including passenger cars, and passenger trucks.

(4) Per passenger emissions need be considered in the policy and planning stages in addition to considering total emissions. Per passenger emissions could largely vary depending on the time of the day, direction of travel, route characteristics, and the level of passenger ridership. It was observed that with the addition of onboard passengers, per passenger emissions largely reduce initially and later, the reduction becomes little while making the bus over-crowded. Studies should be conducted to identify the optimum level of onboard passenger to achieve minimal per passenger emissions while providing sufficient comfort to the passengers. It would also help to find the optimal frequency of bus arrivals.

(5) The benefits of alternative fuel and transit service improvement can vary largely depending on the level of congestion, roadway grade, passenger ridership, and transit service facilities. Studies need be conducted to develop a systematic approach that can select bus routes to achieve the highest reduction of emissions due to service

improvements and alternative fuel buses. This type of approach would definitely help the transit agencies to select the best possible routes for introducing alternative fuel buses and for implementing improvement strategies.

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