University of Alberta

Investigating the Effects of Transportation Infrastructure Development on Energy Consumption and Emissions

by

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Abstract

This study outlines the development of an emissions modeling process in which tractive power based emissions functions are applied to microscopic traffic simulation data. The model enables transportation planners to evaluate the effects of transportation infrastructure projects on emissions and fuel consumption to aid in selecting the projects providing the greatest environmental return on investment.

Using the developed model, the performance of a set of simplified macroscopic velocity profiles used in an existing emissions model has been evaluated. The profiles were found to under predict the vehicle emissions due to the low acceleration rates used.

To illustrate the use of the model in evaluating transportation infrastructure projects, the benefits of two potential development scenarios in a major transportation corridor were evaluated. Weighing the benefits provided by each scenario against their associated costs revealed that greenhouse gas emissions would be reduced at a cost an order of magnitude greater than the value of a carbon credit suggesting that neither option is economical solely as a greenhouse gas emissions reduction tool.

Acknowledgements

The time spent completing this thesis was a rewarding, enjoyable experience and I would like to thank those who helped make it possible.

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I would also like to thank those who offered their expertise in traffic simulation, namely Hadi and Dr. Qiu from the Civil Engineering Transportation Group, and the City of Edmonton Emissions Modeling Group.

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Lastly, but certainly not least, I would like to thank my family for their support and for encouraging me to pursue a graduate level degree.

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Nomenclature

CALMOB6	CALibrated against MOBile6
CO	Carbon monoxide
CO_2	Carbon dioxide
EMME/2	Macroscopic traffic simulation package
MOBILE6	US EPA's vehicle emissions inventory
NMHC	Non-methane hydrocarbons
NO_x	Oxides of nitrogen
PM	Particulate matter
VISSIM	Microscopic traffic simulation package
VKT	Vehicle kilometers traveled

Chapter 1

Introduction

This chapter introduces the transportation sector as a major energy consumer and source of greenhouse gas emissions. Vehicle emissions modeling is presented as a way to address this by enabling planners to ensure transportation systems are designed in a manner which minimizes energy use and emissions.

1.1 Transportation and Energy Use

The environmental implications of our society's growing energy consumption have been well researched and documented in recent years. In Canada, the transportation sector accounts for nearly 30% of total energy consumption [1, Natural Resources Canada]. To meet emission and energy consumption reduction targets, substantial improvements must be made in this sector. These improvements will be realized not only through technical developments that improve the efficiency and emissions of individual vehicles but by ensuring that transportation systems are designed in a manner that allows trips to be made as efficiently as possible.

1.2 Transportation Infrastructure Development

Major transportation infrastructure investments can have large impacts on system efficiency. The reduced congestion, more direct travel routes, and increased use of more efficient modes resulting from infrastructure development all help reduce energy consumption and emissions. Furthermore, infrastructure developments can shape land use patterns over time, resulting in denser neighborhoods which require less motorized transportation to maintain a high level of accessibility. In an article outlining the potential for reductions in greenhouse gas emissions from the U.S. transportation sector, Greene and Schafer [2] identify land-use planning and infrastructure development among the avenues having the greatest potential long-term effects.

1.3 Emissions Modeling

To facilitate the development of efficient transportation infrastructure, transportation planners require a technique to quantify the amounts of fuel consumed and emissions produced in a transportation system. This dissertation outlines a microscopic emissions[1] modeling process that allows transportation planners to quantitatively assess the potential environmental impacts of different investments in transportation infrastructure. With this tool, statistics outlining the potential benefits of a project relative to its cost can be rapidly generated to ensure that available funding is spent on projects that provide the greatest environmental return on investment.

[1] To improve readability, the term "emissions" is used to collectively refer to energy use, greenhouse gas emissions, and criteria pollutant emissions

1.4 Contents of this Dissertation

This thesis outlines the current state of emissions modeling, the limitations of current models, and the motivation behind this work in Chapter 2. The models and sub-models used and their characteristics are discussed in Chapter 3. Chapter 4 shows the application of emissions modeling on a single link level. Results obtained using different simulation techniques are presented and discussed. In Chapter 5, emissions modeling is applied at a corridor level and used to compare competing infrastructure development scenarios. The results and achievements of this work are summarized in Chapter 6.

Chapter 2

Background

This section outlines the current state of emissions modeling, discussing the advantages and limitations of each of the available approaches. The region of interest for this study and the available traffic simulation data for it is then introduced.

2.1 Current State of Emissions Modeling

Emissions models are currently used in numerous regions to track the energy use, greenhouse gas emissions, and criteria pollutant emissions resulting from vehicle traffic. As travel demand continues to grow and large urban centers face increased congestion and air quality problems, the importance of emissions modeling will continue to grow. Developing countries, which may have large populations and poorer vehicle emissions standards than more developed nations, represent an example where the application of emissions modeling could be extremely beneficial.

As emissions modeling is a field in development, numerous models using a number of different approaches currently exist. In a study comparing the ability of different emissions models to capture the effects of traffic congestion, Smit et al[3] classified the current range of emissions models into three categories: models that are based on vehicle kilometers traveled (VKT) and incorporate driving pattern data in their development, models that generate simplified velocity profiles as part of the emissions modeling process, and models that use velocity profiles generated through microscopic traffic simulation. The characteristics of these approaches, and Smit's findings on their suitability in accounting for the effects of congestion, are discussed below.

2.1.1 VKT Models

As their name implies, VKT models are based on the total distance travelled by vehicles in the road network. Distance based emissions factors (e.g. g CO2 per km) are developed for the types of vehicles for which emissions are to be modeled. The factors developed are often stated as a function of average vehicle speed to take into account different driving conditions. Total emissions in the road network are found by multiplying the total vehicle kilometers travelled by the appropriate factors. An example of a VKT based model is MOBILE6 [4] which is the most commonly used vehicle emissions model.

The biggest advantage of VKT based emissions modeling is its simplicity. Estimates of total kilometers travelled can be generated through macroscopic traffic simulation or measured using household travel survey data (which is collected by most municipalities for transportation planning purposes). When applied over a large area, which includes a wide range of road types and traffic congestion levels, Smit found VKT based emissions modeling to be quite accurate [3].

The disadvantage of this approach is that it is unable to model emissions at a localized level. Typical congestion levels are built into the model emissions factors which are not updated to account for changes in traffic conditions. Noland and Quddus identify this as a limitation of standard VKT modeling approaches and advise against applying them in situations where the effects of changes in accelerations are to be studied[5]. Furthermore, the congestion level built into the model is often hidden, making it unclear as to which situations it is appropriate to apply the model in.

2.1.2 Macroscopic Models with Simplified Velocity Traces

Another approach taken in emissions modeling involves applying simplified driving profiles to macroscopic traffic simulation data. Using the aggregate traffic performance data (e.g. average travel speed, traffic volume, and traffic density) provided by the macroscopic simulation, the traffic characteristics on each link in the road network can be assessed. Simplified driving profiles that are representative of the traffic characteristics on each link are then generated and applied to the vehicles travelling on them. Total emissions are found by applying power based emissions functions to the driving profiles for all the vehicles in the network.

Since this class of emissions model takes the traffic congestion level into account explicitly (by adjusting the driving profiles of the vehicles affected by it), Smit found that they were fully capable of capturing the effects of traffic congestion on emissions [3]. As a result of this, macroscopic models with simplified velocity traces can produce acceptable results when applied at a localized level making them appropriate for analyzing changes in transportation infrastructure.

The main limitation of this emissions modeling approach is that the simplified driving profiles may not be able to accurately represent real driving behavior in all situations. If the simulated driving profiles do not respond to changes in traffic conditions in the same manner which real drivers do then the results will not reflect the actual effect that the traffic conditions have on emissions.

2.1.3 Microscopic Models

Microscopic emissions models use velocity traces generated through microscopic traffic simulation for each vehicle in the network. Using the vehicle characteristics, the emissions model computes tractive power traces for each vehicle in the network. Power-based emissions functions are used to convert these to emissions traces and the results summed over all the vehicles in the network.

While microscopic traffic simulation has existed for a number of years, in the past its use was limited to small networks (e.g. single intersections) with macroscopic models being used to analyze larger situations. Increases in computational power have made it possible to begin to apply microscopic traffic simulation on a larger scale (e.g. transportation corridors, whole neighborhoods, etc.). The growth of the field of intelligent transportation systems (ITS) has led to an increase in the use of microscopic models since simulating ITS systems requires simulating the actions of individual drivers[6, Chu et al].

Microscopic emissions models explicitly take the level of traffic congestion into account, and Smit found that they were capable of simulating the effects of traffic congestion on vehicle emissions [3]. Since microscopic models simulate traffic with the highest level of detail, they are well suited to modeling emissions at a localized level making them useful for analyzing changes in transportation infrastructure.

While the level of detail provided by microscopic emissions modeling is advantageous, there are a number of drawbacks associated with this characteristic. First of all, microscopic emissions modeling is much more computationally intensive than the other two modeling approaches outlined. While advances in computer processing speed have helped make microscopic modeling feasible, simulating the second-by-second motion of all the vehicles in a large area still requires a considerable amount of time. A second drawback to this approach is that microscopic models are more difficult to calibrate and tune[7, Jha et al]. To simulate the actions of individual drivers, microscopic traffic models use a number of tuning parameters, all of which must be adjusted to reflect the behavior of drivers in the region being studied.

2.1.4 Summary of Approaches

The characteristics of the three different modeling approaches discussed are outlined below in Table 2.1. Since the focus of this study is on evaluating the effects of localized changes in transportation infrastructure, the use of VKT based emissions models is not explored further as they are not useful for this application. Macroscopic models with simplified driving profiles and microscopic models have both been shown to be suitable for modeling emissions at a localized level and are explored further in subsequent chapters.

While VKT models are not directly applied in this study, many of these models contain large databases of vehicle emissions data which can be used for calibration. MOBILE6, the U.S. EPA's mobile vehicle emissions inventory, is used as the calibration standard for emissions modeling done in this

Table 2.1: Summary of emissions modeling approaches

	VKT Models	Macroscopic Models	Microscopic Models
Model Basis	Total distance travelled	Simplified driving profiles	Microscopic traffic simulation
Level of Detail	Low	Medium	High
Computational Requirements	Low	Medium	High
Suitable for this Study?	No	Yes	Yes

study. The emissions inventory contained in MOBILE6 is based on over thirty years of experimental measurements and represents the wide range of vehicles making up the North American fleet. A discussion on the strengths and weaknesses of the MOBILE6 inventory can be found in Parrish's work[8]. Using MOBILE6 as a calibration standard ensures that the results obtained can be compared with results from other studies in the proper context.

2.2 Study Region

This study used a microscopic traffic simulation model covering the Whitemud Drive corridor in the city of Edmonton, Alberta, Canada between 111 Street and 178 Street. The model was developed and calibrated by the city's transportation department using traffic count data from the fall of 2005. The geometry of the model is outlined in Figure 2.1.

Whitemud Drive is the busiest transportation corridor in the City of Edmonton. The road is a controlled access freeway with three lanes of traffic in each direction through most of the study region. In 2010, over 120,000 vehicles per day travelled through its busiest section, the Quesnel Bridge, with a peak hourly flow of 10,000 vehicles per hour [9]. In 2005, the year of model calibration, peak hourly flow over the Quesnel Bridge was approximately 8,000 vehicles per hour [10]. The Whitemud Drive corridor was selected for this study since it provides the greatest potential in the Edmonton region for transportation infrastructure improvements to impact vehicle emissions due to the sheer volume of traffic.

2.3 Summary

This section outlined the current state of emissions modeling and the region of interest for this study. The characteristics of VKT models, macroscopic models with simplified velocity profiles, and microscopic models were presented and discussed. Due to their inability to capture the effects of localized changes in transportation infrastructure, VKT models are not explored further in this study. Macroscopic models with simplified velocity profiles and microscopic models are both suitable for this application and will be investigated further in subsequent chapters.

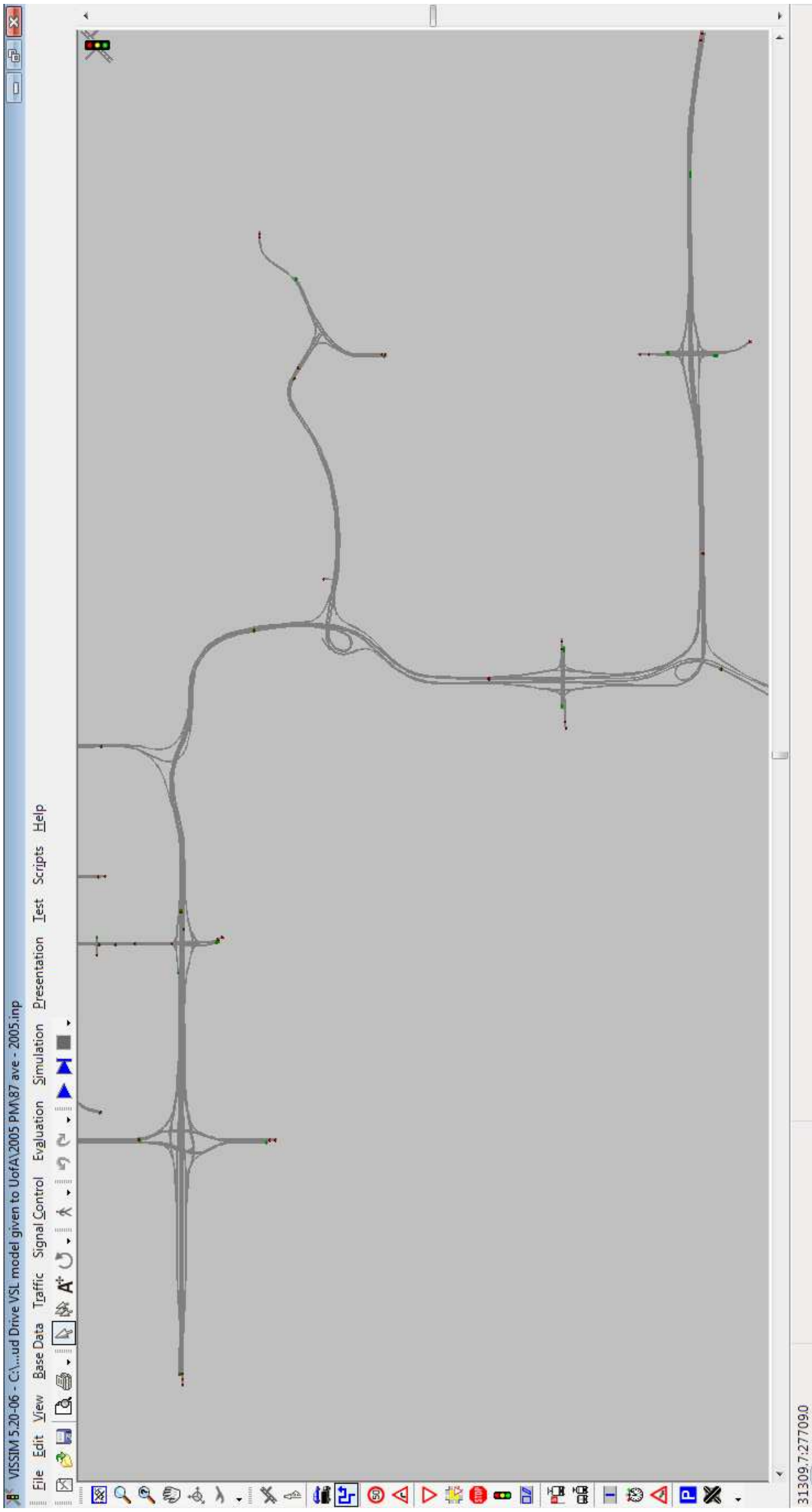

Figure 2.1: Region of study - Whitemud Drive corridor.

Chapter 3

Models and Sub-Models

The software model CALMOB6 is used to model emissions using velocity traces generated by both the macroscopic and microscopic approaches outlined in Chapter 2. The inner workings of the model are discussed in this chapter as well as the differences that arise with the two traffic simulation approaches.

3.1 The Software Model CALMOB6

CALMOB6 is a tractive power based vehicle emissions model that was developed by Checkel and some of his previous graduate students [11]. The model was initially created for the City of Edmonton to assist them in developing their transportation master plan. Since then, enhancements have been made to the model with it currently being capable of modeling energy use (gasoline and diesel, as well as a number of alternative fuels), greenhouse gas emissions, and a number of criteria pollutant emissions. Results from the model are calibrated against data from the MOBILE6 vehicle emissions inventory, hence the name CALMOB6.

Modeling emissions using a tractive power based model is a two step process: simulating the motion of the vehicles in the network, then using the simulated motion to model the corresponding emissions. These two steps will be described in detail in the sections below.

3.2 Vehicle Motion Simulation

The first step in the emissions modeling process involves simulating the motion of the vehicles in the network. As outlined in Chapter 2, there are two approaches that can be applied at this step that are capable of capturing the effects of traffic congestion at a localized level: macroscopic modeling with simplified velocity traces and microscopic modeling. CALMOB6 is capable of modeling emissions using either approach.

3.2.1 Macroscopic Traffic Data with Simplified Velocity Traces

CALMOB6 was initially developed to use traffic simulation data from the macroscopic model EMME/2[1]. Each section of road in the region being studied is defined in EMME/2 as a link with known gradient, length, and maximum velocity. Based on the demand for travel, EMME/2 distributes the traffic on the links in the region of study based on their capacity. The resulting traffic volumes and average travel speed for each link are stored with the link characteristics for use in CALMOB6. Further information on the EMME software package can be found at [12].

To model emissions, CALMOB6 requires second by second velocity traces for each vehicle in the network. To accomplish this, CALMOB6 compares the average travel speed on a link to the maximum velocity and uses this ratio to estimate the level of congestion on each link in the network. Based

[1]EMME is a French-English acronym for Equilibre Multimodal/Multimodal Equilibrium

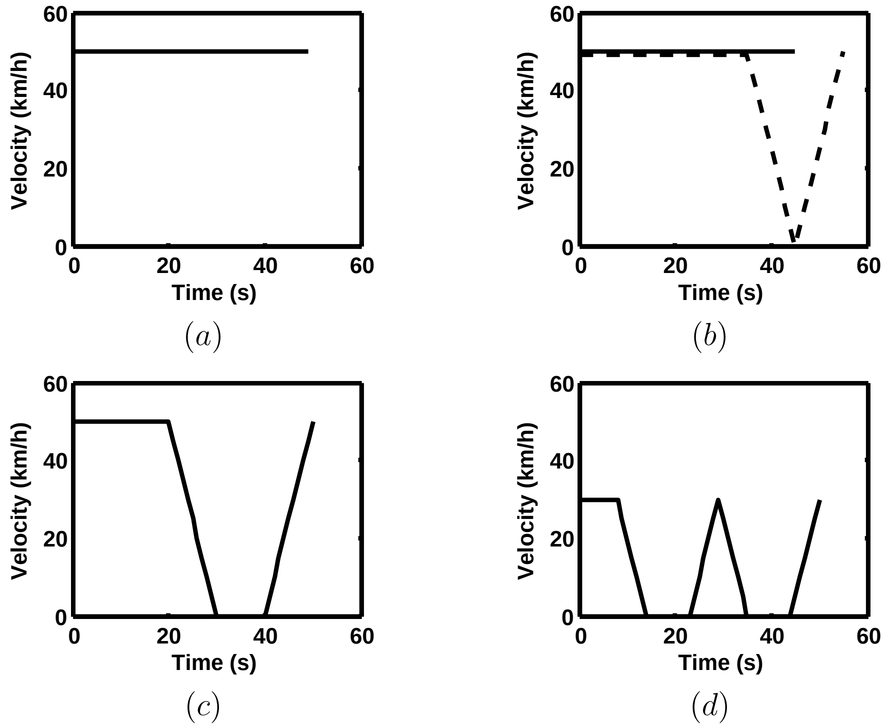

Figure 3.1: CALMOB6 simplified driving profiles: (a) Type 1, (b) Type 2, (c) Type 3, and (d) Type 4.

on the estimated level of congestion, one of four simplified velocity traces is assigned to the vehicles on the link:

- *Type 1 - Free flow* - all vehicles cruise through at a constant velocity.
- *Type 2 - Some stop* - some vehicles cruise through at a constant velocity and some are forced to make a stop.
- *Type 3 - All stop* - all vehicles make a single stop and possibly idle.
- *Type 4 - Congestion* - all vehicles make multiple stops and experience periods of idle. Maximum speeds and acceleration rates are reduced.

For light duty passenger vehicles, a constant acceleration rate of 1.5 m/s^2 is used when the vehicle starts and stops. At speeds above 50 km/h, the acceleration rate is adjusted to 1.0 m/s^2. Large, heavy duty vehicles are held to lower acceleration rates. Furthermore, their acceleration rates are reduced when traveling on links with large gradients to reflect the maximum power output of the vehicle. The process for generating the simplified profiles and the acceleration rates used are described in more detail by Busawon[13]. The four simplified velocity profiles are shown in Figure 3.1.

3.2.2 Microscopic Traffic Data

To expand the versatility of CALMOB6, work has been done enabling it to interface with traffic data from the microscopic traffic model VISSIM[2]. The current method requires the velocity profiles for all the vehicles in the VISSIM simulation to be recorded and the emissions computed by running CALMOB6 as an offline post-processor. Work is currently underway to enable emissions to be modeled while the VISSIM simulation is running in an online process.

In microscopic traffic simulation, the motion of each individual driver is simulated using a psycho-physical model. VISSIM uses the Wiedemann 74[14] car following model to describe the action of drivers as they react to the presence of other vehicles on the network[15]. Acceleration profiles are defined to determine the aggressiveness with which the drivers react when prompted by the psycho-physical model.

Figure 3.2 illustrates the Wiedemann 74 car following model. In the figure, the reaction of a driver approaching a slower travelling car from the rear is illustrated. As the distance between the two vehicles reaches the driver's reaction region, the faster vehicle begins to slow down to ensure an accident doesn't occur. The driver eventually settles at a speed that

[2] A German acronym translating to "traffic in towns - simulation"

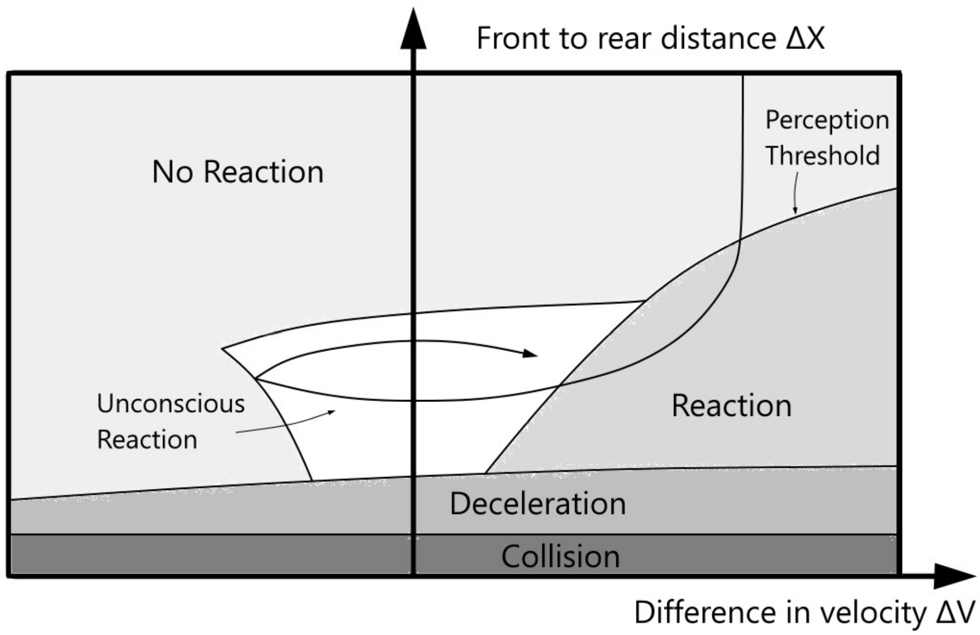

Figure 3.2: Simplified illustration of the Wiedemann 74 car following model as used in VISSIM[14, 15]

maintains a safe separation between the two vehicles. Similarly to a real driver, the simulated driver's speed and following distance oscillate within a region defined by unconscious reaction as a result of the driver's inability to perceive small changes in velocity and distance.

Acceleration profiles in VISSIM are defined as a function of vehicle velocity and contain maximum, mean, and minimum curves. Profiles outlining the desired acceleration and deceleration rates are specified to dictate how a driver reacts under typical conditions, as well as profiles outlining the maximum acceleration and deceleration rates which outline the physical limitations of the vehicle. VISSIM contains a number of built in profiles that can be used when performing simulations.

To improve the ability of the model to represent actual driving conditions in the study region, a custom desired acceleration profile, shown in Figure 3.3,

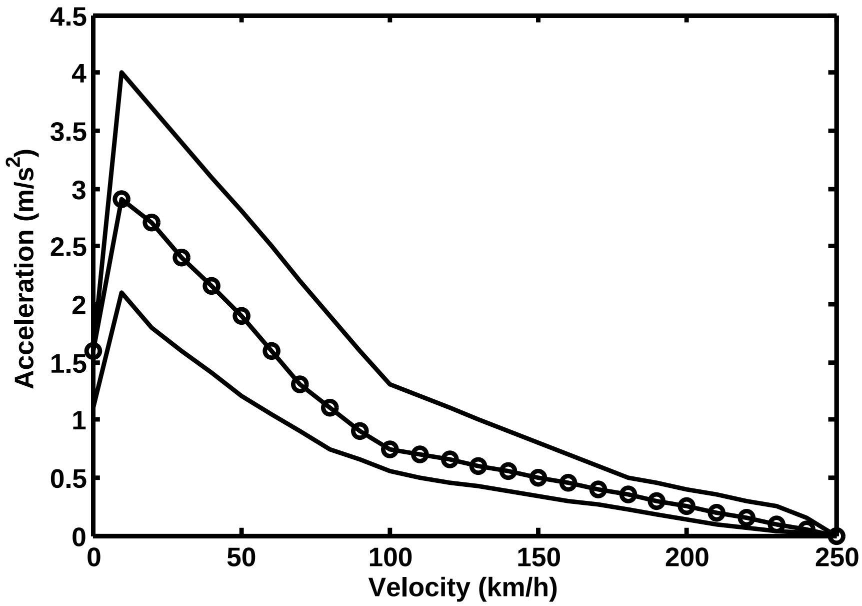

Figure 3.3: Custom desired acceleration profile (maximum, mean, and minimum acceleration rates)

was used. The profile was developed by Birtch[16] using data recorded in vehicles operating in the city of Edmonton during the fall of 2008. Further information on the development of the custom acceleration profile can be found in Birtch's report and in Appendix A. Default VISSIM profiles were used to define the desired and maximum deceleration rates and the maximum acceleration rates.

While calibration of the VISSIM model used in this study was handled by the city of Edmonton, adjusting the time step of the model was necessary to ensure that the modeled vehicle motion accurately represented reality. Using a time step of 1.0 s (typical in microscopic traffic simulation) reduces computational requirements; however, since drivers are only assessing their surroundings once every second, they are forced to make more emergency evasive maneuvers which results in larger than normal acceleration rates. When microscopic traffic simulation is performed for roadway capacity modeling, this generally isn't a concern as the motion of each individual vehicle is not as important as the aggregate performance of the network. However, when microscopic simulation is used for emissions modeling, this effect is important and the time step must be reduced.

A review of the literature suggested that a time step of 0.2 s produces acceptable results[17, Fellendorf]. The use of this time step has been investigated in Appendix B where time steps of 0.1 s and 0.2 s were found to produce similar results. Performing simulations with a 1.0 s time step resulted in the energy use and greenhouse gas emissions being 26 percent and 11 percent higher respectively due to the unrealistically jerky vehicle motion. As a result, a time step of 0.2 s was used in all simulations performed as part of this study.

3.3 Emissions and Fuel Consumption Simulation

The second step in the emissions modeling process is to use the simulated vehicle motion to compute the corresponding emissions. CALMOB6 handles this process using a tractive power based approach which involves defining the vehicle fleet, applying emissions and fuel consumption functions, and then calibrating the results against MOBILE6. This process is described in more detail below.

3.3.1 Defining the Vehicle Fleet

To model the emissions associated with a set of traffic simulation data, the characteristics of the vehicles operating in the region of interest must be specified. This involves breaking the fleet up into different classes, specifying the portion of the fleet made up by each class, and specifying the age distribution of the vehicles in the region. The effects of changes to the fleet operating in a region on emissions have been explored in [18].

3.3.1.1 Vehicle Classes

To describe the vehicles in the region being studied, CALMOB6 breaks the fleet up into twenty-one classes, as shown in Table 3.1. Representative characteristics for each of these vehicles classes, such as mass, frontal area, and coefficients of drag and rolling resistance, are built into the model. To facilitate calibration against MOBILE6 data, each of these classes correspond to MOBILE6 group numbers.

While the emissions modeling process requires that the fleet be broken up into very detailed classifications, traffic forecasting generally makes use of a smaller number of classes. EMME/2, for example, classifies traffic using five classes: passenger cars, light-duty trucks, medium-duty vehicles, heavy-duty vehicles, and buses. To accommodate these more general classification schemes, the twenty-one CALMOB6 classes are assigned to the more general EMME/2 classes as shown in Table 3.1. The traffic classification scheme used in the VISSIM microscopic model was set up to match the EMME/2 classification system and the same distribution procedure used.

To determine the characteristics of the vehicle fleet in the study region,

Table 3.1: Vehicle classification

EMME/2 Classification	CALMOB6 Classification	MOBILE6 Groups	Description
Light-Duty Vehicles	Light-Duty Vehicle - Mini	1,14	Passenger car Mini
	Light-Duty Vehicle - Economy	1,14	Passenger car Economy
	Light-Duty Vehicle - Large	1,14	Passenger car Large
	Light-Duty Truck 2	3,15	0-6000 lbs GVWR; 3751-5750 lbs LVW
	Light-Duty Truck 1	2,15	0-6000 lbs GVWR; 0-3750 lbs LVW
Light-Duty Trucks	Light-Duty Truck 3	4,28	6001-8500 lbs GVWR; 0-5750 lbs LVW
	Light-Duty Truck 4	5,28	6001-8500 lbs GVWR; >5751 lbs LVW
Medium-Duty Vehicles	Medium-Duty Vehicle 2b	6,16	8501-10000 lbs GVWR
	Medium-Duty Vehicle 3	7,17	10001-14000 lbs GVWR
	Medium-Duty Vehicle 4	8,18	14001-16000 lbs GVWR
	Medium-Duty Vehicle 5	9,19	16001-19500 lbs GVWR
Heavy-Duty Vehicles	Heavy-Duty Vehicle 6	10,20	19501-26000 lbs GVWR
	Heavy-Duty Vehicle 7	11,21	26001-33000 lbs GVWR
	Heavy-Duty Vehicle 8a	12,22	33001-60000 lbs GVWR
	Heavy-Duty Vehicle 8b	13,23	>60000 lbs GVWR
Buses	Transit Long	25,26	60’ articulating transit buses
	Transit New	25,26	40’ transit buses
	Transit Old	25,26	Older 2-stroke 40’ transit buses
	Transit Short	25,26	Community transit buses
	School Bus Long	25,27	Long school buses
	School Bus Short	25,27	Short school buses

the city of Edmonton periodically purchases vehicle registry data from the province of Alberta. A vehicle identification number (VIN) decoder is used to determine the class of each vehicle registered within the city. From this, appropriate fractions are determined for distributing the CALMOB6 classes within the traffic simulation classes. The registry data used in the simulations performed in this study was from 2006 and has been included in Appendix C.

3.3.1.2 Fleet Age Distribution

As time passes, technical advancements lead to more efficient, less-polluting vehicles. However, the fleet operating in a region is comprised of a mix of new and old vehicles manufactured over recent decades. To account for the differences in fuel consumption and emissions production between vehicles of different model years, a fleet age distribution is defined in CALMOB6. As shown in Figure 3.4, the fraction of the fleet made up of vehicles between zero and twenty-three years old is defined with older vehicles lumped at twenty-three years.

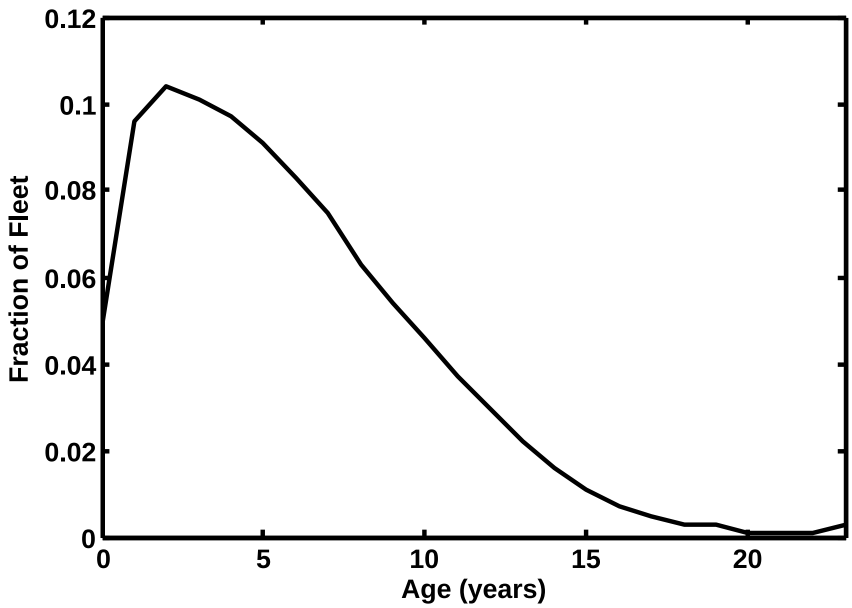

Figure 3.4: Fleet age distribution for vehicles in Edmonton.

Similarly to the vehicle classification step, the city of Edmonton uses vehicle registry data to determine the fleet age distribution. The fleet age distribution used in this study was based on registry data from 2006 and has been included in Appendix C.

3.3.2 Tractive Power Based Emissions Modeling

Once velocity traces have been simulated for all the vehicles in the network, and the fleet operating in the region of study defined, tractive power based emissions functions can be applied. Using Equation 3.1, CALMOB6 computes the second-by-second power requirements for all the vehicles traveling through the network. The vehicle mass, m, frontal area, A, coefficient of rolling resistance, C_R, and coefficient of drag, C_D, for each vehicle are known based on the vehicle's classification while the slope of the road, β, is given by the traffic model. The vehicle velocity, $\dot{x}$, and acceleration, $\ddot{x}$, are taken from the velocity profile at the instant in time for which the tractive power, u, is being computed.

$$u = \dot{x}\Big[m\ddot{x} + \rho C_D A\frac{\dot{x}^2}{2} + mC_R g + mg\sin(\beta)\Big] \tag{3.1}$$

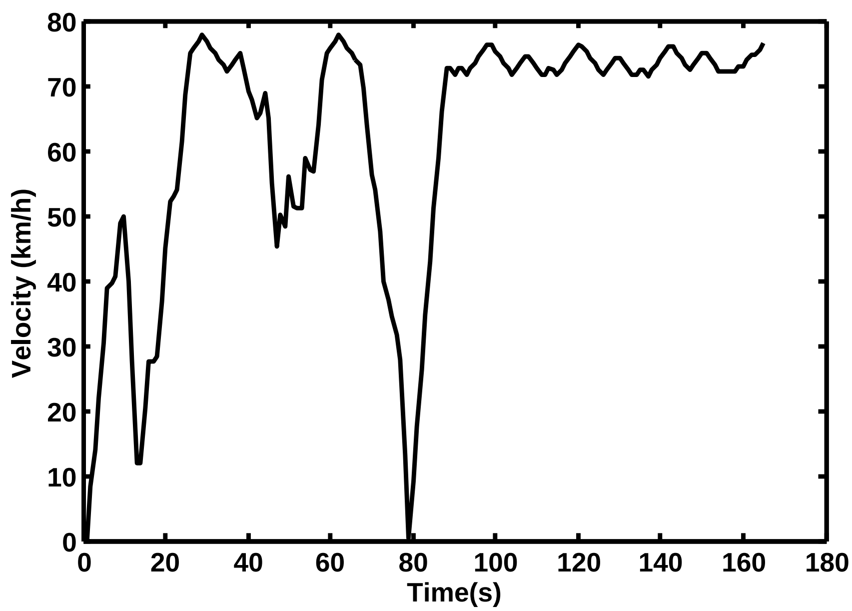

Figure 3.5: Sample velocity trace.

A sample velocity trace can be seen in Figure 3.5. In the trace, the vehicle travels a distance of 2.83 km with an average speed of 61.7 km/h. Using the characteristics associated with a large passenger car, the corresponding tractive power trace has been computed and is shown in Figure 3.6. The total power used by the vehicle while driving the velocity profile shown is 0.65 kWh with a peak instantaneous power requirement of 73.7 kW.

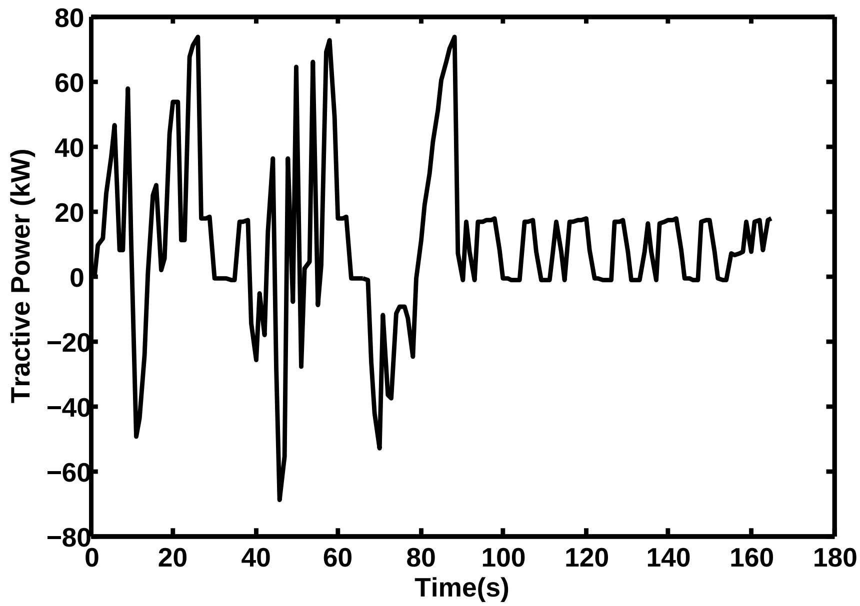

Figure 3.6: Sample tractive power trace.

Using the tractive power traces, CALMOB6 next determines the second-by-second fuel consumption and emissions production for all the vehicles traveling in the network. This is done using functions that relate the rate of consumption or production to the instantaneous tractive power. CALMOB6 incorporates functions relating tractive power to fuel consumption and production of carbon monoxide (CO), oxides of nitrogen (NO_x), non-methane hydrocarbons (NMHC) and particulate matter (PM). These functions, which have been developed for each class of vehicle, are based on dynamometer testing. Carbon dioxide (CO_2) emissions are determined from the fuel consumption using stoichiometry.

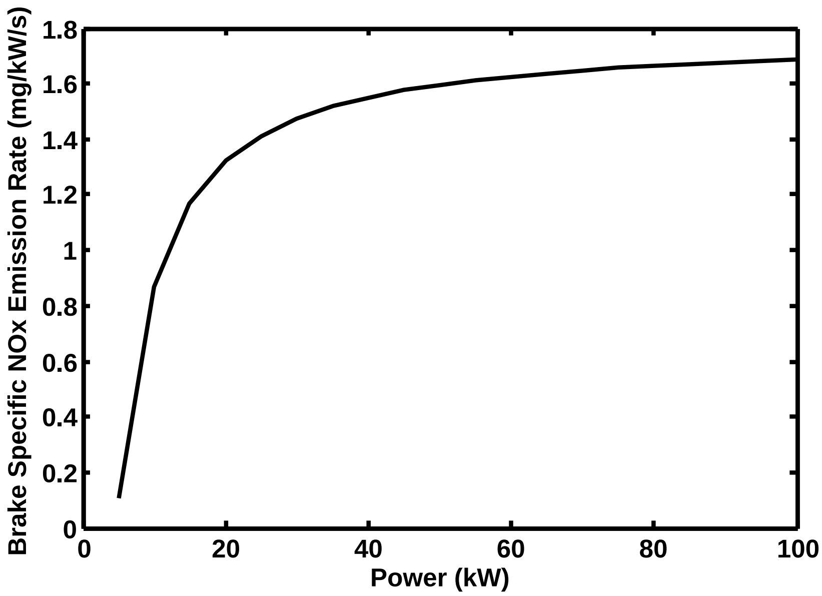

Figure 3.7: NO_x emission function for light duty gasoline vehicles.

A sample emissions function, showing the relationship between NO_x production and tractive power in a large passenger car, can be seen in Figure 3.7. Using this function, the second-by-second NO_x production rate for the sample tractive power trace shown above has been computed and is shown in Figure 3.8. The total amount of NO_x emitted by the vehicle driving the sample velocity profile is 4.09 g with a peak instantaneous rate of 0.13 g/s.

The total amount of fuel consumed and emissions produced by each vehicle while traveling through the network is determined by integrating its corresponding fuel consumption and emissions traces over time. The aggregate fuel consumption and emissions production is then determined by summing the results from all the vehicles in the network.

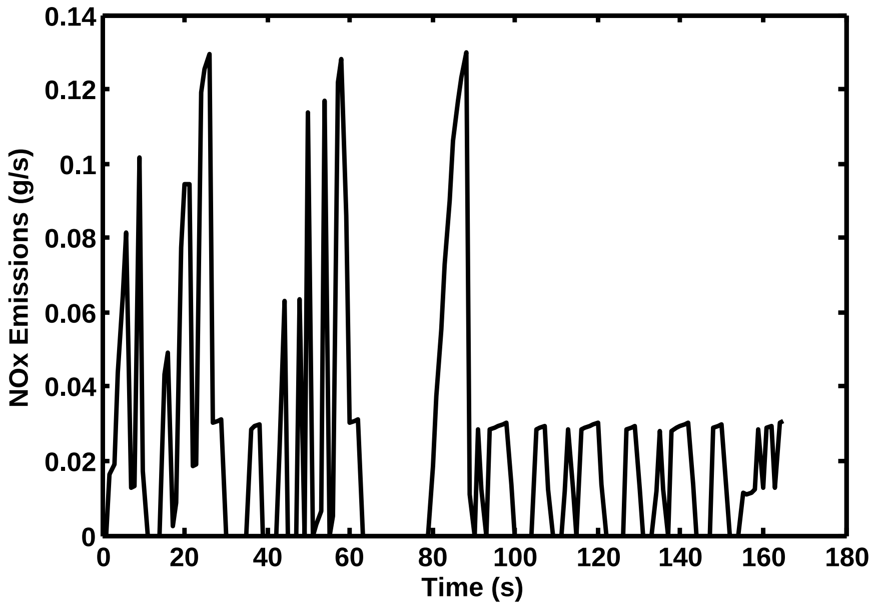

Figure 3.8: Sample NO_x emissions trace.

3.3.3 Calibration

The total amount of emissions produced by the traffic in the region of study is adjusted by a calibration factor. As outlined in Chapter 2, MOBILE6 is used as a calibration standard. MOBILE6's large database of vehicle emissions data and its widespread adoption as an emissions model make it a suitable choice for a calibration standard.

The calibration process is performed by running a vehicle from each class through a standard Federal Test Procedure (FTP) driving cycle. The emissions produced by each vehicle as it drives the cycle are computed using CALMOB6's tractive power based emissions functions. The results obtained are then compared to the emissions MOBILE6 predicts for the same class of vehicle over the same FTP driving cycle. Appropriate scaling factors are determined by comparing the two amounts and applied to the results obtained for the region of study. The calibration process is described in more detail in [13].

3.4 Summary

This section introduced the emissions model CALMOB6. The model can be used with both the macroscopic with simplified velocity traces and microscopic emissions modeling approaches. The power based emissions modeling approach used by the model was outlined and discussed as well as the differences that arise in the two traffic simulation techniques.

The development of the microscopic emissions modeling approach enables a number of analyses which could not be done using the existing macroscopic modeling approach to be performed. In Chapter 4, the microscopic emissions modeling approach is used to evaluate the performance of the simplified velocity profiles used in the macroscopic approach. The microscopic emissions modeling approach is then applied at a corridor level in Chapter 5 and used to evaluate the effects of potential transportation infrastructure projects on emissions.

Chapter 4

Application to a Single Link

In this chapter, the macroscopic with simplified velocity profiles and microscopic emissions modeling approaches are applied to traffic operating on a single link. The ability of each approach to capture the effects of a number of different traffic scenarios is investigated.

4.1 Introduction

CALMOB6's power-based emissions functions can be applied to simplified velocity profiles based on macroscopic traffic simulation and to velocity traces generated through microscopic simulation. While less computationally intensive than microscopic simulation, the use of simplified macroscopic profiles does not offer the same level of detail as microscopic simulation.

Velocity profiles for vehicles traveling along short sections of roadway in a variety of different driving conditions were simulated using the macroscopic approach with simplified velocity profiles and the microscopic approach. The short roadway links studied were selected to represent the wide variety of driving situations that vehicles experience while traveling in a large urban center. CALMOB6's power based emissions functions were then applied to the velocity profiles generated by the two approaches for each situation.

The purpose of this investigation was to study the effects that the different vehicle motion simulation approaches would have on the modeled emissions. The results obtained using the macroscopic and microscopic approaches were compared in each situation considered. From the results, comments on the suitability of each modeling approach have been made.

4.2 Procedure

To perform the analysis, velocity profiles were generated with the city of Edmonton's VISSIM model of the region of study. An algorithm was then used to sift through the data and identify ten microscopic velocity profiles with identical average speed, distance traveled, and free flow speed for each of the traffic situations considered. That set of link characteristics was then used to generate the macroscopic driving profiles for the same average conditions.

In each situation studied, CALMOB6's power-based emissions functions were applied to the velocity profiles generated using the two vehicle motion simulation approaches. To perform the analysis, the vehicle driving the velocity profiles was assumed to be a large passenger car with the characteristics shown in Table 4.1. The age of the vehicle was specified using the 2006 fleet age distribution for the City of Edmonton, which is shown in Appendix C, with a model base year of 2006.

Table 4.1: Large passenger vehicle characteristics

Classification	Large Passenger Car
Mass (kg)	1735
Frontal Area (m^2)	2.118
Coefficient of Drag	0.313
Coefficient of Rolling Resistance	0.013

Since this investigation involves the comparison of two modeling approaches, it is not possible to say that one method is correct and the other is not; however, since the microscopic method is based on measured acceleration rates and has been tuned by the city of Edmonton's transportation department to represent local drivers as accurately as possible, it makes sense to use it as a standard to which the macroscopic approach can be compared. For each traffic situation, the range of the mean modeled emissions for the ten microscopic profiles was determined with 95 percent confidence. These values were compared to the modeled emissions from the macroscopic approach to determine the suitability of the simplified profiles.

When identifying appropriate sets of microscopic traffic simulation data, care was taken to ensure that the distance traveled by the vehicles was appropriate for applying the simplified macroscopic driving profiles used by CALMOB6. Considering this was important since the driving profile generator was developed with a certain average link length in mind. Attempting to apply the model to links that are significantly longer or shorter than the intended length can result in the number of vehicle starts and stops being modeled incorrectly. In the city of Edmonton's EMME/2 macroscopic traffic model, the average link length is 0.46 km with a maximum length of 2.35 km. In the Whitemud Drive corridor specifically, the length of most of the links falls between 0.75 km and 1.00 km. Since CALMOB6 was initially designed for use with the city's EMME/2 model, these lengths were used as guidelines.

4.3 Results

The traffic situations studied can be split up into three categories: freeway driving, stop and go city driving, and congested driving. The results from the scenarios studied are presented below.

4.3.1 Freeway Driving

The first traffic condition studied was freeway driving. Two possible freeway driving scenarios were considered: a vehicle cruising at the speed limit along a freeway for an extended period of time, and a vehicle accelerating and decelerating while operating on a freeway. The two scenarios were chosen as they provide the opportunity to evaluate the ability of the two modeling approaches to capture the effects of the high speeds and acceleration rates typical of freeway driving.

4.3.1.1 Freeway Driving - Cruising

The first freeway driving situation studied represents a vehicle cruising at a constant velocity. As shown in Table 4.2, the link chosen was 1.68 km long with a speed limit of 80 km/h and an average travel speed of 79.8 km/h. By comparing the average travel speed to the speed limit, CALMOB6's simplified driving profile generator classified this as a Type 1 link. While the length of the link used in this scenario is slightly longer than the typical links used in the city of Edmonton's macroscopic EMME/2 model, the fact that it has been classified as a Type 1 link (which has no starts and stops) means that this will not affect the results.

The ten microscopic driving profiles identified for this situation are plot-

Table 4.2: Link characteristics for freeway cruising

Link Length (km)	1.68
Speed Limit (km/h)	80
Average Travel Speed (km/h)	79.8
CALMOB6 Link Type	1

ted in Figure 4.1. Being a Type 1 link, the vehicle driving the macroscopic profile travels through the link at exactly 80 km/h. In the microscopic profiles, on the other hand, the vehicle's velocity oscillates between approximately 75 and 85 km/h as a result of the region of unconscious reaction defined in the psycho-physical car following model.

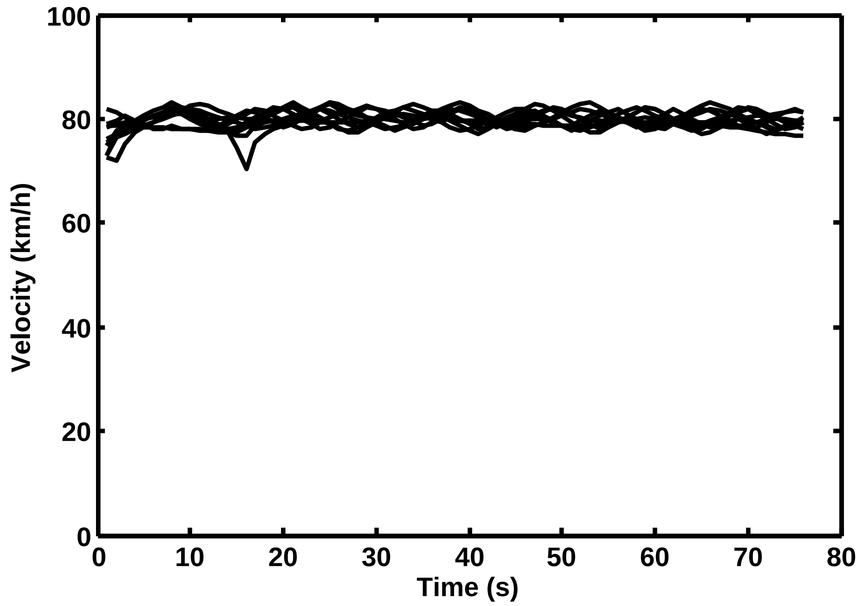

Figure 4.1: Ten microscopic velocity profiles for freeway cruising

Applying CALMOB6's power based emissions functions to the microscopic and macroscopic profiles resulted in the values presented in Table 4.3. As seen in the table, the maximum tractive power requirement was the largest discrepancy between two approaches with the microscopic profiles having a

Table 4.3: Freeway cruising link results. The range of microscopic values shown represent the mean with 95 percent confidence.

	Microscopic	**Macroscopic**	**Micro/Macro**
Energy Use (kWh/km)	0.122±0.004	0.116	1.05
Maximum Tractive Power (kW)	19.8	9.20	2.15
Gasoline Consumption (g/km)	54.8±1.4	57.4	0.95
CO Emissions (g/km)	2.23±0.07	2.37	0.94
NO_x Emissions (g/km)	0.160±0.007	0.148	1.08

peak requirement more than double that of the macroscopic profile. The difference between the values is a result of the periods of acceleration and deceleration experienced by the vehicles driving the microscopic profiles due to the oscillation in their velocity. The vehicle driving the macroscopic profile, on the other hand, maintained a constant velocity and experienced no acceleration or deceleration.

As a result of the periods of acceleration and deceleration experienced by the vehicles driving the microscopic profiles, their average energy use and NO_x emissions come out slightly higher (5 percent and 8 percent respectively) than in the macroscopic profile. The fuel consumption and CO emissions, on the other hand, come out slightly lower (5 percent and 6 percent) in the microscopic profiles due to the vehicles operating at a higher thermal efficiency while under higher loads. Aside from the peak tractive power, all of the modeled values agree within 8 percent suggesting that the simplified macroscopic profile does an acceptable job of capturing the effects of free flowing freeway traffic.

4.3.1.2 Freeway Driving - Acceleration and Deceleration

The second freeway driving situation studied represents a vehicle experiencing significant periods of acceleration and deceleration while traveling at freeway speeds. As shown in Table 4.4, the link chosen to represent this situation has a length of 0.76 km, a speed limit of 80 km/h, and an average travel speed of 59.4 km/h. To generate the simplified driving profile from these macroscopic characteristics, CALMOB6 classified this as a Type 2 link. To meet the required average travel speed, 74.6 percent of the vehicles are required to make a stop while traveling through the link while 25.4 percent cruise through freely.

Table 4.4: Link characteristics for freeway driving with acceleration and deceleration

Link Length (km)	0.76
Speed Limit (km/h)	80
Average Travel Speed (km/h)	59.4
CALMOB6 Link Type	2 (74.6% stop, 25.4% cruise)

To illustrate this situation, one of the ten microscopic profiles identified has been plotted in Figure 4.2 along with the simplified macroscopic profile. Since the link has been classified as a Type 2 link by the simplified driving profile generator, two macroscopic velocity profiles, representing vehicles that cruise through freely and vehicles that are forced to stop, exist on the plot.

Table 4.5: Freeway driving with acceleration and deceleration results

	Microscopic	**Macroscopic**	**Micro/Macro**
Energy Use (kWh/km)	0.255±0.039	0.196	1.30
Maximum Tractive Power (kW)	54.1	47.9	1.13
Gasoline Consumption (g/km)	80.2±7.6	69.6	1.22
CO Emissions (g/km)	3.52±0.31	3.06	1.15
NO_x Emissions (g/km)	0.339±0.052	0.259	1.31

Applying CALMOB6's power based emissions functions to the microscopic and macroscopic profiles produced the results seen in Table 4.5. In this case, the 95 percent confidence intervals for the mean microscopic emissions

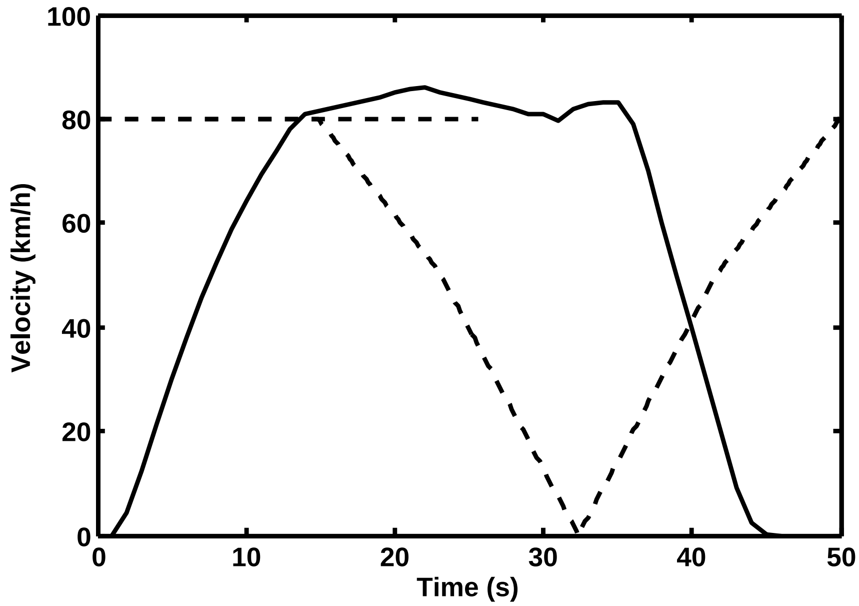

Figure 4.2: Comparison of microscopic (solid) and macroscopic (dashed) driving profiles for freeway driving with acceleration and deceleration

are very wide due to the wide variety of ways in which a vehicle can travel the specified link at an average speed of 59.4 km/h. Even with the large uncertainty in the mean microscopic emissions rates, the modeled macroscopic emissions fall significantly below the lower bounds of the mean microscopic emissions. Based on this, it does not seem that the simplified velocity profile adequately captured the effects of this traffic situation on emissions.

As shown in the table, the average energy use in the microscopic profiles was 30 percent higher than in the macroscopic profile. The discrepancy between these results is due to the substantially higher acceleration rates present in the microscopic profile. As outlined in Chapter 3, the desired acceleration rates used in the microscopic driving profiles vary between 3.0 m/s^2 and 1.0 m/s^2 for the velocities present in the driving profile above. On the other hand, the macroscopic profiles use acceleration rates that vary between 1.5 m/s^2 and 1.0 m/s^2. Furthermore, due to this being classified as a type 2 link, only a portion of the vehicles driving the macroscopic profile accelerate and decelerate with the rest cruising through the link at a constant velocity.

Although the total energy required by the vehicles driving the microscopic profile is 30 percent greater than required in the macroscopic profile, the fuel consumption rate is only 22 percent higher. The discrepancy between these two values is due to internal combustion engines operating at higher thermal efficiencies under higher loads. So although the vehicles driving the microscopic profiles did consume more fuel than the vehicle driving the macroscopic profile, the fuel consumption ratio is lower than the energy ratio.

The modeled emissions rates for both profiles show that the vehicles driving the microscopic profiles produced 15 percent more CO and 31 percent more NO_x than those driving the macroscopic profiles. Based on the results presented above, CO emissions are closely tied to fuel consumption while NO_x emissions are strongly dependent on energy use.

4.3.2 City Driving

The next traffic condition studied was city driving. Vehicles traveling on city streets operate at lower speeds than on freeways and are forced to start and stop more often due to the presence of signalized intersections. As a result of this, correctly capturing the acceleration events becomes even more important as they represent a larger portion of the resulting vehicle emissions than in freeway driving. To perform the comparison between the driving profiles, two possible city driving situations were considered: city driving with vehicles making a single stop on a roadway link and city driving with vehicles making multiple stops along a link.

4.3.2.1 City Driving - One Stop

The first city driving situation studied represents vehicles traveling along a section of roadway and making a single start and stop. As shown in Table 4.6, the vehicles in the microscopic profiles chosen travel a distance of 0.77 km at an average travel speed of 52.3 km/h along a road with a 60 km/h speed limit. While generating the simplified driving profile from these macroscopic characteristics, CALMOB6 classified this as a Type 2 link with 60.5 percent of the vehicles making a stop while traveling along the link and 39.5 percent driving through freely.

Table 4.6: Link characteristics for city driving with a single stop

Link Length (km)	0.77
Speed Limit (km/h)	60
Average Travel Speed (km/h)	52.3
CALMOB6 Link Type	2 (60.5% stop, 39.5% cruise)

The macroscopic profile and one of the ten microscopic profiles have been plotted together in Figure 4.3. As in Figure 4.2, two macroscopic driving profiles are included in the plot due to this being classified as a Type 2 link. The Type 2 classification for this link is a result of the lower acceleration rates and maximum velocity used in the macroscopic driving profiles. By accelerating more aggressively and occasionally exceeding the speed limit, the vehicles driving the microscopic profiles are able to meet the average link speed while making a complete start and stop. In the macroscopic profile, a fraction of the vehicles make a complete start and stop while the rest cruise through freely to give the specified average travel speed.

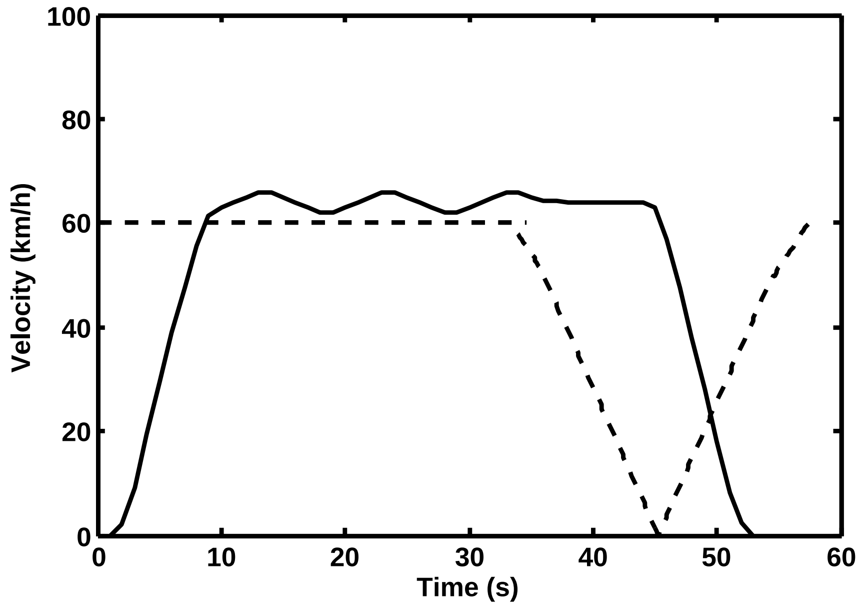

Figure 4.3: Comparison of microscopic (solid) and macroscopic (dashed) driving profiles on a city driving link with one stop

Table 4.7: Results for city driving with a single stop

	Microscopic	**Macroscopic**	**Micro/Macro**
Energy Use (kWh/km)	0.197±0.013	0.127	1.55
Maximum Tractive Power (kW)	63.4	40.2	1.58
Gasoline Consumption (g/km)	70.2±2.2	57.7	1.22
CO Emissions (g/km)	3.24±0.12	2.63	1.23
NO_x Emissions (g/km)	0.259±0.018	0.162	1.60

When CALMOB6's power based emissions functions are applied to the velocity profiles, the results shown in Table 4.7 are obtained. Comparing the macroscopic and microscopic results reveals that the results obtained do not agree within the 95 percent confidence interval. Energy use and NO_x emissions are approximately 60 percent higher in the microscopic profile than in the macroscopic profile while fuel consumption and CO emissions are 22 and 23 percent higher respectively. The larger difference between the energy used in the microscopic and macroscopic profiles in this case than in the previous freeway driving case is due to a larger portion of the vehicles driving the macroscopic profile traveling freely through the link without stopping.

Comparing these city driving results with those from the previous freeway driving situation reveals that the modeled emissions are responding to the changes in the driving profiles in the manner expected. The lower city travel speeds result in decreased distance specific rates of energy use and emissions.

4.3.2.2 City Driving - Multiple Stops

The second city driving situation studied represents lightly congested traffic with vehicles being forced to make multiple starts and stops. As shown in Table 4.8, the link selected to represent this situation has a length of 1.02 km, a speed limit of 50 km/h, and an average traffic speed of 35.0 km/h. To produce a simplified macroscopic driving profile based on these specifications, CALMOB6 classified this as a Type 3 link.

Table 4.8: Link characteristics for city driving with multiple stops

Link Length (km)	1.02
Speed Limit (km/h)	50
Average Travel Speed (km/h)	35.0
CALMOB6 Link Type	3

The simplified macroscopic driving profile and one of the microscopic driving profiles have been plotted in Figure 4.4. Due to this being classified as a Type 3 link, the macroscopic profile only simulates a single start and stop while the displayed microscopic profile involves two starts and stops. Idle time is inserted into the macroscopic profile to allow the vehicle to meet the specified average travel speed.

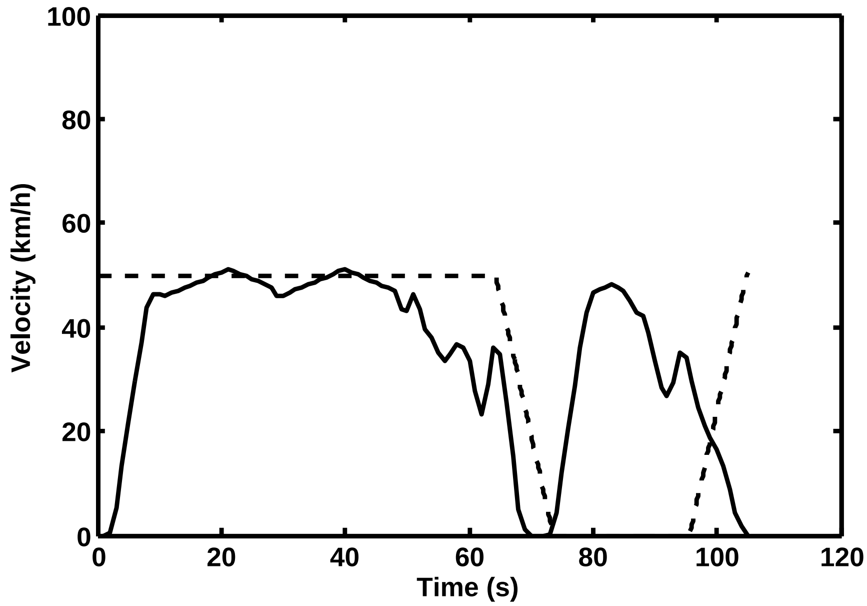

Figure 4.4: Comparison of microscopic (solid) and macroscopic (dashed) driving profiles on a city driving link with multiple stops

Table 4.9: Results for city driving with multiple stops

	Microscopic	**Macroscopic**	**Micro/Macro**
Energy Use (kWh/km)	0.220±0.005	0.123	1.79
Maximum Tractive Power (kW)	42.9	40.2	1.07
Gasoline Consumption (g/km)	80.1±0.8	70.2	1.14
CO Emissions (g/km)	3.77±0.04	3.15	1.20
NO_x Emissions (g/km)	0.292±0.007	0.155	1.88

Using CALMOB6's power based emissions functions to simulate the emissions resulting from the two driving profiles produces the results shown in Table 4.9. Due to the macroscopic profile incorporating only a single start and stop, the modeled energy use and NO_x emissions in the microscopic profile are approximately 80 percent higher. The idle time inserted in the macroscopic profile did a reasonable job of modeling the fuel consumption and CO emissions with the results from the two profiles being within 20 percent of each other. However, none of the modeled macroscopic emissions rates fall within the 95 percent confidence intervals of the microscopic simulations.

The lack of a second acceleration event in the simplified macroscopic velocity profile is due to the lower acceleration rates used in generating it. Performing a complete start and stop takes more time than in the microscopic profiles which results in it not being possible for the vehicle to start and stop twice while still meeting the required average travel speed.

4.3.3 Heavy Congestion

The last traffic condition studied was heavy congestion. Vehicles traveling on congested roads are forced to accelerate and decelerate more often than in light traffic conditions and the maximum velocities and acceleration rates they can attain are reduced. To perform the comparison between the two velocity profile simulation techniques, two congestion scenarios were considered: congested freeway traffic and congested city traffic.

4.3.3.1 Heavy Congestion - Freeway

The first congestion scenario considered was congested freeway traffic. As shown in Table 4.10, the link chosen to illustrate this has a length of 1.26 km, a speed limit of 80 km/h, and an average travel speed of 31.3 km/h. When producing the simplified macroscopic velocity profile to match these conditions, CALMOB6 classified this as a Type 4 link.

The Type 4 simplified macroscopic driving profile and one of the microscopic driving profiles have been plotted in Figure 4.5. By classifying this as a congested Type 4 link, CALMOB6 reduced the maximum travel speed from 80 km/h to 53.3 km/h and the maximum acceleration rate from 1.5 m/s^2 to

Table 4.10: Link characteristics for freeway congestion

Link Length (km)	1.26
Speed Limit (km/h)	80
Average Travel Speed (km/h)	31.3
CALMOB6 Link Type	4

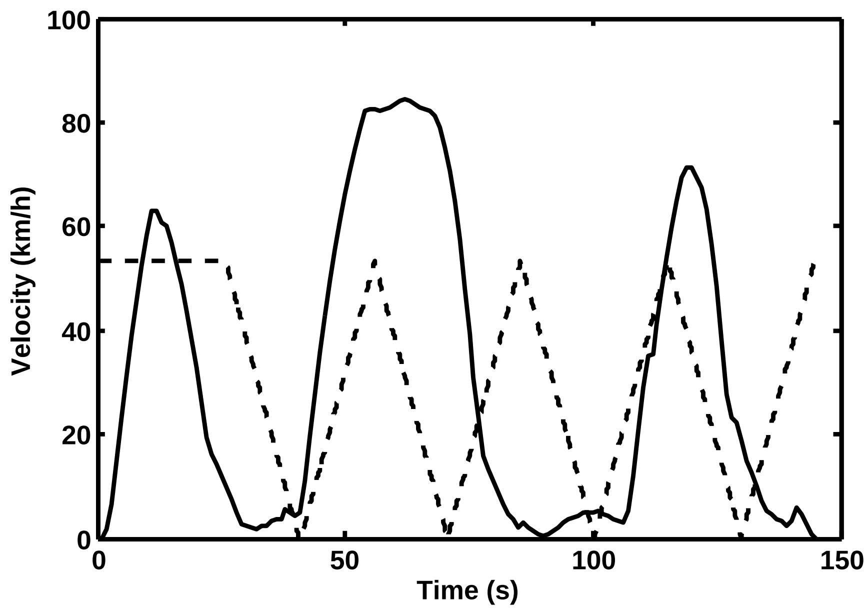

Figure 4.5: Comparison of microscopic (solid) and macroscopic (dashed) driving profiles on a heavily congested freeway link

1.0 m/s^2, as reflected in the macroscopic profile.

Applying CALMOB6's power based emissions functions to the driving profiles produced the results shown in Table 4.11. As seen in the table, energy use and NO_x emissions are approximately 35 percent higher in the microscopic profiles while gasoline consumption and CO emissions are 9 percent and 2 percent higher in the microscopic profiles respectively. All of the values modeled with the macroscopic profile come close to falling within the confidence intervals for the emissions from the microscopic profiles; however

Table 4.11: Congested freeway link results

	Microscopic	Macroscopic	Micro/Macro
Energy Use (kWh/km)	0.295±0.031	0.219	1.35
Maximum Tractive Power (kW)	50.6	30.3	1.67
Gasoline Consumption (g/km)	98.5±5.7	90.6	1.09
CO Emissions (g/km)	4.37±0.29	4.30	1.02
NO_x Emissions (g/km)	0.397±0.041	0.287	1.38

the intervals are fairly wide due to the wide variety of ways in which a vehicle can drive the chosen link at the specified average travel speed.

4.3.3.2 Heavy Congestion - City

The second congestion scenario was congested city traffic. As shown in Table 4.12, the link chosen to illustrate this has a length of 0.40 km, a speed limit of 60 km/h, and an average travel speed of 16.8 km/h. Due to the average travel speed being substantially lower than the speed limit, CALMOB6 classified this as a Type 4 link in producing the simplified macroscopic driving profile.

Table 4.12: Link characteristics for city congestion

Link Length (km)	0.40
Speed Limit (km/h)	60
Average Travel Speed (km/h)	16.8
CALMOB6 Link Type	4

The simplified macroscopic driving profile and one of the microscopic driving profiles have been plotted in Figure 4.6. Similarly to the Type 4 link used in the freeway congestion scenario, the maximum acceleration rate and travel speed were reduced when producing the simplified driving profile.

When CALMOB6's power based emissions functions were applied to the driving profiles the results shown in Table 4.13 were produced. Some of

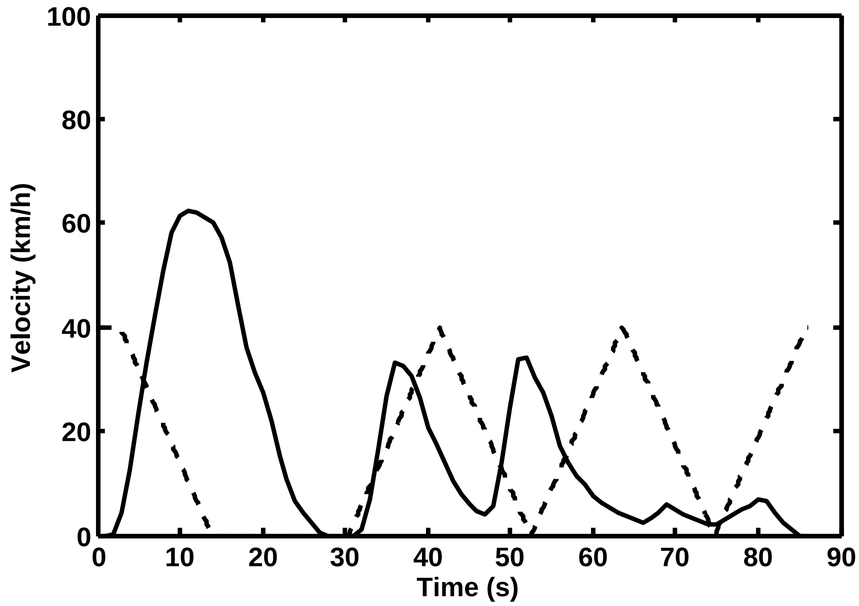

Figure 4.6: Comparison of microscopic and macroscopic driving profiles on a heavily congested city link

Table 4.13: Congested city link results

	Microscopic	Macroscopic	Micro/Macro
Energy Use (kWh/km)	0.333±0.042	0.255	1.31
Maximum Tractive Power (kW)	63.0	22.3	2.83
Gasoline Consumption (g/km)	132±6	131	1.01
CO Emissions (g/km)	5.96±0.40	6.09	0.98
NO_x Emissions (g/km)	0.453±0.056	.341	1.33

the values obtained from the macroscopic profile fall within the confidence intervals for the microscopic profiles; however, the intervals are fairly wide due to the variability that exists in congested driving situations. Energy use and NO_x emissions are both approximately 30 percent higher in the microscopic profiles than in the simplified macroscopic profile. The modeled fuel consumption and CO emissions, on the other hand, come out very close with both approaches.

4.3.4 Summary

The results from the six traffic situations studied have been summarized in Table 4.14. The distance specific energy use and fuel consumption from the microscopic and macroscopic profiles used in each scenario have been presented as well as the ratio between the two results. Since the NO_x emissions were found to closely follow energy use and the CO emissions to closely follow fuel consumption, these vales were not included in the summary table.

Table 4.14: Summary of microscopic and macroscopic approach comparison

Situation	**Modeled Emissions**	**Microscopic**	**Macroscopic**	**Micro/Macro**
Freeway - Cruising	Energy Use (kWh/km)	0.122±0.004	0.116	1.05
	Gasoline Consumption (g/km)	54.8±1.4	57.4	0.95
Freeway - Acceleration	Energy Use (kWh/km)	0.255±0.039	0.196	1.30
	Gasoline Consumption (g/km)	80.2±7.6	69.6	1.15
City - One Stop	Energy Use (kWh/km)	0.197±0.013	0.127	1.55
	Gasoline Consumption (g/km)	70.2±2.2	57.7	1.22
City - Multiple Stops	Energy Use (kWh/km)	0.220±0.005	0.123	1.79
	Gasoline Consumption (g/km)	80.1±0.8	70.2	1.14
Congestion - Freeway	Energy Use (kWh/km)	0.295±0.032	0.219	1.35
	Gasoline Consumption (g/km)	98.5±5.7	90.6	1.09
Congestion - City	Energy Use (kWh/km)	0.333±0.042	0.255	1.31
	Gasoline Consumption (g/km)	132±6	131	1.01

The Type 1 simplified macroscopic profile used in the freeway cruising scenario produced results that most closely matched those obtained from the microscopic profiles. As seen in the table, the energy use and fuel consumption predicted using both approaches fell within 5 percent of each other. Based on the similarity of the results obtained in this scenario, it does not appear that the oscillation in speed present in the microscopic profiles due to the drivers' inability to hold their speed perfectly constant is worth the additional complexity.

In the other traffic situations studied, the simplified macroscopic velocity profiles consistently resulted in lower modeled emissions rates than the microscopic profiles. The difference in the results is due to the simplified driving profiles using lower acceleration rates than the microscopic profiles. These lower acceleration rates resulted in lower peak power requirements in the macroscopic profiles than in the microscopic profiles. Furthermore, the slower acceleration rates meant that each start and stop in the macroscopic profiles required more time to complete than in the microscopic profiles. As a result of this, the macroscopic profiles required fewer acceleration events to meet the same average travel time. The disparity in gasoline consumption between the two modeling approaches was consistently less than the disparity in energy consumption due to the higher thermal efficiencies arising under higher tractive power loads in gasoline internal combustion engines.

4.3.5 Increased Acceleration Rates

When CALMOB6 was initially developed, the acceleration rate of 1.5 m/s^2 used in the simplified macroscopic driving profiles was selected based on the acceleration rates used in the US EPA FTP driving cycles. Based on the acceleration rates measured by Birtch[16], this value seems too low to represent typical drivers. To determine whether the simplified macroscopic profiles would more closely match the microscopic results if higher rates were used, the analysis was performed again using acceleration rates varying between 2.0 m/s^2 and 3.0 m/s^2.

As seen in Table 4.15, increasing the acceleration rate improved the performance of the simplified profiles in most of the traffic conditions. Both the freeway with acceleration and city driving with one stop situations showed

Table 4.15: Simplified macroscopic profiles with modified acceleration rates. The ratio of microscopic/macroscopic modeled emissions rate is shown in brackets after each value

		Macroscopic Profile Acceleration Rate			
Situation	**Modeled Emissions**	**1.5 m/s^2**	**2.0 m/s^2**	**2.5 m/s^2**	**3.0 m/s^2**
Freeway - Cruising	Energy (kWh/km)	0.116 (1.05)	0.116 (1.05)	0.116 (1.05)	0.116 (1.05)
	Gasoline (g/km)	57.4 (0.95)	57.4 (0.95)	57.4 (0.95)	57.4 (0.95)
Freeway - Acceleration	Energy (kWh/km)	0.196 (1.30)	0.243 (1.05)	0.252 (1.01)	0.253 (1.01)
	Gasoline g/km)	69.6 (1.15)	78.0 (1.03)	79.0 (1.01)	78.6 (1.02)
City - One Stop	Energy (kWh/km)	0.127 (1.55)	0.150 (1.31)	0.171 (1.15)	0.172 (1.15)
	Gasoline (g/km)	57.7 (1.22)	62.4 (1.13)	66.7 (1.05)	66.2 (1.06)
City - Multiple Stops	Energy (kWh/km)	0.123 (1.79)	0.125 (1.76)	0.127 (1.73)	0.126 (1.75)
	Gasoline (g/km)	70.2 (1.14)	70.1 (1.13)	69.8 (1.13)	69.3 (1.14)
Congestion - Freeway	Energy (kWh/km)	0.219 (1.35)	0.261 (1.13)	0.301 (0.98)	0.387 (0.76)
	Gasoline (g/km)	90.6 (1.09)	95.6 (1.03)	99.7 (0.99)	109 (0.90)
Congestion - City	Energy (kWh/km)	0.255 (1.31)	0.330 (1.01)	0.406 (0.82)	0.497 (0.67)
	Gasoline (g/km)	131 (1.01)	141 (0.94)	150 (0.88)	160 (0.82)

substantial improvements when acceleration rates of 2.5 m/s^2 and 3.0 m/s^2 were used. In both cases, the gap between the difference in energy use and the difference in fuel consumption was narrowed by increasing the acceleration rate.

Increasing the acceleration rate initially improved the performance of the simplified profiles in the congested scenarios; however, continuing to increase the rate resulted in the simplified profiles becoming too aggressive. When using Type 4 links to represent the congestion scenarios, CALMOB6 followed its standard practice of scaling the acceleration rates down to two thirds of the base value. Based on the results obtained here, this scaling factor would need to be adjusted if higher acceleration rates are desired for the Type 2 and 3 simplified profiles to ensure that the acceleration rate used in the Type 4 congested profile is not too high.

The results from the simplified macroscopic profile in the city with multiple stops scenario showed almost no improvement when the acceleration rate was increased. While surprising, it is possible that the link characteristics selected for this scenario result in a simplified profile that does not accurately represent the traffic conditions. When this modeling approach is applied over a number of links, inaccurate results from the occasional link are averaged out.

As expected, the simplified profile used in the freeway cruising scenario was unaffected by the changes in acceleration rate since the Type 1 link used does not include any acceleration events.

4.4 Conclusions

In this section, CALMOB6's power-based emissions functions have been used to compare microscopic and macroscopic velocity profile simulation techniques in a number of different traffic conditions. In situations where acceleration events were present, the simplified macroscopic velocity profiles were found to significantly under predict the emissions. By increasing the acceleration rates used in the simplified profiles, the modeled emissions were found to better match those obtained using microscopic traffic simulation methods.

The analysis performed in this chapter highlights the importance of accurate vehicle motion simulation in emissions modeling. If the modeled vehicle motion does not accurately represent driver behavior in the region of study, then the corresponding emissions will not be modeled reliably.

Chapter 5

Application to a Corridor

In this chapter, the microscopic emissions modeling approach is applied to an entire transportation corridor. The effects of two possible public transit initiatives on emissions are evaluated and a cost benefit analysis performed.

5.1 Introduction

Using the available microscopic traffic simulation data, the emissions resulting from the vehicular traffic in the study region were evaluated. The effects on emissions of two different public transit initiatives, which would shift trips from passenger vehicles to more efficient modes, were then evaluated by adjusting the volume of traffic present in the model. In each scenario, CO_2 emissions were focused on since they represent an effective way to track energy consumption when a variety of different fuels are used. Furthermore, climate change research has resulted in greenhouse gas emissions becoming a major emphasis in government policy. Estimates for the cost of each public transit initiative were developed and cost-benefit analyses performed.

To perform this analysis, the microscopic emissions modeling approach was used. The decision to use this approach rather than the macroscopic approach with simplified velocity profiles was based on the higher level of detail it offers and the available traffic simulation data provided by the city. It also provides more realistic vehicle motion simulation, as discussed in Chapter 4 of this dissertation.

The goal of this analysis was to illustrate how emissions modeling can be used to evaluate transportation infrastructure development scenarios. When performing the analysis, a number of assumptions needed to be made. Demand for travel was assumed to be fixed at the level the model was calibrated to. As a result, no latent demand was introduced when traffic volumes decreased as trips were shifted to other modes. Furthermore, no interaction with the demand on roadways outside the region of study was accounted for. While these assumptions make it difficult to provide a definitive answer as to how city planners should develop infrastructure in the region of study, the results obtained provide useful insight into the cost effectiveness of transit investments in reducing greenhouse gas emissions.

5.2 Scenarios Studied

In performing the analysis, three different scenarios were considered: the corridor in its current configuration, the corridor with a light rail transit (LRT) line running parallel to it, and the corridor with a major bus route running parallel to it. The scenarios studied are illustrated in Figure 5.1. When performing analyses involving competing parallel modes, determining the expected mode split is a crucial step in the analysis process. In this analysis, rather than estimating the mode split in the corridor a wide range of potential mode splits have been evaluated.

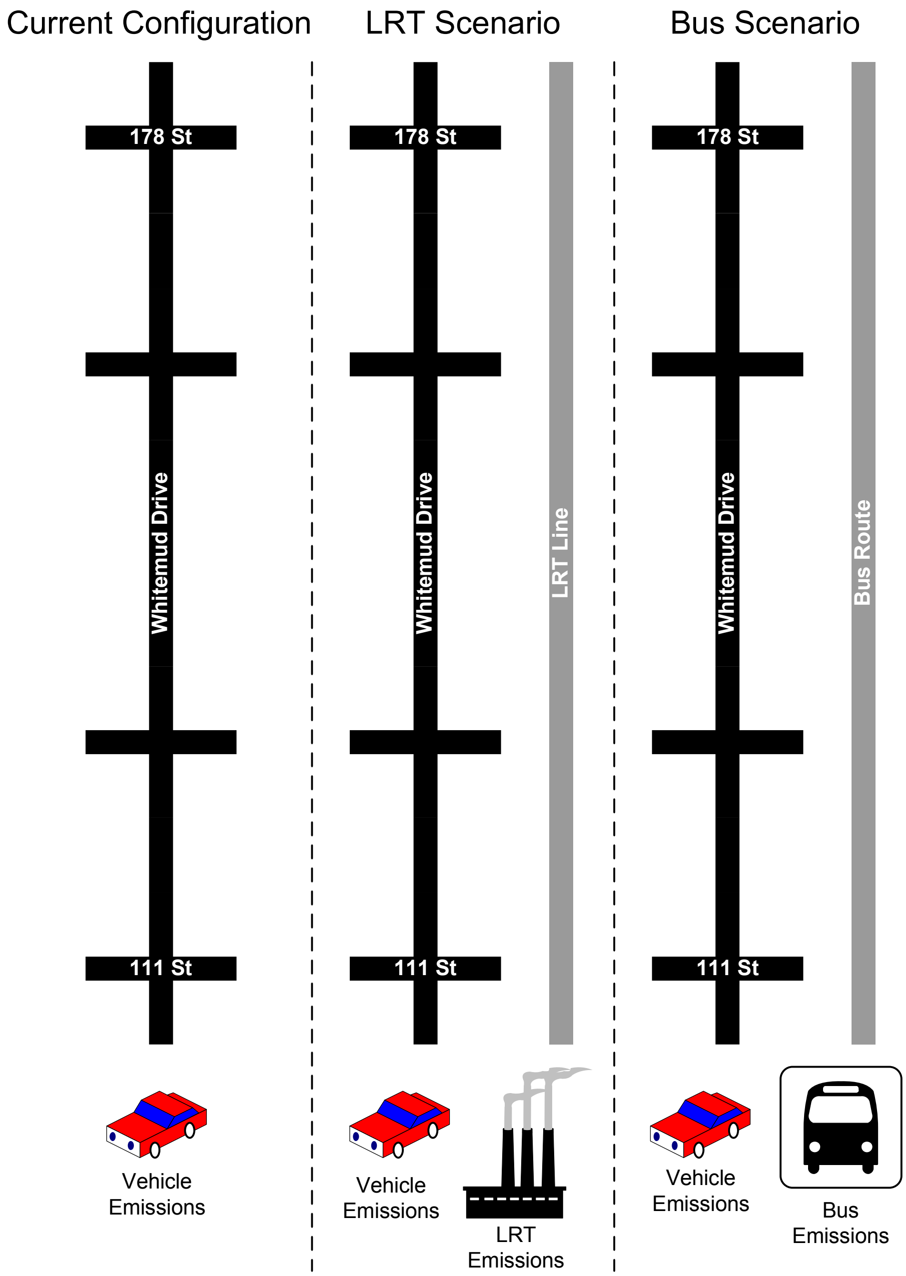

Figure 5.1: Illustrations of the scenarios studied: corridor in its current configuration, corridor with parallel LRT line, and corridor with parallel bus route. In this study, the number of trips through the corridor was held constant in all scenarios.

5.2.1 Current Configuration

Whitemud Drive is the busiest transportation corridor in the city of Edmonton. In 2005, the calibration year of the microscopic corridor model, nearly 8,000 vehicles per hour passed through the corridor during the PM peak period[10]. Using the mode split outlined in Edmonton's 2005 Household Travel Survey[19], it can be estimated that each vehicle trip represents 1.35 passenger trips. Applying this value to the region of study indicates that over 10,000 passenger trips per hour are made during the PM peak period, as illustrated in Table 5.1.

Table 5.1: Whitemud Drive PM peak hour traffic characteristics

PM Peak Hour Vehicle Trips	Eastbound	3,114
	Westbound	4,790
PM Peak Hour Passenger Trips	Eastbound	4,204
	Westbound	6,476

Using the VISSIM model of the region of study, traffic simulation data representing one hour of PM peak conditions was generated. As shown in Table 5.2, 24,493 vehicles traveled a distance of 124,480 km at an average speed of 47.0 km/h during that time. CALMOB6's power based emissions functions were applied to the velocity traces for each of the vehicles traveling through the corridor to evaluate the resulting emissions. The amounts of CO_2, CO, and NO_x emitted during the one hour simulation period are outlined in Table 5.2. When simulating the emissions, the fleet composition and age distribution outlined in Appendix C were utilized.

To determine the total daily emissions produced in the region of study, the 2005 Household Travel Survey[19] was again utilized. In the survey, 18 percent of travel is found to occur between the hours of 4-6 PM. The results

Table 5.2: PM peak period one hour results

Volume	24,493
VKT (km)	124,480
Average Speed (km/h)	47.0
CO_2 Emissions (kg)	23,607
CO Emissions (kg)	324.8
NO_x Emissions (kg)	36.7

shown above, representing one hour of PM peak travel, were doubled to estimate the emissions occurring between 4-6 PM. The 18 percent factor was then applied to determine the total daily emissions produced in the region of study, as shown in Table 5.3. Scaling the results in this manner assumes that the distance specific emissions rates remain constant throughout the day. While not the best assumption, this approach had to be used due to the limited traffic simulation data set available.

Table 5.3: Daily emissions

VKT (km)	1,383,112
CO_2 Emissions (kg)	262,302
CO Emissions (kg)	3,608
NO_x Emissions (kg)	408.2

To convert the daily emissions produced in the corridor to total annual emissions, two factors have to be taken into account: seasonal variations in traffic volumes and the differences between weekday, weekend, and holiday traffic volumes. The factors used by planners at the city of Edmonton to perform this step are outlined in Table 5.4[20]. As shown in the table, an average weekday is assumed to have 99 percent of the traffic present in the fall weekday represented in the traffic model. Saturdays and statutory holidays are assumed to have 81.8 percent of the traffic that a fall weekday does while Sundays are assumed to have 63.1 percent of the traffic.

Table 5.4: Process for converting daily emissions to annual emissions

	Fraction of Fall Day	Number of Occurances	Product
Weekday	0.99	249	246.5
Saturdays and Stat. Holidays	0.818	64	52.36
Sundays	0.631	52	32.79
		Sum:	331.7

Using the process outlined above, the emissions produced in the region of study on a typical fall day were converted to annual emissions. As shown in Table 5.5, 86,966 tonnes of CO_2, 1,197 kg of CO, and 135 kg of NO_x are emitted in the corridor every year. These values are treated as a baseline to which the alternative scenarios studied are compared.

Table 5.5: Annual emissions

CO_2 Emissions (tonne)	86,966
CO Emissions (kg)	1,197
NO_x Emissions (kg)	135

5.2.2 Reduced Traffic

Since both the LRT line and bus route scenarios involve shifting trips currently made by passenger vehicles to other modes, the effects of reduced traffic levels in the region of study had to be determined. Using the VISSIM model of the region, traffic volumes were scaled to 90 percent, 75 percent, and 50 percent of the baseline scenario. The resulting emissions are shown in Table 5.6. As seen in the table, reducing the traffic volume resulted in a decrease in the distance specific emissions rates due to congestion being reduced.

Since the focus of this study is on comparing the CO_2 emissions resulting from each scenario, a function to describe the distance specific CO_2 emissions

Table 5.6: Effect of reduced traffic on emissions

	100%	90%	75%	50%
Vehicles	24,493	22,288	18,548	12,381
VKT (km)	124,480	115,869	98,063	65,658
Avg. Speed (km/h)	46.97	51.46	56.37	58.40
Total CO_2 (tonne)	23.59	21.15	17.28	11.62
Distance Specific CO_2 (g/km)	189.6	182.5	176.4	177.2

as a function of the fraction of original traffic volume was fit to the data. As shown in Figure 5.2, the CO_2 emissions were found to initially decrease as the traffic volume was reduced before leveling off at approximately 177 g/km at 80 percent of the original traffic volume. The function used took the form of an exponential plus a constant and fit the data with an R^2 value of 0.97.

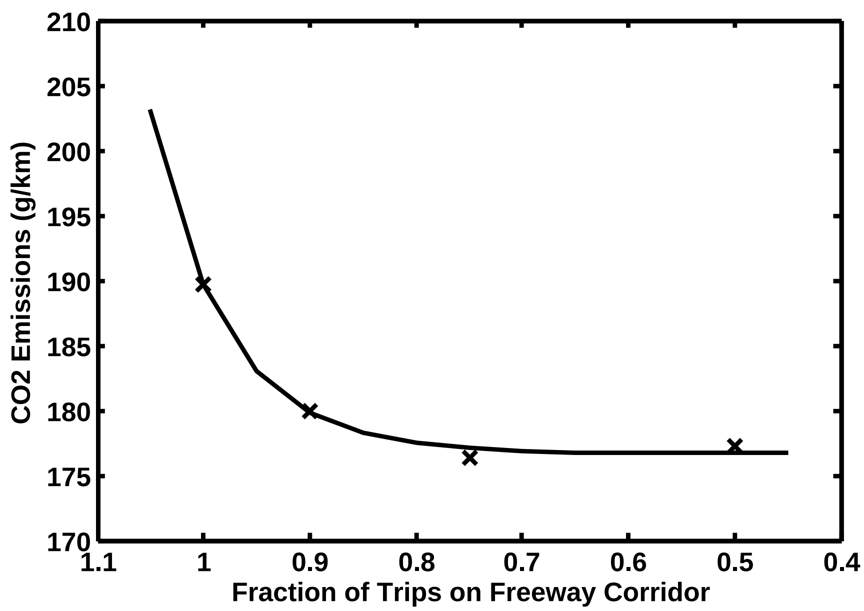

Figure 5.2: Distance specific CO_2 emissions as a function of traffic volume

The function developed was then used to evaluate the effects of shifting vehicle trips to the transit modes present in each of the scenarios studied. The process used to evaluate the LRT and bus route scenarios and the results obtained are presented below.

5.2.3 Light Rail Transit

The first alternative scenario considered for the corridor involved the construction of an LRT line. The line was assumed to run parallel to Whitemud Drive from one end of the corridor to the other, a distance of 10.9 km. As with all the scenarios studied, the number of trips made through the corridor was held constant with no latent demand being introduced as traffic volumes decreased due to the shift in travel mode. No interaction between the line and the traffic on the roadway was considered as the line was assumed to be completely grade separated. While it would be expected that trips made in nearby corridors would be shifted to a new LRT line, this effect was not accounted for in this analysis.

Trains on the line were assumed to operate in a fashion similar to Edmonton's current LRT system. As outlined in Table 5.7, cars were taken to have a capacity of 140 passengers and operate in a mix of three and four car trains. The 5 minute headway during the peak period gives the system the capacity to move 5,880 passengers per hour in each direction. Based on the traffic volumes presented above in Table 5.1, the line would be capable of handling over 90 percent of the trips in the corridor that are currently made by passenger vehicles, with flow in the westbound direction being the limiting factor. It is unlikely that the LRT mode split in the corridor would ever be that high; however, since this analysis does not account for interaction with parallel corridors (which would contribute trips to the LRT line) large mode splits will be considered.

While shifting passenger trips to an LRT line reduces emissions from ve-

Table 5.7: LRT line characteristics

Length	10.9 km
Car Capacity	140 passengers
Average Train Length	3.5 cars
Peak Headway	5 minutes
Peak Capacity	5,880 passengers/hour

hicles, emissions are produced in generating the electricity required to power the trains. To account for this, the daily electricity consumption for the system had to be estimated.

Similarly to Edmonton's current LRT system, trains were assumed to operate with a 5 minute headway during the AM and PM peak periods, a 10 minute headway during the midday period, and a 15 minute headway during the evening. Based on these frequencies, and accounting for a few deadheading trips, 302 trips along the 10.9 km line would be made everyday. Using an average train length of 3.5 cars gives a daily VKT of 11,674 km, as shown in Table 5.8.

Table 5.8: LRT electricity requirements

Link Length	10.9 km
Daily Train Trips	302
VKT	11,674 km
Electricity Requirements	3.5 kWh/km
Daily Electricity Consumption	40,859 kWh

The city of Edmonton currently utilizes Siemens SD-160 light rail vehicles in its LRT system. Assuming that the LRT line in this scenario would use the same vehicles, an average electricity consumption rate of 3.5 kWh/vehicle km[21] can be used to estimate a total daily electricity consumption of 40,859 kWh.

To evaluate the emissions resulting from producing the electricity powering the LRT line, the electricity generation mix for the region of study must be specified. As shown in Table 5.9, the majority of the electricity produced in Alberta is generated using coal and natural gas with the remainder coming from hydro and wind[22, Handford]. Using factors determined by Handford through life cycle analyses of each of the generation sources, the greenhouse emissions resulting from producing the 40,859 kWh required by the LRT every day were found to be 32,194 kg, as shown in Table 5.10.

Table 5.9: Electricity generation mix

Generation Method	**Percent**
Hydro (reservoir)	3.37
Coal	59.31
Natural Gas	37.17
Wind	0.15

Table 5.10: Daily LRT emissions

CO_2 Emissions (kg)	32,194
SO_2 Emissions (kg)	22
NO_x Emissions (kg)	20

The emissions benefits of running the LRT line depend on the fraction of vehicle trips assumed to be shifted to the line. Plots of the daily CO_2 emissions in the corridor and the amount of CO_2 mitigated as a function of the fraction of trips made by vehicular traffic are shown in Figure 5.3 and Figure 5.4. Both plots are shown over the range of 0 to 90 percent of trips being shifted to LRT, as limited by its capacity.

As seen in Figure 5.3, daily CO_2 emissions in the corridor would be 295 tonnes if no trips were shifted to the LRT. This value represents the 262.5 tonnes currently emitted by vehicles in the corridor plus the 32.2 tonnes emitted as a result of the LRT electricity requirements. With 90 percent of trips shifted to the LRT line, daily CO_2 emissions are decreased to 56.6 tonnes per day.

Figure 5.4 illustrates the level of LRT ridership required to offset its electricity requirements. When less than 10 percent of trips are shifted to the LRT line, more CO_2 is emitted in the corridor than in the baseline case. The peak amount of CO_2 mitigated is 206.0 tonnes when 90 percent of trips are shifted to the LRT line.

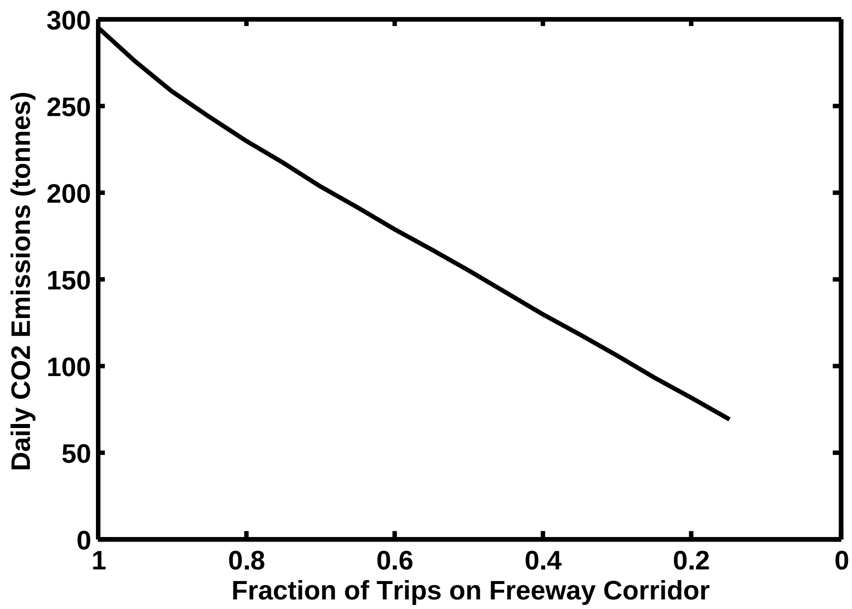

Figure 5.3: Daily corridor CO_2 emissions versus fraction of trips shifted to LRT

While an LRT line can provide substantial reductions in emissions, a substantial investment in infrastructure is required in constructing one. To determine the cost effectiveness with which an LRT line would reduce greenhouse gas emissions in the corridor, a cost-benefit analysis was performed. Based on previous LRT construction in the city of Edmonton, the 10.9 km line considered, and the light rail vehicles required to service it, was assumed

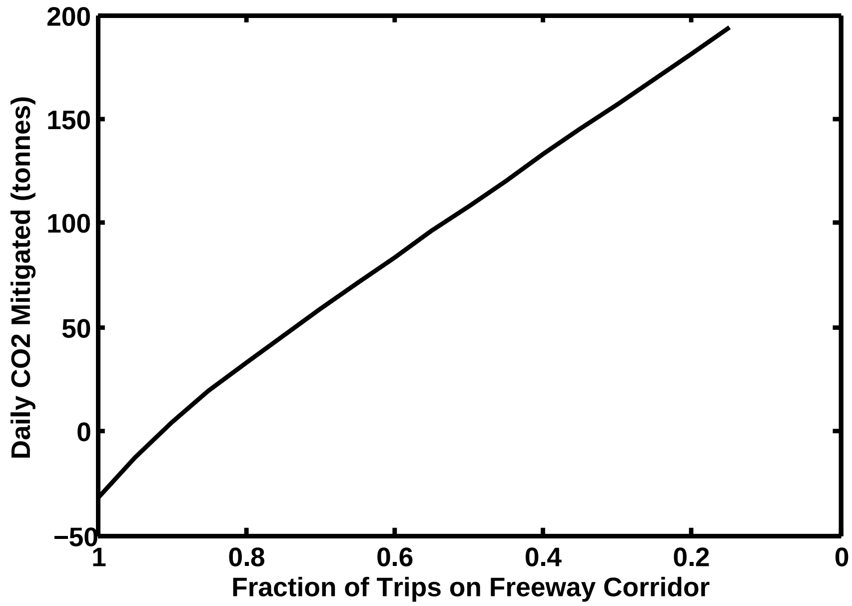

Figure 5.4: Daily CO_2 mitigated versus fraction of trips shifted to LRT

to cost $1 billion. When LRT lines are constructed in Edmonton, a 75 year lifespan is used in their design[23]; therefore, the construction cost was split over this timeframe. The annual electricity costs were factored into the analysis with an assumed price of $0.10 per kWh. No data on maintenance or other operating costs was available so these costs were not included in this calculation. The resulting cost per tonne of CO_2 mitigated was plotted against the fraction of trips made by vehicular traffic, as shown in Figure 5.5.

As seen on the plot, the cost effectiveness of an LRT line at reducing greenhouse gas emissions is largely dependent on ridership levels. The cost per tonne of CO_2 mitigated ranges from several thousand dollars when less than 25 percent of trips are shifted to the LRT line to $215 when 90 percent of trips are made using the LRT.

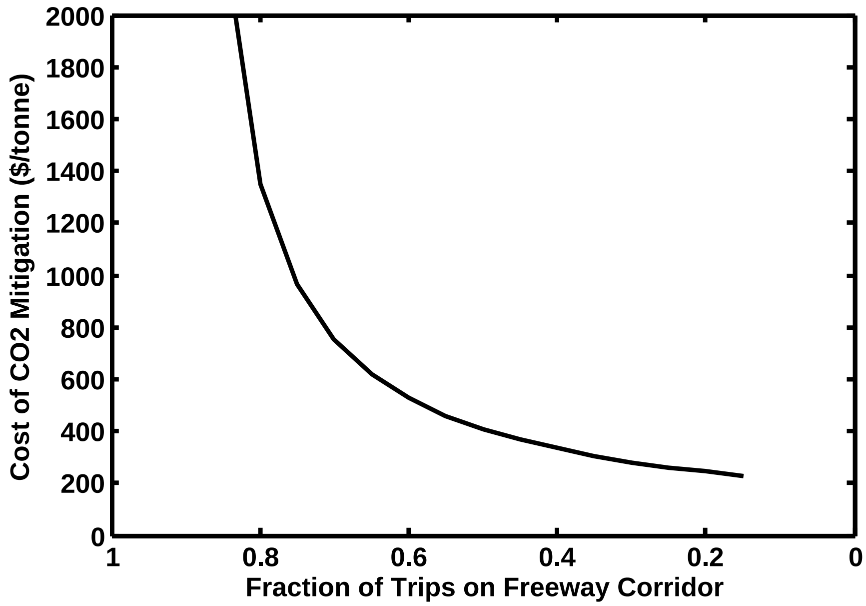

Figure 5.5: Cost-benefit analysis on LRT line

5.2.4 Bus Route

The second alternative for the study corridor involved operating a high frequency express bus route. The route was assumed to follow Whitemud Drive for its 10.9 km length through the corridor and the buses were assumed to not interfere with the flow of traffic on the roadway. As with the other two scenarios, the number of trips through the corridor was held constant with no latent demand being introduced when traffic volumes were reduced.

The characteristics of the proposed bus route are outlined in Table 5.11. Buses were assumed to have a capacity of 80 passengers and operate with a one minute headway during the PM peak period. As shown in the table, the proposed route would have a capacity of 4,800 passengers per hour in each direction. Based on the traffic volumes currently present, the bus line would be capable of handling approximately 75 percent of the trips made in the corridor with flow in the westbound direction being the limiting factor. Rather than estimating an appropriate bus mode split for the corridor, the entire possible range (from zero ridership to the system at full capacity) has been investigated.

Table 5.11: Bus route characteristics

Route Length	10.9 km
Bus Capacity	80 passengers
Peak Headway	1 minute
Peak Capacity	4,800 passengers/hour

To account for the fuel consumed and emissions produced by the bus route, the results from the ETS Technology Review performed by Checkel were used[24]. Checkel's work established the distance specific fuel consumption, emissions, and operating costs for a variety of transit buses operating in the city of Edmonton. The buses operating on the route proposed in this scenario were assumed to be clean diesel buses (model year 2007 and newer) similar to what the city of Edmonton uses to service the majority of its routes.

To apply the factors, the daily VKT for the buses servicing the route needed to be established. Buses were assumed to service the route with a 1 minute headway during the AM and PM peak periods, a 2 minute headway during the midday period, and a 3 minute headway during the evening. As shown in Table 5.12, this resulted in a daily VKT of 15,914 km. Using factors of 1.966 kg/km of CO_2 emitted and a cost of $2.25/km[24, Checkel], the daily CO_2 emissions and operating costs were determined to be 31,287 kg and $35,806.50 respectively.

Similarly to the LRT line, the emissions benefits of the bus route are

Table 5.12: Bus route daily VKT

Route Length	10.9 km
Daily Bus Trips	1,460
VKT	15,914 km
CO_2 Emissions Rate	1.966 kg/km
Daily CO_2 Emissions	31,287 kg
Operating Cost	\$2.25/km
Daily Operating Cost	\$35,806.50

dependent on the fraction of vehicle trips it absorbs. To illustrate this, plots of the daily CO_2 emissions in the corridor and the amount of CO_2 mitigated as a function of the fraction of trips made by vehicular traffic are shown in Figure 5.6 and Figure 5.7. The plots have been created over the range of 0 to 75 percent of trips being shifted to the bus route, as limited by its capacity.

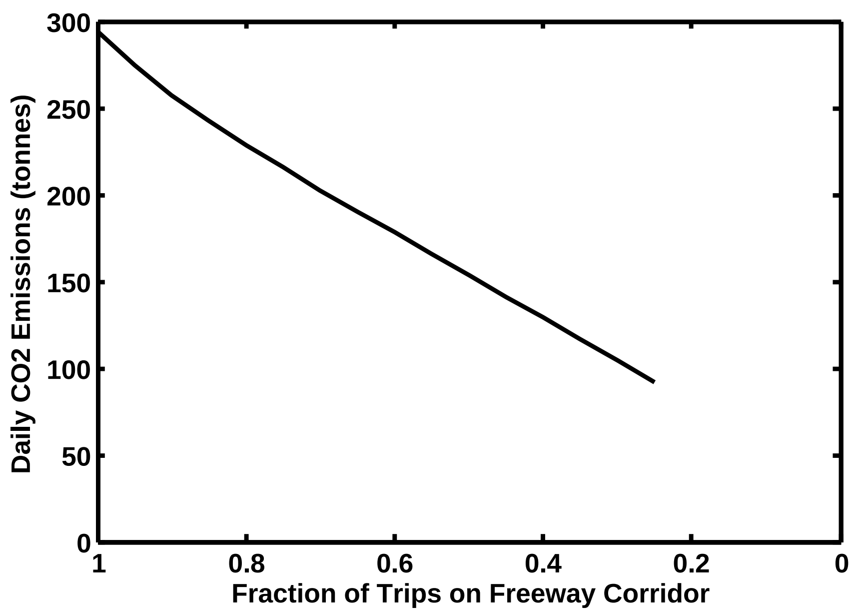

Figure 5.6: Daily corridor CO_2 emissions versus fraction of trips shifted to bus

As illustrated in Figure 5.6, daily CO_2 emissions in the corridor would range from 293.8 tonnes when no trips are shifted to the bus route to 92.3

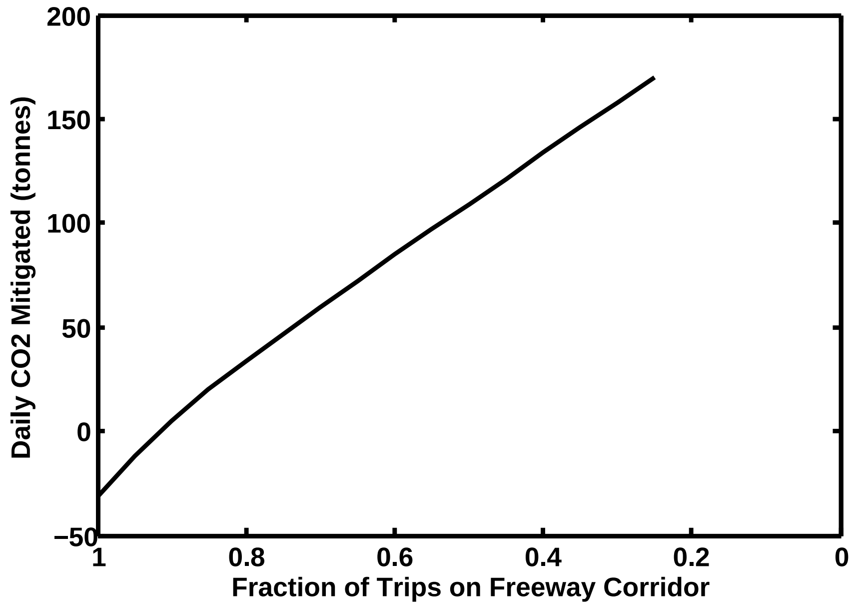

Figure 5.7: Daily CO_2 mitigated versus fraction of trips shifted to bus

tonnes when 75 percent of the trips are shifted to the route, putting it at full capacity. The CO_2 emissions mitigated by the bus route are plotted in Figure 5.7. As seen in the plot, offsetting the extra CO_2 emissions produced by the buses servicing the route requires 10 percent of the trips made by vehicles to be shifted to the bus route. The bus route has the potential to mitigate 170.3 tonnes of CO_2 per day when operating at its full capacity.

To determine the cost effectiveness with which the bus route reduces greenhouse gas emissions, a cost-benefit analysis was performed. Using the unit operating cost of \$2.25/km developed by Checkel[24], the route was found to require \$35,806.50 per day to service. Checkel's estimate takes into account the capital cost of purchasing buses (assuming an 18 year lifespan), as well as recurring costs such as fuel and maintenance. The resulting cost per ton of CO_2 mitigated was plotted against the fraction of trips made by vehicular traffic, as shown in Figure 5.8.

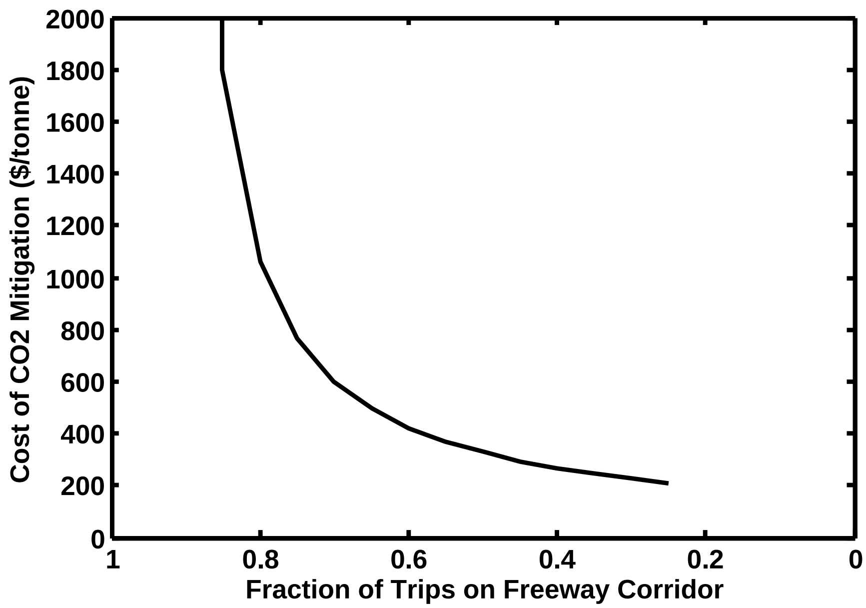

Figure 5.8: Cost-benefit analysis on bus route

As seen in the plot, the bus route reduces CO_2 emissions with a cost similar to the LRT line. The cost per tonne of CO_2 mitigated ranges from several thousand dollars when less than 25 percent of trips are shifted to buses to $210 when the buses operate at full capacity.

5.3 Discussion

The results from the three scenarios considered have been summarized in Table 5.13. The values shown for the daily CO_2 emitted in the corridor and the cost per ton of CO_2 mitigated for the LRT and bus scenarios assume that both systems operate at full capacity.

While both the LRT line and the bus route are capable of substantially reducing greenhouse gas emissions in the corridor, both approaches come

Table 5.13: Summary of scenarios

	Current Configuration	LRT Scenario	Bus Scenario
Daily CO_2 Emissions (tonnes)	262.3	56.6	92.25
Daily CO_2 Mitigated(tonnes)	-	206.0	170.3
Annual Cost ($'000s)	-	14,688	11,876
Cost of Mitigation ($/tonne)	-	$215	$210

with immense costs. Comparing the greenhouse gas reduction costs of over $200/tonne for both transit systems to the $15/tonne regulated value of carbon credits in the Province of Alberta suggests that the development of a public transit system in this corridor is not economical solely as a greenhouse gas reduction tool.

The presence of more traffic and congestion in the baseline scenario would result in the proposed transit systems providing greater benefits. If initial traffic volumes were 10 percent greater, the cost per tonne of CO_2 reduced would drop to $185/tonne for the LRT and $188/tonne for the bus route. Initial traffic volumes 20 percent higher would decrease those values to $136/tonne for the LRT and $129/tonne for the bus route. While lower than the values corresponding to current traffic situations in the corridor, the cost per tonne of greenhouse gas emissions reduced is still substantially higher than the value of a carbon credit.

One factor that has not been accounted for in the cost benefit analyses is the reduction in personal travel expenses in the public transit scenarios. With increased transit service, individuals spend less on fuel and vehicle costs as they use their personal vehicles less frequently. While including this would have improved the cost effectiveness of the public transit initiatives studied, it is unlikely that it would have brought unit cost of greenhouse gas emissions reduction down to the level of a carbon credit.

The values discussed above assume that the transit systems operate at their full capacity. In situations where this isn't the case, the bus route has the advantage of being more scalable than the LRT line due to not requiring the substantial investment in infrastructure the LRT tracks represent. Scaling the frequencies that both systems operate at to cut their capacities in half results in the LRT line having a cost of \$440/tonne of CO_2 reduced compared to a cost of \$204/tonne for the bus route.

While neither transit option studied is economical solely as a greenhouse gas reduction tool, the additional benefits they offer may make their implementation worthwhile. The major financial benefit is often the reduced capital and operating cost of building more road capacity. Beyond this, public transit can provide benefits such as providing transportation to those with reduced mobility and shaping land use through high density housing developing near major transit centers.

5.4 Conclusions

This chapter tests the use of emissions modeling in evaluating potential transportation infrastructure projects. Using microscopic traffic simulation data, the quantitative effects of two transit initiatives on emissions in the study region were compared to the emissions in the current state. The ability to capture the effects of traffic pattern changes on emissions with a high level of detail at a corridor level as illustrated here is due to the use of microscopic emissions modeling techniques. Performing analyses like this enables planners to ensure that available funding is directed to projects providing the greatest environmental return on investment.

Chapter 6

Summary and Recommendations

This dissertation has outlined the development of a microscopic emissions modeling process in which tractive power based emissions functions are applied to microscopic traffic simulation data. The results and achievements of the work performed are summarized in this chapter.

6.1 Evaluation of Simplified Macroscopic Velocity Profiles

Using the developed microscopic emissions modeling process, the performance of the simplified macroscopic velocity profiles used in the emissions model CALMOB6 was evaluated. Vehicles operating in a variety of traffic conditions were simulated using microscopic traffic simulation. The corresponding simplified macroscopic profiles were generated and the emissions resulting from both sets of traffic simulation data computed.

In all cases where acceleration events were present, the simplified velocity profiles were found to significantly under predict the emissions compared to the microscopic simulation profiles. The discrepancy in the results was due to the significantly lower acceleration rates used in the simplified macroscopic profiles. Increasing the acceleration rates was found to make the modeled emissions from the simplified macroscopic profiles closer to those from the microscopic profiles. The analysis performed highlights the importance of accurate vehicle motion simulation in emissions modeling and suggests that the simplified macroscopic velocity profiles currently used in CALMOB6 should be made more aggressive.

6.2 Transportation Corridor Analysis

To test the potential for using microscopic emissions modeling to evaluate potential transportation infrastructure projects, the model was applied to the Whitemud Drive corridor in Edmonton, Alberta. Scenarios representing the development of a light rail transit (LRT) line and a high frequency express bus route in the corridor were evaluated and compared to the corridor in its current configuration. Cost estimates for the two alternative scenarios were developed and used to perform cost benefit analyses.

Both the LRT line and bus route were found to be capable of significantly reducing greenhouse gas emissions in the corridor. However, performing cost benefit analyses on the two alternatives revealed that the unit cost of the greenhouse gas emissions reduction was an order of magnitude larger than the value of a carbon credit suggesting that neither alternate configuration for the corridor is cost effective solely as a greenhouse gas emissions reduction strategy. The analysis performed illustrates the potential for transportation planners to use microscopic emissions modeling in evaluating potential transportation infrastructure projects to ensure that funding is directed to projects providing the greatest environmental return on investment.

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Appendix A

Acceleration Profiles

Acceleration profiles are used in microscopic traffic simulation to determine the aggressiveness with which drivers operate their vehicles. This appendix outlines the selection of the acceleration profile used in the simulations contained in this dissertation.

A.1 Introduction

In VISSIM, acceleration profiles are defined as a function of vehicle velocity and contain maximum, mean, and minimum curves. Desired acceleration and deceleration profiles are defined to dictate how drivers react under typical conditions while maximum acceleration and deceleration profiles are defined to specify the physical limitations of the vehicle. VISSIM contains a number of default profiles that can be used when performing simulations.

Since emissions modeling is highly dependent on the simulated motion of the vehicles in the network, the use of a custom desired acceleration profile developed by Birtch[16] using measured acceleration data was investigated. Since the maximum acceleration and deceleration profiles define the physical limits of the vehicle, these profiles were not adjusted. The desired deceleration profile was also not adjusted since deceleration events do not have a large impact on energy consumption and emissions as the vehicle is essentially idling during deceleration events.

A.2 Default VISSIM Desired Acceleration Profile

VISSIM's default desired acceleration profile is shown in Figure A.1. As seen in the figure, vehicles accelerate at a peak rate of 3.5 m/s^2 from rest. The rate of acceleration decreases as vehicle speed increases.

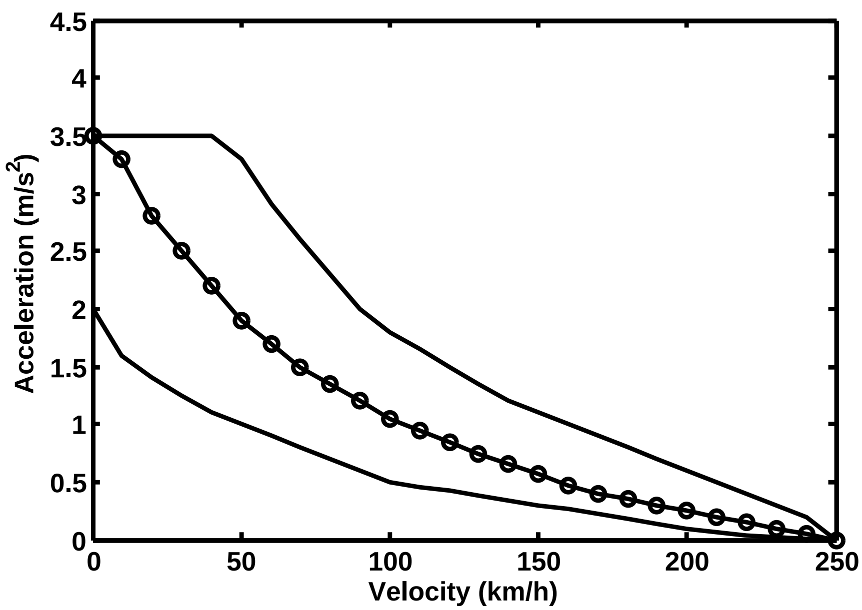

Figure A.1: Default max, mean and min acceleration profiles.

The performance of the default profile was investigated by observing VISSIM simulation data created using it. When the default profile was used, the resulting vehicle motion was found to be overly aggressive, particularly at low speeds. The 3.5 m/s^2 acceleration rate from rest resulted in saw tooth velocity profiles when vehicles were operating in heavily congested situations with frequent starts and stops. The aggressive acceleration rates were found to result in higher than expected modeled energy consumption and emissions.

A.3 Custom Desired Acceleration Profile

To improve the accuracy of the simulated vehicle motion, the use of a custom desired acceleration profile developed by Birtch[16] was investigated. The profile is based on acceleration data recorded in vehicles operating in the city of Edmonton during the fall of 2008. Datalogging computers were fit to a number of vehicles and used to record second by second velocity data over a period of several weeks. Acceleration rates were computed from the data and plotted versus velocity. From the data set, Birtch developed maximum,

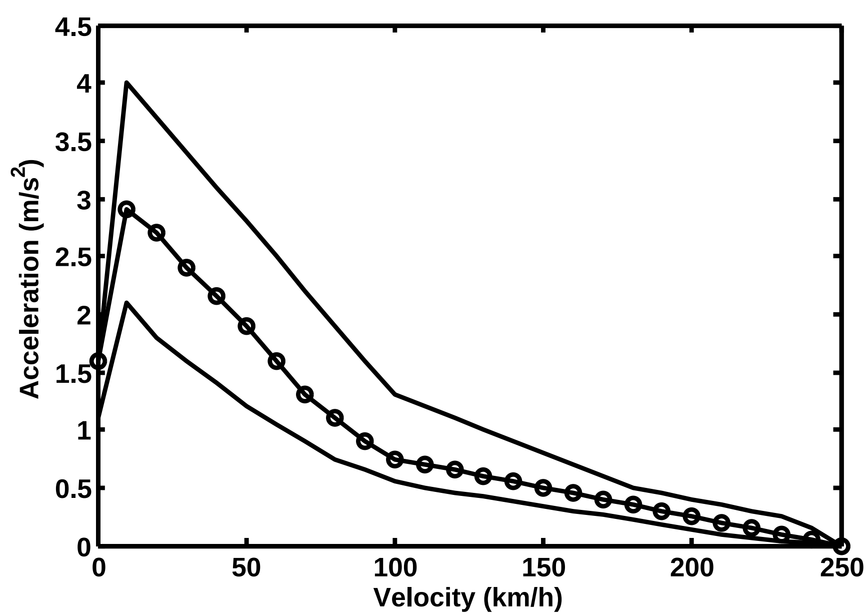

Figure A.2: Measured max, mean and min acceleration profiles.

mean, and minimum desired acceleration profiles, as shown in Figure A.2.

As seen in the figure, vehicles accelerate at a rate of 1.5 m/s^2 from rest, reach a peak mean acceleration rate of 3 m/s^2 at 10 km/h at which point the rate begins to decrease. The 1.5 m/s^2 acceleration rate from rest was found to result in smoother vehicle motion in congested situations where vehicles make frequent starts and stops. As a result, modeled energy consumption and emissions were found to be lower than when the default profile was used.

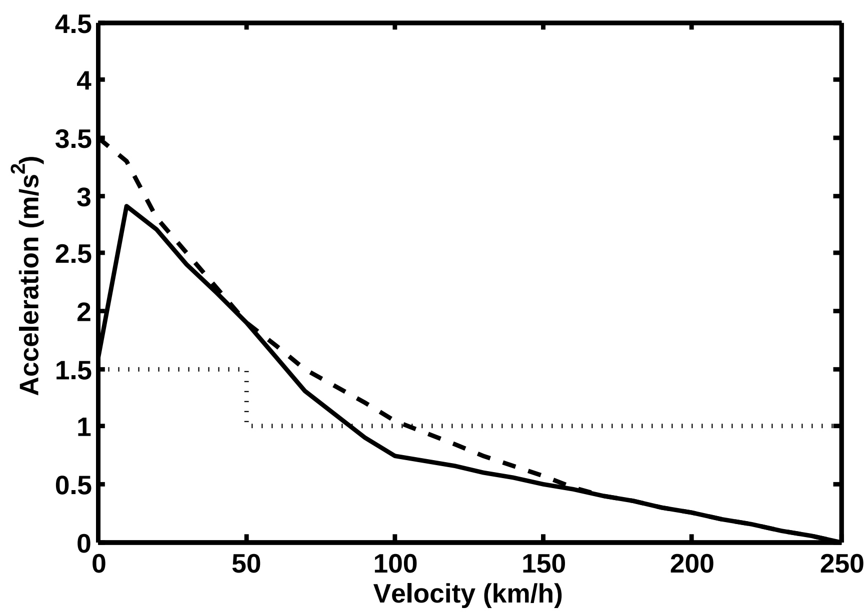

Figure A.3: Comparison between default (dashed), custom (solid) and CAL-MOB6 simplified macroscopic (dotted) acceleration rates.

For comparison, the default and custom desired mean acceleration profiles have been plotted together in Figure A.3. As seen in the figure, the largest difference between the profiles is at low speeds where the acceleration rates in the custom profile are significantly lower. Additionally, the acceleration rates used in the simplified macroscopic profiles generated by CALMOB6 have been included in the figure. Compared with the measured acceleration rates used in the custom acceleration profile, the rates used in the macroscopic profile appear to be too low to accurately reflect traffic conditions in the region of interest, as supported by the results presented in Chapter 4.

Since Birtch's profile is based on acceleration data recorded in the region of study and was found produce smoother, more realistic vehicle motion, it was used in all simulations contained in this dissertation.

Appendix B

Time Step Sensitivity Analysis

One of the most important parameters in microscopic traffic simulation is the time step. This appendix describes the literature review and sensitivity analyses that were performed in selecting a suitable time step.

B.1 Introduction

In microscopic traffic simulation, the time step defines the incremental change in time at which the position, velocity, and acceleration rate of each vehicle in the network is reevaluated. Selecting a suitable time step involves a balance between simulation speed and detail. A short time step ensures that the simulated motion of the vehicles in the network is smooth but requires more computation time to run the simulation while a long time step speeds up the simulation but simulates the motion of the vehicles less accurately.

B.2 Traffic Simulation Time Step

When performing microscopic traffic simulation with the purpose of roadway capacity modeling, a 1.0 second time step is generally used. While this leads to favorable computation times, it also results in the simulated motion of the vehicles being jerky. Since drivers are only assessing their surroundings once every second, they are forced to make more emergency evasive maneuvers. These evasive maneuvers result in higher than normal acceleration and deceleration rates. In roadway capacity modeling, this generally isn't a concern since the aggregate performance of the network is more important than the motion of individual vehicles. However, when performing microscopic traffic simulation with the purpose of emissions modeling, the motion of the individual vehicles is extremely important.

A review of the literature on microscopic traffic simulation time steps suggested that a smaller time step would be required for emissions modeling. Fellendorf found that a 0.2 second time step was suitable for emissions modeling as it produced smooth vehicle motion[17]. To evaluate the use of this time step, a simulation was run using time steps of 0.1, 0.2, and 1.0 seconds. The simulated energy use and CO_2, CO, and NO_x emissions resulting from each time step are shown in Table B.1. The relative difference of each parameter from the 0.1 second results is shown below the results from the 0.2 and 1.0 second results.

Table B.1: VISSIM time step comparison

Time Step (s)	0.1	0.2	1.0
Energy Use (kWh/km)	0.1559	0.1569	0.1969
	(-)	(0.63%)	(26.28%)
CO_2 Emissions (g/km)	191.7	189.6	213.5
	(-)	(1.08%)	(11.38%)
CO Emissions (g/km)	2.645	2.609	2.967
	(-)	(0.97%)	(12.61%)
NO_x Emissions (g/km)	0.2947	0.2951	0.3955
	(-)	(0.13%)	(34.20%)

As seen in the table, the 0.1 second and 0.2 second simulations produced similar results. The slight variation between them is expected due to the randomness inherent in microscopic traffic simulation with many parameters being defined as distributions. On the other hand, the emissions resulting from the 1.0 second time step were significantly higher due to the jerkier simulated vehicle motion. Based on the results obtained here and Fellendorf's findings, a 0.2 second time step was selected as providing the best compromise between simulation speed and accuracy and used in all simulations contained in this study.

B.3 Emissions Modeling Time Step

The process used to model emissions from the microscopic traffic simulation data involved storing the velocity of each vehicle on the network at each time step. With a time step of 0.2 seconds, this approach became impractical due to the vast amount of data that needed to be stored. For example, a one hour simulation using a 0.2 second time step in which 25,000 vehicles are present requires 450 million velocities to be stored. To reduce the data storage requirement, the effect of sub-sampling the microscopic traffic simulation data was investigated.

To perform the analysis, a simulation was run with a 0.1 second time step. The stored data was then sub-sampled to produce files with 0.2, 0.5, 1.0, 1.5, 2.0, and 4.0 second time steps. The emissions resulting from each sub-sample set of data were then computed, as shown in Table B.2.

As seen in the table, sub-sampling the traffic simulation data resulted in very minor impacts on the modeled emissions. Based on the results obtained, the decision to use a 1.0 second time step for emissions modeling was made.

Table B.2: Emissions modeling time step comparison

Time Step (s)	0.1	0.2	0.5	1.0	1.5	2.0	4.0
Energy Use (kWh/km)	0.1491	0.1493	0.1497	0.1501	0.1499	0.1494	0.1461
	(-)	(0.13%)	(0.45%)	(0.67%)	(0.55%)	(0.20%)	(1.96%)
CO_2 Emissions (g/km)	180.8	181.1	181.8	182.8	183.6	184.2	185.6
	(-)	(0.14%)	(0.53%)	(1.10%)	(1.53%)	(1.86%)	(2.67%)
CO Emissions (g/km)	2.481	2.484	2.493	2.505	2.514	2.520	2.534
	(-)	(0.13%)	(0.50%)	(0.99%)	(1.34%)	(1.60%)	(2.17%)
NO_x Emissions (g/km)	0.2816	0.2823	0.2831	0.2840	0.2839	0.2827	0.2782
	(-)	(0.22%)	(0.53%)	(0.83%)	(0.80%)	(0.36%)	(1.21%)

Sub-sampling the results to 1.0 seconds significantly reduces the data storage requirements and results in modeled emissions that are generally within 1 percent of those modeled using a 0.1 second time step.

Appendix C

Fleet Composition Data

This appendix contains the fleet composition data used in the simulations performed in this study.

C.1 Introduction

When modeling emissions, the characteristics of the vehicle fleet operating in the region of study must be defined. This involves breaking the fleet up into different classes, specifying the portion of the fleet made up by each class, and specifying the age distribution of the vehicles in the region. The data used to define the fleet in the region of study was provided by the city of Edmonton and is based on registry data from 2006.

C.2 Distribution of Vehicle Classes

To describe the vehicles operating in the region of study, CALMOB6 breaks the fleet up into twenty-one classes. Representative characteristics for each of these classes, such as mass, frontal area, and coefficients of rolling resistance and drag, are built into the model. In contrast, the microscopic and macroscopic traffic simulation packages used in this study break the fleet up into five classes.

Table C.1: Distribution of vehicle classes

Vehicly Type	CALMOB6 Classification	Percent Fleet Composition
Light-Duty Vehicles	Light-Duty Vehicle - Mini	28.3
	Light-Duty Vehicle - Economy	32.3
	Light-Duty Vehicle - Large	6.9
	Light-Duty Truck 2	7.2
	Light-Duty Truck 1	25.2
Light-Duty Trucks	Light-Duty Truck 3	67.5
	Light-Duty Truck 4	32.5
Medium-Duty Vehicles	Medium-Duty Vehicle 2b	47.7
	Medium-Duty Vehicle 3	31.2
	Medium-Duty Vehicle 4	15.1
	Medium-Duty Vehicle 5	5.9
Heavy-Duty Vehicles	Heavy-Duty Vehicle 6	7.3
	Heavy-Duty Vehicle 7	18
	Heavy-Duty Vehicle 8a	24.9
	Heavy-Duty Vehicle 8b	49.8
Buses	Transit Long	16.2
	Transit New	32.5
	Transit Old	17.6
	Transit Short	31.2
	School Bus Long	0.8
	School Bus Short	1.7

The distribution of the five traffic simulation classes into the twenty-one CALMOB6 classes is illustrated in Table C.1. The fleet composition percentages shown are based on vehicle registry data provided by the city of Edmonton. These values were used in all simulations contained in this dissertation.

C.3 Fleet Age Distribution

Advancements in technology are continuously leading to more efficient, less polluting vehicles. As a result, the age of the vehicles in a region must be taken into account when modeling emissions. To describe the age of the vehicles operating in the region of study, the fraction of the fleet made up of vehicles between zero and twenty-three years old is specified.

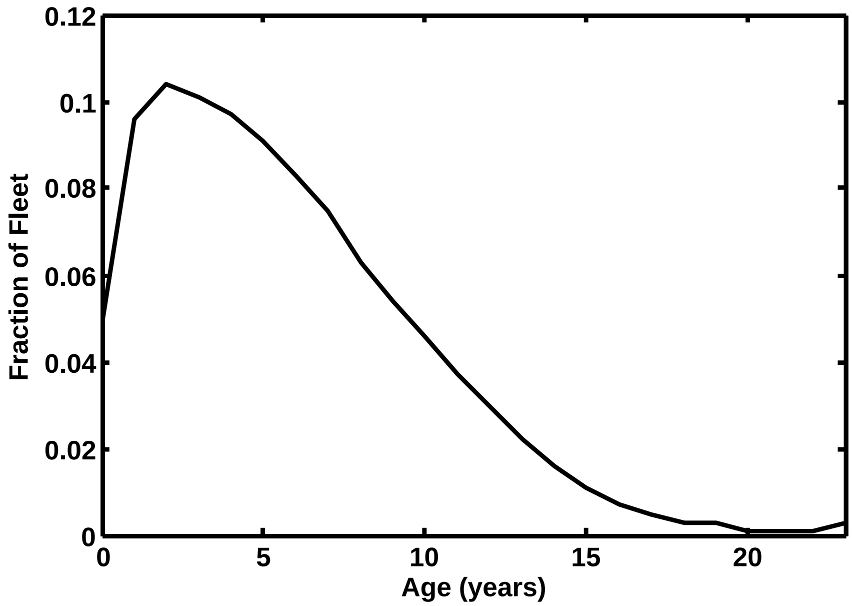

Figure C.1: Fleet age distribution

Figure C.1 illustrates the fleet age distribution for vehicles operating in the city of Edmonton. The data used to produce the figure, shown in Table C.2, has been provided by the city of Edmonton (reference) and is based on vehicle registry data from 2006. The age distribution shown was used in all simulations performed as part of this study.

Table C.2: Fleet age distribution data

Age	Fraction of Fleet
0	0.050
1	0.096
2	0.104
3	0.101
4	0.097
5	0.091
6	0.083
7	0.075
8	0.063
9	0.054
10	0.046
11	0.037
12	0.030
13	0.022
14	0.016
15	0.011
16	0.007
17	0.005
18	0.003
19	0.003
20	0.001
21	0.001
22	0.001
23+	0.003